Department of Mathematics and Statistics

Effective Computational Models for Timetabling Problem

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Declaration

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made.

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

Nur Aidya Hanum Aizam

Date: …….…………………………………

Abstract

Timetabling is a table of information showing when certain events are scheduled to take place. Timetabling is in fact very essential in making sure that all events occur in the time and place required. It is critical in areas such as: education, production and manufacturing, sport competitions, transport and logistics. The difficulty in timetabling is satisfying all the restrictions and requirements. The restrictions relate to resources such as time and location as well as conflicts. The requirements relate to the preferences of customers and service providers. The problem is further complicated by the desire to optimize an objective function that usually relates to the cost or effectiveness of the schedule. The task of how to construct a high quality timetable which satisfies all requirements is definitely not an easy one. A further difficulty is the dynamic aspect of timetabling and the need to accommodate changes after the schedule has been announced. Our focus in this study is on university timetabling problems.

Mathematically, the problem is to optimize an objective function that reflects the value of the schedule subject to a set of constraints that relate to various operational requirements and a range of resource constraints (lecturers, rooms, etc). The usual objective is to maximize the total preferences or to minimize the number of students affected by clashes. The problem can be conveniently expressed as an Integer Programming (IP) problem. The computational difficulty is due to the integer restrictions on the variables. Various computational models including both heuristics and exact methods have been proposed.

The timetabling problem in universities courses has existed for a long time, but due to the complexity and its variation, many researchers are still trying to decipher the solution for this problem. Numerous methods have been developed over the years and most of them have been successful. However, according to McCollum (2006) based on the international review of Operational Research in the UK (Commissioned by the Engineering and Physical Sciences Research Council), a gap still exists

between the theory and practice of timetabling. Additionally, Burke and Petrovic (2002) also mentioned that many methods that have succeeded in solving this problem are applicable to specific institutions where they are designed. Nevertheless, Benli and Botsali (2004) explained that there is no generalized model for this problem because of the variation present in each university. Moreover, the limited availability of facilities and growth of flexibility of the student's choices of courses makes the problem even tighter.

This thesis in whole outlines studies which gain a step in a pathway to develop a more general IP model for university course timetabling problem. We incorporate all important features of this problem which includes the hard constraints and the desirable soft constraints. AIMMS 3.11 mathematical software is employed as a tool to solve the models with CPLEX 12.1 as the solver.

In the first study (Chapter 3), we aim to develop models for timetabling problems which are flexible in terms of the ability to be applied in various institutions. To achieve this, we gather the information obtained on features that are used in other studies, which is covered in the literature review (Chapter 2) of this thesis. From the information on the gathered features, we observed that some features are compulsory, being that they are always used in models to solve timetabling problems. These features therefore form a basic model of university course timetabling problem in this study. We then develop an extended model by incorporating additional features found from the literature. The extended model also contains a few more additional features which we generate that are significant to be included in a model for solving this problem. Different combinations of the features which form the extended model are extracted to produce a range of models. These models are useful to be used by any institutions which require some relevant features to solve their timetabling problem. These models are tested with a small randomly generated test problem. In the following chapter (Chapter 4), we apply the developed model into 3 case studies obtained from the literature. The objective of this is to test the efficiency of the developed models for application to larger problems. Appropriate variation models are used to solve each of the case studies. This application testing is further extended by including a number of additional features. This is to illustrate that the developed model is able to be applied in institutions even when changes of requirements occur. Results from these tests demonstrate successful outcomes from application of our developed models to the chosen case studies.

In Chapter 5, we tested the application of the developed models application in a case study using a pre-assignment approach as a simplification in solving timetabling problem. In this approach, the core units are determined and prioritized to be assigned into prime time slots at the very beginning of the scheduling process. It then follows with the assignment of the remainder units subject to the university requirements. One case study which is applied in Chapter 4 is used for the purpose of testing the pre-assignment approach. From this testing, we show that the pre-assignment is a useful simplification tool in solving timetabling problem of the chosen case study using the developed model, especially in reducing the computational time. We believe that this approach can be applied in other case studies using the developed model.

As an overview of the thesis, we believe that the developed models will be applicable to other problems apart from the ones tested.

List of Publication and Presentations

Publication arising from works in this thesis:

Louis Caccetta and Nur Aidya Hanum Aizam, "Mixed Integer Linear Programming Models for University Timetabling," *East-West Journal of Mathematics*, a special volume, 2012.

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1. International Conference of Techniques and Applications (ICOTA). 2010. Shanghai, China. (Oral presentation).
2. International Conference of Mathematical and Applications: Mixed Integer Linear Programming for Timetabling Problem. 2011. Bangkok, Thailand (Oral presentation)
3. International Conference in Mathematical Sciences and Applications. 2012. Abu Dhabi, United Arab Emirates. (Oral presentation)

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Through laughter, tears and smiles, it has been one splendid journey. Everything was worth it. Note that, each and every one of you contributes to my success. I can't thank you enough. I really appreciate the kindness and precious help. Cheers!!

It is always true about the saying that….

"There is always a light at the end of the tunnel".

Table of Contents

List of Tables and Figures

List of Tables

List of Figures

List of Abbreviations

Abbreviations	Full name
%	Percent
#	Number
AI	Artificial intelligence
AHP	Analytic hierarchy process
ANP	Analytic network process
BIP	Binary integer programming
CP	Constraint programming
CLP	Constraint logic programming
GA	Genetic algorithm
GC	Graph colouring
IP	Integer programming
Lec	Lecturer
LP	Linear programming
MILP	Mixed integer linear programming
NP	Non-polynomial
OR	Operations research
SA	Simulated annealing
Sec	Second
Stud	Student
TS	Tabu search
VAR	Variable
UCTP	University course timetabling problem

CHAPTER 1

Introduction

The central aim of this thesis is to study the features used in models of university course timetabling. It is essential to gather the key features into a single model as much of the research to date has focused on constructing timetabling models based on the requirements and features of specific cases. Such models have been applied only to the particular institution considered and thus cannot be easily applied to other institutions. In this thesis, we provide a more general model for university course timetabling which incorporates a superset of constraints. University course timetabling has received much attention from researchers in both the Operations Research (OR) and Artificial Intelligence (AI) fields and this work is a continuation of this effort specifically towards assisting the timetabling model development by avoiding application in a specific institution only. In this thesis we aim to improve the university course timetabling models by performing the following tasks:

a) We identify through the literature the requirements needed to be included in a university course timetabling model.
b) We formulate the requirements into mixed integer linear programming models.
c) We create random test problems to validate the developed models.
d) We apply these models to a number of case studies found in the literature which are inspired by the real world applications.
e) We analyze the outcomes.

Our improvements are expressed from both the model and computational points of view.

1.1 Background

We begin by the notion of a timetable.

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

(Wren, 1996)

“The timetabling problem consists in scheduling a sequence of lectures between teachers and students in a prefixed period of time (typically a week), satisfying a set of constraints of various types”

(Schaerf, 1999)

“A timetable is a placement of a set of meetings in time. A meeting is a combination of resources (e.g. rooms, people and items of equipment), some of which may be specified by the problem, and some of which must be allocated as part of the solution”

(Burke et al., 1997)

As depicted in Figure 1.1, timetabling arises in transportation, machine scheduling, sports, employee work shifts and even within a university.

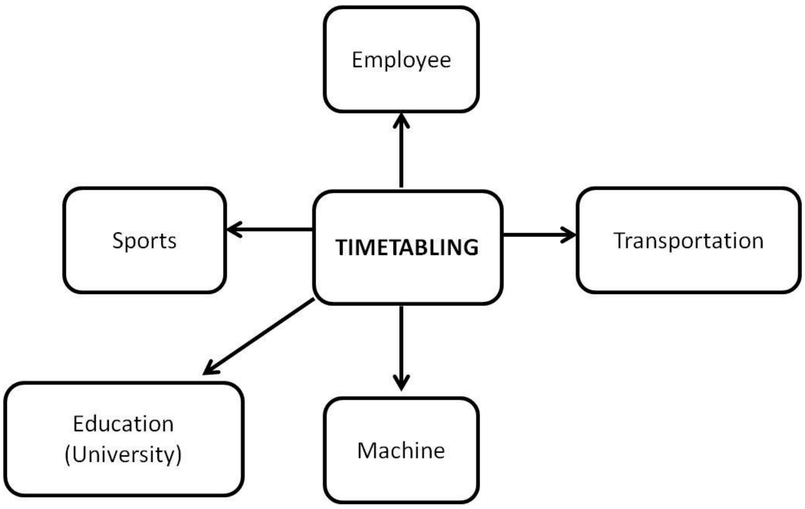

Figure 1.1: Areas in which timetabling arises

A timetable is essential especially for people who are involved in a university. Therefore, the university course timetabling problem (UCTP) is the main focus of this thesis. Basically, the fundamental problem is: given a set of class meetings, student groups, lecturers and rooms, assign a suitable timeslot and location for each meeting subject to a number of hard and soft constraints. Figure 1.2 depicts the structure of a timetable. The constraints are normally the restrictions relating to resources such as time and location as well as conflicts. Also included as part of the constraints are the requirements of the timetabling communities, especially those related to their preferences. The problem is further complicated as there is usually an objective to be optimized. In UCTP, the objective typically relates to optimizing the total preferences of class meetings assigned to their desired slots.

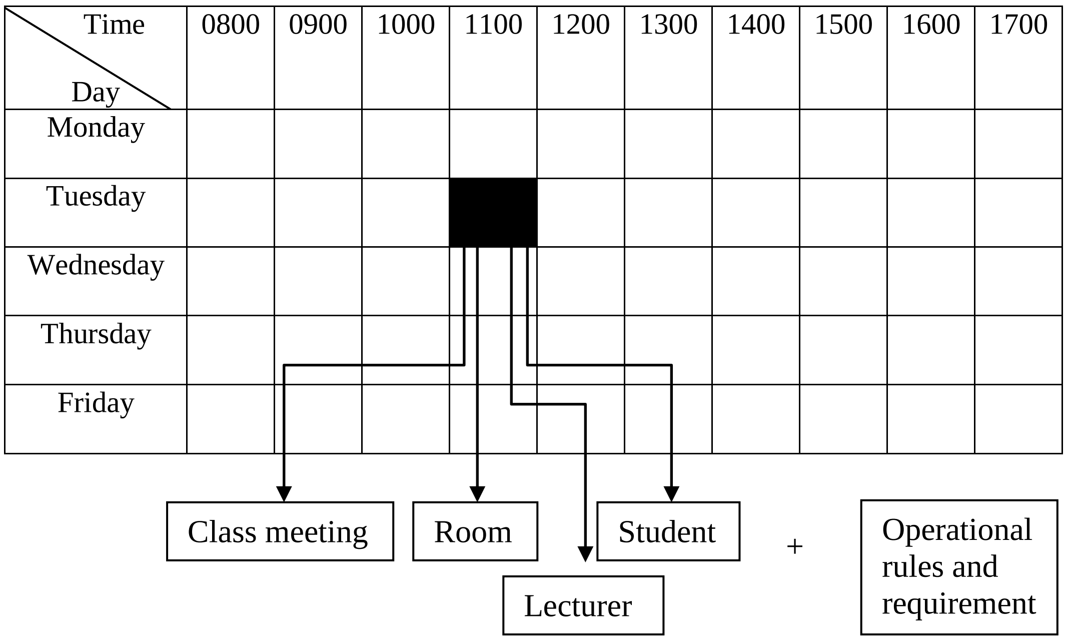

Figure 1.2: Definition of university course timetabling problem

It is definitely not an easy task to construct a timetable that satisfies every involved party. Common complaints normally received from the timetabling communities are:

"The timetable is too hectic"

"No time for my research work"

"Venues for consecutive meetings are too far apart"

"Longer time gaps between meetings"

The timetabling problem in universities courses has existed for a long time, but due to the complexity and its variation, many researchers are still trying to decipher the solution for this problem. Numerous methods have been developed over the years and most of them have been successful. However, according to McCollum (2006) based on the international review of Operational Research in the UK (Commissioned by the Engineering and Physical Sciences Research Council), a gap still exists between the theory and practice of timetabling. Additionally, Burke and Petrovic (2002) also mentioned that many methods that have succeeded in solving this problem are applicable only to specific institutions where they are designed. Nevertheless, Benli and Botsali (2004) explained that there is no generalized model for this problem because of the variation present in each university. Moreover, the limited availability of facilities and growth of flexibility of the student's choices of courses makes the problem even tighter. Therefore, it is necessary to construct a model which includes all the important features of timetabling.

The approaches used to solve these problems can range from integer (Lawrie, 1969; Daskalaki et al. 2004), or constraint programming (Kruk et al. 2005) to graph colouring (Redl, 2007) and heuristics such as tabu search in Costa (1994) and Alvarez-Valdes et al. (2002), and also other local search techniques (Kostuch, 2004). Generally, problems involving optimizing a function subject to a certain set of constraints can be solved using a mathematical programming approach.

In university timetabling, mathematically, the problem is to optimize an objective function that reflects the value of the schedule subject to a set of constraints that relate to various operational requirements and a range of resource constraints (lecturers, rooms, etc). The usual objective is to maximize the total preferences or to minimize the total number of students affected by clashes. The problem can be conveniently expressed as an Integer Programming (IP) problem. The problem may be expressed as:

$$\text{Optimize } z = \sum_{j=1}^{n} c_j x_j$$

subject to

$$\sum_{j=1}^{n} a_{ij} x_j \begin{Bmatrix} \leq \\ = \\ \geq \end{Bmatrix} b_i \text{ for } i = 1 \ldots m$$

$$x_j = 0 \text{ or } 1 \text{ for } j = 1 \ldots n$$

where:

c_j = cost coefficient; x_j = variable; a_{ij} = technological coefficient; b_i = right-hand side value (boundaries or constraints limits such as resources limits); n = number of variables; m = number of constraints.

A Linear Program (LP) is when the objective function and constraint set are linear. It can be efficiently solved using the simplex method. If some of the variables are specified as integer, it will then be a Mixed Integer Linear Program (MILP). The problem is a pure Integer Linear Program (ILP), if all variable values must be integral and Binary Integer Program (BIP) if every variable x is either 0 or 1. The university course timetabling problem can be formulated as one of the above, but we apply IP in our study, as the variables represent an assignment.

1.2 Significance

The mathematical modeling of university course timetable problem has been a wide area of study and research since 1960’s. Whilst many models and methods have been put forward, none have proven to be effective in universities other than where they are developed. In recent times the problems have become more difficult because of an increase in the number of students, the number of courses and options available. Thus, there is an urgent need for improvement. Such improvements will create a most desirable outcome that will satisfy all parties involved especially lecturers, students as well as the administration staff. This will indirectly generate an excellent environment for teaching and learning process. Furthermore, an effective timetabling tool will result in considerable time-saving for the administration. The importance of an automated system is to assure a high-quality service and to develop efficient operational decisions that make the best use of the educational institution available resources. The tools developed will be in part generic and will have applications to a range of scheduling sequencing problems.

1.3 Objectives

In this study, we aim to incorporate as many features as possible that are mostly found in universities into a mathematical model. The model constructed is then tested with the aid of the AIMMS mathematical programming software with CPLEX 12.1 as the solver.

The ultimate objectives of this study are to:

a) Develop mathematical models that incorporate all the important features of timetabling.

b) Investigate the performance of the models developed.

These models can be applied at all levels of university course timetable development. The technology developed can also be used to evaluate the impact of imposing new requirements.

1.4 Thesis Organization

The thesis proceeds as follows:

Chapter 2 is the literature review. We present a brief overview of the timetabling problem, focusing mainly on university course timetabling problem. It looks at the definitions, problems that are encountered and also explains the variety of methods that have been used by researchers in solving the timetabling problem since the early years. In this particular chapter, we will also be observing, analyzing and gathering the features that are required in one's model of university course timetable as a step to our objective in generating a model incorporating all important features. The features include the resource restrictions, operational requirements and also the class meeting patterns.

Chapter 3 focuses more on the modeling aspect of the problem. The aim is to develop a model which incorporates as many features as possible. This would consequently benefit timetabling construction by avoiding application in a specific institution only. Initially, we identify the basic model of the problem by observing the features that are frequently employed in other research papers. We extend the basic model by adding additional features that arise from the literature analyzed in Chapter 2. Three new additional features that we believe should be part of the requirements in a university based on the previous features used are added. These features are basically related to the class meeting patterns particularly on how the class meetings of a course could be assigned. Apart from the basic and extended models, we would also define a number of variations of the models using different combination of features described in the extended model. The problem is formulated as an Integer Programming and the AIMMS mathematical software is used to solve the problem. Concluding the chapter, we evaluate our models by generating a random small test problem. In the following chapter, we apply our models to larger case studies. Our computational results demonstrate the value of our approach in both the computational time and satisfaction percentage, where we achieved almost 100% of the lectures' preference of class meetings to the preferred time slots.

Chapter 4 further verifies the models developed in terms of the application and the results towards solving bigger problems. The performances of the models are evaluated through solving a number of test cases using available data from the literature. Three case studies with different requirements needed in the problem are used. The first case is from one of the Malaysian University. The second case study is taken from Zhang and Lau (2005). They used a randomly generated data for their problem. As for the last case study, we take data from the International Timetabling Competition 2 (www.cs.qub.ac.uk/itc2007). We consider track number 3 of the competition which is the Curriculum-based timetabling problem based on real-world data for the Udine University. We consider 7 out of a total of 21 problem instances as our test data. Overall, there would be a total of 9 sets of problems that are implemented to validate the models in Chapter 3. Originally the main problem is solved using one of the variation models introduced in Chapter 3. We extend the problem by including more additional features which arise in applications. These are also brought up in the previous chapter. This is to evaluate the variation and extended models introduced. All computational results together with the percentage level of satisfaction for all optimization experiments, the original problems and when the additional features added are presented. These results showed that the models generated were effective in giving excellent outcomes in the application towards larger case studies.

Chapter 5 provides an alternative approach in solving the timetabling problem. In this chapter, we tested the efficiency of pre-assigning courses as to simplify the scheduling process. In this approach, we determined the core units and assigned them to the preferred time slots first. The remaining units are scheduled into the timetable only after the assignments of the core units are completed. Using the developed models, the application of this alternative approach in solving timetabling problem was successful.

Chapter 6 provides the conclusions and highlights the major contributions of the study. We conclude the chapter with a number of suggestions of possible directions for future research in the area.

CHAPTER 2

Literature Review

2.1 Introduction

This literature review chapter will focus on the fundamental aspects of the study into the university course timetabling problem. The general definitions on the timetabling problem, problems that arise, constraints used in the various models and also the main approaches related to university course timetabling that have been proposed will be presented. This chapter comprises five sections. Starting off with the brief definition of different timetabling problems, we discuss the literature models and methods. As we are focusing on university course timetabling problem, Section 2.3 presents the area in more detail. It describes the difficulties faced by researchers towards solving the problem. Discussion on the constraints that are being used in the models over the years will be included in Section 2.4. Section 2.5 presents the solution techniques that are employed to solve the university course timetabling problem. These include the exact and heuristic methods. We conclude the chapter with some concluding remarks in Section 2.6. The steps that need to be taken in addressing the timetabling problem are summarized in Figure 2.1.

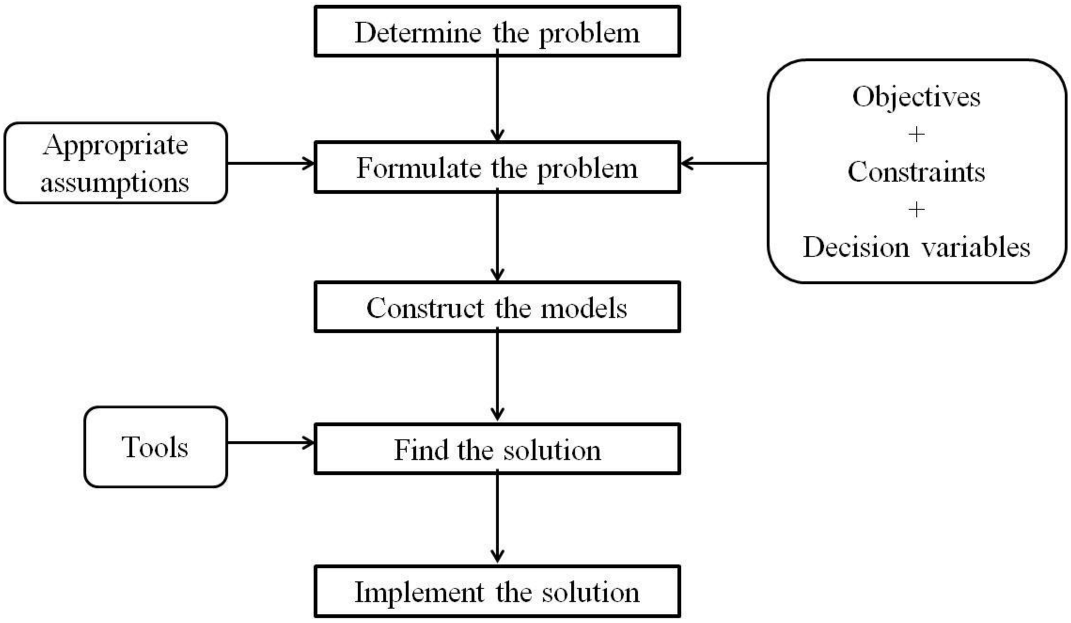

Figure 2.1: Steps in the Operation Research process

2.2 Timetabling Problem

A timetable is generally defined as a table of information showing when and where certain events are scheduled to take place. Wren (1996) expressed timetabling as:

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

Timetabling arises in a wide variety of domains; education, transport, logistic institutions etc. (Burke et al. 2001). It is the one aspect that is required for a well-organized and effective schedule. Among the various related problems on timetabling are the transportation problem (Amirteimoori, 2011), the machine scheduling problem (Blazsik et al. 2008), and staff scheduling such as the nurse scheduling problem (Jenal et al. 2011). There are also other problems such as the sports timetabling (Trick, 2000). Educational timetabling is another essential problem in timetabling. Transportation timetable is the listings of times that transport services arrive and depart from one location to another. Transport institutions need timetables to get all the transportation services running at specific time while fulfilling other constraints such as quantity of vehicle besides maximizing the demand of passenger served and total profit. Logistics distribution defines the association of transportation of one or more supplies from a point of origin to the point of consumption. Timetabling of the logistic distribution ensures that the transportation of certain products to specific locations meet the requirement of time and customer demand. As for the educational institutions, timetabling is a process of assigning courses taken by a group of students taught by a lecturer to a limited number of timeslots and to an appropriate classroom in a way that there are no conflicts (rooms, students and lecturers) while fulfilling a set of differing types of constraints.

Schaerf (1999) classifies timetabling at educational institutions as school timetabling, course timetabling, and exam timetabling problems. Even though these three problems are quite similar in the sense of assigning a number of elements to slots, but they are slightly different. As reported in Carter and Laporte (1998), 5 major differences between high school and university course timetabling can be stated. Among the differences between high school and university course timetabling is the difference in number of rooms to be considered in the scheduling process. There are fewer rooms to be considered in high school timetabling and the sizes of the rooms are alike contrary to different room sizes considered in university course timetabling. In addition, most courses in high school timetabling are often fixed where all students are registered for the same courses, whereby university course timetabling involves many elective courses. This increases the difficulty of assigning student to courses without having conflicts among them. Also, the level of scheduling tightness differs between the two timetabling, where high school timetabling often have a tighter schedule than university course timetabling (Carter & Laporte 1998).

In universities, there are basically two categories of timetabling problems, course and examination timetabling problems. Significant differences occur between the two categories, where in a course timetabling, a single course must be scheduled into one single room but in an examination timetabling, several examinations may be scheduled in either a single room or divided into a few rooms. Another difference is that course timetabling aims at providing students the possibility of having courses simultaneously, while examination timetabling aims at reducing the number of students having concurrent examinations (Burke & Petrovic, 2002).

Course scheduling problem can be broken down into 5 sub-problems:

a) Course timetabling, whether it is a master or demand driven timetabling.
   Carter and Laporte (1998) describe these components in their research. We can find more on demand driven approach in Rudova and Murray (2003).

b) Class-teacher timetabling.
   The problem is to schedule class-teacher meetings without creating conflicts while satisfying other required constraints.

c) Student scheduling.
   Students firstly choose their preferred courses. Once chosen, these courses are to assign to slots. The objective is to minimize the conflict between students.

d) Teacher assignment.
   Teacher assignment problem is where we assign number of teachers available to courses.

e) Classroom assignment.
   This type of problem is to assign the events to specific rooms to satisfy the size, location and facilities preferred.

In this study, we will be focusing on the university course timetabling problem.

2.3 University Course Timetabling Problem

University course timetabling is a classical combinatorial optimization problem (Ismayilova et al. 2007) and can be considered as one of the hard problems in combinatorial optimization (Benli & Botsali, 2004). It is well known that all timetabling problems are NP-complete (Cooper & Kingston, 1993), even in its simplest form. So it is unlikely that an algorithm can be constructed to solve the problem to optimality in a polynomial time. This justifies the search for heuristic methods which are capable of quickly generating a good quality feasible solution without the guarantee of optimality (Pearl, 1984). University course timetabling can be viewed as a multi-assignment problem where students, teachers are assigned to courses, courses to specific time periods and also rooms while satisfying a large amount of complex constraints (Carter & Laporte, 1998).

Useful and satisfying timetable development has been each university main objective. A contented and high quality university timetable is a timetable that can fulfill the user preferences besides avoiding clashes between courses taken by the same group of students, lecturers handling the courses and classrooms being used. Constructing a timetable is a tedious task but creating a high quality timetable is even a tougher assignment. In most institutions, this is left to the administrative staff and has become a major problem to the division. Many problems arise in the process of developing a timetable when assigning a course to day and timeslot in classrooms, while meeting the university terms and policies as well as fulfilling the preferences of the timetable communities.

Among the most critical problem of creating a timetable is the varied nature of different institutions (Zhang & Lau, 2005). No matter what timetable is considered, it usually varies between one institution to another due to the variety of specific requirements and conflict of objective functions (Burke & Petrovic 2002; Benli & Botsali 2004; Ismayilova et al. 2007). The rules are highly dependent on the structure of the school, departments' curriculum, and the availability of resources (Daskalaki et al. 2004). Apart from rules being setup by an institution, individual demands also influence the timetable development (MirHassani, 2006). This will leads to the increment of difficulties towards the problem. Difficulties increase because individuals involved may have different preferences related to instructor, course and timeslot (Ismayilova et al. 2007). Political issues, for example "terrorialist" culture which occurs in an institution would further complicate the construction of timetable (Carter, 2001; Dimopoulou & Miliotis, 2004; McCollum, 2006). According to Carter (2001), many papers ignore human factors in consideration of timetabling construction. McCollum (2006) explained that consideration of this factor in this assignment would produce a timetable which can be applied to a wide range of institutions.

It is therefore not surprising that there is not a single commonly used tool to solve this planning problem even though a rich body of literature exists and there are studies attempting to establish a common structure representing timetabling problems, but there does not exist a general model that is applicable for all cases. Grobner et al. (2003) and Reis & Oliveira (2001) have attempted to establish a general formation representing the timetabling problems in their research. However, Benli and Botsali (2004) explained that a general model that is applicable for all cases does not exist. This is mainly due to the fact that every educational institution has its own special constraints and objectives depending on the rules set up by each university. This is mentioned in Schimmelpfeng and Helber (2007) also in Schaerf and Gaspero (2007).

Due to the varied constraints, the timetable models developed are usually applied to the case it is designed (Bardadym, 1996). Carter and Laporte 1998 mentioned that there are very few papers published that describe actual implementations of course timetabling. In fact the existing universities examples are all restricted to a single department or school (Burke et al., 1997; Carter, 2001) and some are then further simplified (McCollum, 2006). Most papers tend to describe the authors specific problem and ad-hoc solution algorithm (Schaerf & Gaspero, 2007). Even if there are, it is rather limited to a single department or simplified (Burke et al. 1997; Carter, 2001; McCollum, 2006).

2.4 Constraints

The sets of constraints in universities differ significantly from university to university. Each has its target of producing the preferred timetable. Every university has its own unique characteristic which indirectly leads to the different requirements needed in their timetable construction. These rules and requirements are the constraints that have to be considered in their model as a step in the process towards constructing a timetable. Operational rules refer to things such as avoiding conflicts among lecturers, whilst the requirements are more towards the preference of the timetabling community (students and staffs) involved.

Constraint variations often resulted from the diversity in courses' structure. Courses which are divided into elements such as lectures, tutorials or recitations will then need to be structured in a precise manner according the specific requirements. For example, a course which encompasses a very large number of students will have to be scheduled in repetitive sessions which in some institutes use parallel and others at different times.

Another factor which also influence constraint variant is the different number of "credit hours" for every course. "Credit hours" means the number of teaching periods each course has to be assigned weekly. In most universities, a course normally has 4 credit hours.

Constraint variation is also due to the preference of teaching pattern by the staff, some prefer to teach the courses in a single session others prefer having multi sessions that may or may not be consecutive. When courses with a large number of students are taught by several teaching staffs, they may prefer to have them assigned in a parallel manner.

Detailed explanations on variation and difference of characteristic can be found in Schaerf (1999) and Daskalaki and Birbas (2005) respectively. Schimmelpfeng and Helber (2007) concluded that the constraints can be classified into 4 types: teachers' basic assignment restrictions (availability, conflicts, and parallel), school requirements (consecutive timeslots), institutes' restrictions (precedence) and restrictions related to teachers' preferences (work load, day-off, max number of teaching days and preferences with respect to teaching hours which breaks between teaching group). There are a variety of other constraints that exist in a timetable problem. Yeasin and Khader (2005) listed two essential constraints in any timetabling problem as: (i) No entity must be demanded to be more than one place at a time; (ii) For each period in a timetable, the resources demand made by the events scheduled for that period must not exceed the resources available.

Features included in a university course timetabling model can be either hard or soft constraints. Whether it is needed to be satisfied completely or not, determines the category of each feature in the model. In the case where it has to be satisfied, it will be included as a hard constraint in a specific model. This constraint could not be violated in any circumstances in order to produce a feasible timetable. Otherwise the respective constraint will be considered as soft constraint where it does not necessarily have to be satisfied. A penalty will be incurred if violation of the constraint occurs. However, having said that, if a soft constraint is satisfied, it may produce a high quality timetable which pleases everyone. Both categories play an important role whereby they determine the effectiveness of a generated timetable. A sufficiently good timetable is the one which has a feasible outcome but a higher quality is the one which minimizes the total violation of the soft constraints. The common soft constraints for university course timetabling problem that are agreed to by most of the researchers in the literature are the preferences of the lecturers to a slot. In some cases, the hard constraints can also be treated as the soft constraints in order to find a feasible solution.

Initially the constraints which are looked at (as hard/mandatory constraints) are the completeness, conflicts among the resources, and its availability, lecturers' working load together with a few types of meeting patterns. The meeting patterns employed are basically to have the class meetings of the same course or unit assigned consecutively or having a day off between the class meetings. These features are introduced by Schmidt and Strohlein (1979) in their theoretical work of *"Timetable construction – an annotated bibliography"*. A number of variations and additional constraints are followed thereafter. Additional restrictions on working load are observed being applied in the work by Bardadym (1996) whereby student workload is also considered on top of lecturers' workload. The precedence of elements in a course or unit is also incorporated in the same study. The development of constraints continues over the years, and is also observed in a study by Abdennadher and Marte (2000), where an alteration of an existing feature is applied to avoid having class meetings on consecutive slots or same day slots. In contrast, a paper by Daskalaki and Birbas (2004) showed an application of restriction working on the preference of having class meetings assigned to slots in the same day. Schmmilpfeng and Helber (2007) incorporated parallel constraints to work on assigning class meetings in a parallel timeslots, while another quite recent study by Dammak et al. (2008) progressed by incorporating a different restriction which considers the maximum consecutive of class meetings for lecturer in generating a timetable. Slightest alterations to a restriction have shown huge advances in this area of study. It is especially important in application towards different institutions. Thus, we can classify the university course timetabling features into:

Completeness: this particular feature means that every element of a course or unit has to be assigned into a slot

Conflict of resources: resources here refer to the teaching staff (full and part time lecturers), group of students and the classrooms. These elements should be assigned once at a time.

Work load: this is similar to a type of distribution constraint where staffs and student groups have a limited number of teaching and learning hours either for a day or week.

Availability of resources: Basically this availability feature is with respect to the lecturers and rooms.

Meeting patterns: this specific category of features stipulates how the elements of a course or unit are to be assigned.

The major difference between other models is the requirement included especially on how the meeting patterns are to be designed. Meeting patterns that exists in universities vary. As described above, some might need the class meetings to be set in one day. Others might require them to be scheduled in parallel. A brief summary is given in the following tables. The first table presents the features described in some of the theoretical research papers found in the literature. The second and third tables are with respect to the ones that have case studies; real case studies and simulated data. The detailed ranges of features are shown in the same table.

Reference	Description	Features
Schmidt and Strohlein (1979)	Theory	Completeness, Conflict of all resources, Availability of all resources Work Load : Lecturers Meeting Pattern : Two sessions of a course must be assigned in consecutive periods : Day break between two sessions of a course (day-off) Request for Rooms and Pre-assignment of courses
Bardadym (1996)	Theory	Completeness, Conflict, Availability of Lecturers Work Load : Lecturers and Students Meeting Pattern : Class meetings assigned in consecutive periods : Precedence of class meetings in a course Pre-assignment of courses
Burke et al. (1997)	Theory	Conflict, Availability of Lecturers and Rooms Work Load : Student groups Meeting Pattern: Precedence of two sessions of a course Request of room and Pre-assignment of courses
Schaerf (1999)	Theory	Completeness, Conflict of lecturers and rooms, Availability of Rooms Pre-assignment of courses Soft constraint : Desirability of having a lecture of course at certain period
Burke and Petrovic (2002)	Theory	Conflict, Availability of Lecturers and Room request Meeting Pattern : Precedence of two sessions of a course : Sessions cannot to be assigned on the same day : Sessions cannot to be assigned on consecutive slots
Petrovic and Burke (2004)	Theory	Completeness and Conflict of all resources

Table 2.1**:** Features described in some theoretical research publications

Reference	Description	Features
Abdennadher and Marte (2000)	Implemented at Department of Computer Science, University of Munich **Problem Size:** No data was given	**Conflict** : Lecturers and Student groups **Availability** : Timeslot for courses and Lecturers **Meeting Pattern** : Day break between two sessions of a course (day-off) : Sessions that cannot be assigned on the same day : Sessions that cannot be assigned consecutively **Soft constraint** : Some teachers prefer certain times or days for teaching
Dimopoulou and Miliotis (2001)	Tested and used by Athens University of Economics and Business **Problem size:** Approximately 1000 variables and 500 constraints	**Completeness** **Conflict** : All resources **Soft constraint** : Desirability of the assignment
Rudova and Murray (2003)	Implemented to develop timetabling system for Purdue University **Problem Size:** 747 classes 41 classrooms 28994 students 81328 courses	**Conflict** : All resources **Availability** : Time slots for courses **Meeting Pattern** : prohibited or required times for classes **Request for Room** **Soft constraint** : Faculty time preferences and faculty preferences on the classroom selection for classes

Table 2.2(a): Features employed in some real case studies research

Reference	Description	Features
Avella and Vasil'ev (2005)	Real-world instances (kindly provided by the Facolta di Ingegneria of Universita del Sannio, Benevento, Italy). **Problem Size:** 57-69 courses 207-233 class meetings 9-15 rooms 11-14 student groups 41-59 teachers	**Completeness** **Conflict** : All resources **Work Load** : Lecturers and Student groups **Availability** : Lecturers, Rooms and Slots **Meeting Pattern** : Class meetings must be in consecutive periods : Class meetings in a course that cannot be scheduled in the same day **Room Request** **Soft constraint** : Desirability for lecturer to teach in certain times
Benli and Botsali (2004)	Data for one semester from Bilkent University, Ankara, Turkey **Problem Size:** 670 courses in both semesters 112 and 107 student groups 4 room types	**Completeness** **Conflict** : All resources **Work Load** : Lecturers and Student groups **Meeting Pattern** : Sessions in a course cannot be assigned on two consecutive days (Day Off)

Table 2.2(b): Features employed in some real case studies research

Reference	Description	Features
Daskalaki et al. (2004)	Data was taken from the Department of Electrical and Computer Engineering at the University of Patras **Problem Size:** 25 – 92 courses 8-27 lab courses 139 – 326 teaching periods 70 available time periods 3-6 regular classrooms 6-12 labs 55 professors and lecturers	**Completeness** **Conflict** : All resources **Meeting Pattern**: Sessions that need to be in consecutive slots : Sessions that need to be assigned in the same day : Sessions that cannot be assigned in the same day **Pre-assignment of courses**
Daskalaki and Birbas (2005)	Data was taken from the Department of Electrical and Computer Engineering at the University of Patras **2 problems of different size:** 25/92 courses 8/27 lab courses 30/73 teachers 139-/319 teaching periods 3/11 student groups 3-6 rooms 6-12 labs	**Completeness** **Conflict** : All resources **Work Load** : Lecturers **Meeting Pattern** : Some repetitive sessions must be assigned in the same day some not in the same day : Multi-period sessions to be assigned consecutively **Soft constraint** : Preferences for specific time periods for all courses and for specific days of the week for the courses of multiple periods

Table 2.2(c): Features employed in some real case studies research

Reference	Description	Features
MirHassani (2006)	Performed on a real course-timetabling problem **Problem Size:** 75 courses 3 classroom types 6 timeslots 7 days	**Conflict** : Lecturer and Student group **Work Load** : Lecturer and Student group **Meeting Pattern** : Sessions of a course cannot be set on two consecutive days (day-off) : Sessions not to be in the same day **Pre-assignment of sessions to slots** **Soft constraint** : Preferences of all lecturers and some penalties
Schimmelpfeng and Helber (2007)	Implemented at the School of Economics and Management at Hannover University, Germany **Problem Size:** 156 courses 99 teachers 29 conflict groups 11 room types 5 working days 6 slots per day	**Conflict** : Lecturers and Rooms **Availability** : Lecturer **Work Load** : Lecturer and Student group **Meeting Pattern** : Precedence of two sessions of a course : Sessions that need to be assigned parallel : Sessions that need to be assigned in consecutive slots : Sessions of a course cannot be set on two consecutive days (day-off) **Soft constraint** : Preferences of all teachers referring to the room and time slot combination and some penalties
ITC Competition 2 (2007)	All instances are real data from the University of Udine, Italy **Problem Size:** Courses Rooms Lecturers Timeslots	**Completeness** **Conflict** : All resources **Availability** : Slots, Lecturers and Rooms **Soft constraint**: Room stability : Compactness : Minimum working days

Table 2.2(d): Features employed in some real case studies research

Reference	Description	Features
Burke et al. (2008)	Tested on four real-life instances from the University of Udine School of Engineering	**Completeness** **Conflict** : All resources **Availability** : Slots, Lecturers and Rooms **Soft constraint**: number of students left without a seat : number of events timetabled for a curriculum outside of a single consecutive block of two or more events per day, summed across all curricula : number of missing days of instruction, summed across all courses
Dammak et al. (2008)	Considered the problem for the first section at the FEMSS, for the first semester of the academic year 2004-05. **Problem Size:** 8 subjects 6 days 30 timeslots 58 rooms 38 instructors	**Completeness** **Conflict** : All resources **Maximum Consecutive** : Lecturers **Meeting Pattern** : Sessions that cannot assigned consecutively : Sessions that cannot be assigned on the same day **Soft constraint** : Preferences of teaching periods for professors &

Table 2.2(e): Features employed in some real case studies research

Reference	Description	Features
Zhang and Lau (2005)	Sample Case Study **Problem Size:** 24 subjects 203 class meetings 54 timeslots 12 rooms	**Conflict** : Student groups and Rooms **Availability** : Time slots and Lecturers **Meeting Pattern** : Precedence of two sessions of a course : Class meetings in a course that can only be taught in the morning or evening slots
Gunawan et al. (2006)	Randomly generated data **Problem Size:** 20 timeslots 50 teachers 200-400 number of courses 10-20 rooms	**Conflict** : Lecturers and Rooms **Availability** : Lecturers **Work Load** : Lecturers **Soft constraint** : Preferences of assigning courses to teachers at a time period
Burke et al. (2008)	18 semi-randomly generated instances	**Completeness** **Conflict** **Availability** : Time slots

Table 2.3: Features employed in research using simulated data

We can therefore say that constraints such as the completeness, conflicts and availability of the resources are the main features in a university course timetabling. These features have been used as part of the basic model for almost all problems (Schmidt & Strohlein, 1979; Avella & Vasil'ev, 2005). Burke et al. (2008) and the International Timetabling Competition (2007) considered these features as the only hard constraint in their problem. A university may have more constraints considered depending on the requirements of a specific university.

2.5 Methods

Initially, before the widespread use of the computer technology, timetables are constructed manually. It is a task which required many person-days of work. It is in the 60's where the first attempts with computer aided tools are made for timetable construction (Bardadym 1996; Wren 1996).

As reported in Schmidt and Strohlein (1979) the first computer programs to tackle this problem are closely related to timetabling by hand. One of them is to maintain the lists and tables that are classically used (bookkeeping). Amongst all, one heuristic technique caught the researchers' interest. This is a method which involves basic insert and remove operations regulated by a heuristic where courses are assigned in the descending order of complexity.

These early heuristic papers are followed by many others (Schmidt & Strohlein, 1979). Appleby et al. (1960) used a look-ahead counting argument as their heuristic approach. Berghuis et al. (1964) as well as Barraclough (1965) replicated a manual timetabling process. They claimed to be the first group to apply interchange operations when a course scheduling fails.

Even then, many administrative staffs are constructing timetables manually by replicating the timetable every semester. Due to the unsatisfactory resultant timetable, many researchers have drawn their attention to generating timetabling through automated timetabling. Since Gotlieb (1962), numerous publications have been produced associated with this method (Schaerf, 1999).

Many researchers and programmers have investigated this problem thoroughly and without any doubt further ideas will continually be explored. This is evident by the large numbers of timetabling research papers that could be found in the literature every year (Bardadym, 1996).

2.5.1 Solution Techniques

University course timetabling issues have certainly attracted many scientists to perform studies on the university course timetable problem. The complication of getting a good timetable provides attractive challenges for researchers. The timetabling problem has not only been explored by the operational researchers but also researchers from the field of Artificial Intelligence (Schaerf, 1999). Burke and Petrovic (2002) classify the methodologies used for these problems as sequential methods, cluster methods, constraint-based methods, and meta-heuristic methods. Petrovic and Burke (2004) added 3 more categories which are multi-criteria approaches, case-based reasoning techniques and hyper-heuristic/self-adaptive methods to the ones explained in the previous mentioned papers. We could also possibly classify the timetabling problem in terms of the specific solution technique as done by Benli and Botsali (2004). The methods employed in combinatorial optimization problems can be either exact or heuristics.

This section divides the related techniques applied to university timetabling problems into two categories. The details of these categories are discussed in the following sub-sections.

2.5.1.1 Exact Methods

Exact methods seek an optimal solution. Graph colouring, integer programming and mixed integer programming are examples of preferred methods. In this section, we review some exact methods that are used to solve the course timetabling problems.

Graph Colouring

Graph colouring is known to be the earliest and one of the preferred methods in approaching the solution for timetabling problem. Vertices in a graph are the points representing objects and lines connecting the vertices, called edges represent the relationship between the vertices. In university course timetabling, vertices often correspond to class meetings while the edges normally signify the conflicts between the class meetings. A graph colouring is an assignment of colours to elements of a graph subject to certain constraints. More specifically, a colouring of the vertices of a graph such that no two adjacent vertices are assigned the same colour is called vertex colouring. For example, a colouring using a maximum of *k* colours is called a *k*-colouring. The smallest number of colours needed to colour a graph is called the chromatic number. Collection of vertices assigned to the same colour in a colouring is called a colour class. Note that no two vertices in the same colour class are adjacent in the graph, such as subset of vertices is called an independent set. Thus, a *k*-colouring partitions the vertices of the graphs into *k* or fewer independent sets. The colour sets represent the number of timeslots needed. For example, a *k*-colouring using exactly *k* colours gives rise to a schedule requiring *k* time slots. The chromatic number of the graph gives the minimum number of time slots required in the timetable.

de Werra is a leading person in the graph colouring field especially with his several publications on timetabling using this method, including his PhD thesis back in 1969. de Werra (1985) demonstrated the approach to reduce a course timetabling problem to a graph colouring problem. Several formulations for a set of class teacher timetabling problems are proposed by many researchers using this technique since 1960’s (Welsh & Powell, 1967; Neufeld & Tartar, 1974; de Werra, 1996; Bello, 2008). In Welsh and Powell (1967), the vertices of the graph are ordered sequentially, according to degree and the graph is coloured in a greedy fashion without the use of an upper limit on the number of colours. This heuristic is simple and gives reasonable solutions. Selim (1988) used the graph colouring methodology for a faculty timetabling problem in a university, where the vertices are divided for reducing the chromatic number. This method is also employed by Asratian and de Werra (2002) in solving a class-teacher problem where it is able to handle several disjoint groups of lectures. Redl (2007) proposed an alternative graph colouring method for university timetabling which incorporated room assignment during the colouring process.

The graph colouring technique is often used to solve a part of course timetabling problem which is to get initial solution to the overall problem, basically assignment of courses to their slots. The result obtained is then optimized using other existing techniques (Kostuch, 2005).

Integer and Mixed Integer Programming

Integer programming is an alternative way of formulating a timetable problem (Daskalaki & Birbas, 2005). Integer programming is one of the preferable methods that are used in solving the timetable problem.

Among the first approaches in mathematical programming are Lawrie (1969) and Akkoyunlu (1973). They presented linear and integer programming models for the problem and successfully obtained optimal solutions for a school and a university timetabling problem, respectively. A solution for the faculty assignment problem is obtained in Breslaw (1976) via linear programming models. In the study of McClure and Wells (1984), they too attempted the same problem using the same approach.
Ferland and Roy (1985) formulated the timetabling problem as an assignment of activities to resources using a mathematical programming procedure. As a way to tackle the problem, they decompose it into two sub-problems. These two are solved sequentially; assigning classes to classrooms after classes to periods.

Dimopoulou and Miliotis (2001) employed IP optimization approach for the School of Economics and Business in Athens University by assigning group course to a group time. Daskalaki and Birbas (2005) also used integer programming in their study but with a two stage relaxation procedure which involves the relaxation of computationally heavier constraints in the first stage and solving them in the next stage. They claimed that this procedure is better compared to single stage procedures in terms of time reduction and that additional features could be included in the model. Other studies which also employed integer and mixed integer programming in solving the timetable problem include MirHassani (2006), Al-Yaakob and Sherali (2006; 2007), Schimmelpfeng and Helber (2007) and van den Broek et al. (2009). Natasha Boland (2008) engaged the ILP method to solve high school timetabling problem. This study simplifies the problem by partitioning classes into sets of blocks that will be timetabled in parallel. Blocking the classes into sets avoid clashes between classes that populates the same block. Thus, simplifies the process of solving timetabling problem.

The integer programming method has been a successful method in specific problems that have been solved in previous studies. However, complication in creating the model and the computational difficulties due to the size of the problem results in researcher moving towards other approaches (Daskalaki & Birbas 2005). On the other hand, this problem could be overcome by choosing the right value for the cost coefficient. For this it can significantly reduce the computational time which leads to a faster optimal solution. Furthermore, the existence of mathematical programming software with IP solvers that are available these days have resulted in immediate implementation, even for large department (MirHassani, 2006).

2.5.1.2 Heuristic Methods

Exact methods may sometime face difficulties in getting an optimal solution especially within a reasonable computational time. Heuristic methods are the second option. However, the aim is to reach a good solution that is not necessarily in reasonable time. Heuristics is a conceptual procedure, always tend to give a feasible solution, but not necessarily optimal, in polynomial time. Recently the field of AI began to tackle the timetabling problem with newer, promising heuristics. In this section, we briefly discuss some of the heuristic methods. The commonly used heuristics is the local search techniques.

Local Search Techniques

Whenever there is an approach of two methods involved, it is common that one of the local search techniques will be employed to optimize. Local search techniques are basically used as a follow up approach to optimization from a given initial solution. As the course timetabling problem is an NP-hard, local search techniques are among the techniques that are often selected as they can be used to get a good solution in a small amount of time contrary to mathematical program. However, mathematical program is useful to get an optimal solution although with longer computational time.

The basic principle of the local search techniques is to explore the neighbourhood space while passing from one solution to another. Solutions are compared based on an objective function that needs to be maximized or minimized. The main local search techniques often used are Simulated Annealing (SA), Tabu Search (TS) and Genetic Algorithm (GA).

Simulated annealing algorithm is developed from the annealing process, which is a physical process of thermalization involving a sequence of temperature control. Simulated annealing uses a cooling rate to aid the decision of accepting an optimum neighbouring move. Occasionally, a neighbouring move is accepted although it is not the best as a way to avert getting stuck in a local optimum. This method is applied in Johnson (1990) and Elmohamed et al. (1998) and is used to solve an MP model for examination timetabling and course timetabling problem respectively. Kostuch (2005) also employed this method using two stages of simulated annealing to optimize an initial existing timetable.

Tabu search (TS) has a memory of recent moves that it has performed. The moves are irreversible, therefore avoiding cyclic exploration resulting in increased efficiency of the search. A common move is moving the timeslot of one lecture (Costa, 1994). This way, neighbouring solutions are identical except for the time of one lecture. Tabu search has been applied successfully by Alvarez-Valdes et al. (2002) in developing a course timetabling of a Spanish University. They used a three-phase approach where an initial timetable is generated from the first phase and continued with the use of TS algorithm to improve the outcome on the second phase. A heuristic algorithm is used in the last phase to improve the course-classroom assignments. In another study, Nonobe and Ibaraki (1998) used TS to minimize total weights of unsatisfied constraints in a weighted constraint satisfaction problem. Other examples which used tabu search in relation to course timetabling and school timetabling are Hertz (1991), Hertz (1992) and Costa (1994). Hertz (1992) extended his work in Hertz (1991) using a more difficult problem where the length of lectures are unknown.

GA involves coding of a population of potential solutions. Evolution is made to the population of solutions using the algorithm by changing and crossing of these codes in order to choose high quality solutions. From these genetic operators can therefore generate new individual solution and eliminate the poorer ones. This technique is one of the population-based technique used as a heuristic approach for producing acceptable timetables (Schaerf, 1999). GA requires a coding of the potential solutions similar to the genetic identity. The algorithm proceeds by manipulating these codes to select the solutions of high quality. GA's, inspired from the natural evolution, handle, rather than simple solutions, a population of solutions. It is a question of making evolution to this population by propagating the characteristics of the most valid individuals there, using genetic operators, which allow to produce new individuals and to eliminate the worse. There are a large number of studies that use GA's to solve timetabling problems. For example, Paechter (1994), Paecther et al. (1994) and Lewis and Paechter (2005) used this method to solve university timetabling problems. Surveys of the work in this area can be found in Corne et al. (1994) and in Burke & Petrovic (2002).

Another population-based technique applied in solving university course timetabling is the ant colony approach. This technique is inspired by the behaviour of ants which releases *pheromone* in connecting their colony to the food source. This behaviour is applied to timetabling by assigning courses to timeslots depending on the pheromone value of the constraints. Among researchers who applied this method in relation to university course timetabling are Socha et al. (2002), Rossi-Doria et al. (2003) and Nothegger et al. (2008).

Constraint Programming

Constraint programming has attracted many authors (Schaerf, 1999). The main reasons are the features which simplifies the process of attaining a solution. The features are domain reduction and constraint propagation. These two main features in constraint programming, makes the search process faster thus avoids excessive computation (Benli & Botsali, 2004). Its effectiveness in solving large problems also becomes the reasons of attraction. An example of the application of this method in a large size problem is observed in Deris et al. (1997), which considers 536 courses, 45 time slots and 21 classrooms. Although this method is said to be effective, it tends to find a feasible solution rather than optimal solution. Due to this limitation, the usage of CP is sometimes restricted to mainly obtaining initial solution (Duong & Lam, 2004), or being used as a tool to solve only part of the solution process (Cambazard et al. 2004). Constraint programming is used by many other researches including Azevedo and Barahona (1994), Valouxis and Housos (2003), Benli and Botsali (2004) and Zhang and Lau (2005). Hooker (2000) presents an excellent overview of constraint programming and its relation to mathematical programming.

Constraint Logic Programming

A constraint logic programming (CLP) system (Jaffar & Lassez 1987) is a tool for modeling a specific search problem. The CLP is a system that creates values for variables and circulating them through constraints in a model. This would therefore reduce the solution space and avoiding massive amount of computational time. Back track search is the basic method used, where the constraints allow the system to check in advance the outcomes of decisions and find for failure earlier (Schaerf, 1999). Azevedo and Barahona (1994) deal with the timetabling problem using a CLP language called DOMLOG. Several authors have employed constraint logic programming for course timetabling with a good success such as Deris et al. (1997) and Kang and White (1992).

Other Methods

The solution to timetabling problem is also approached by considering it as network flow model. A few authors (Chahal & de Werra, 1989; Dinkel et al. 1989) suggested using this approach. For instance, Dinkel et al. (1989) used a network-based decision support system approach to schedule university courses.

A technique which is also used for this kind of problem is goal programming. Although it is less common in the literature compared to the other approaches, there are authors which employed this method in their research. For example, the teacher assignment problem is solved by Badri et al. (1998) using goal programming. Shniederjans & Kim (1987) and Harwood and Lawless (1975), also used goal programming and mixed integer goal programming respectively to solve their problems. Recently, Ismayilova et al. (2007) employed the same method with a further development by using Analytic Hierarchy Process (AHP) and Analytic Network Process (ANP) to weigh different and conflicting objectives.

It is becoming a trend these days where we can see authors combine methods. Such a combination of methods in solving timetabling problems are observed in Cooper and Kingston (1993) where a cluster of several heuristics is utilized to obtain a solution for their problem. There are also suggestions of combining CP and IP, for developing a valuable tool for the solving timetabling problem (Kruk et al. 2005). This combination of methods is observed in Benli and Botsali (2004) being used to solve combinatorial optimization problem, and is reported to be an efficient approach for large scale scheduling problem.

Among other methods proposed includes meta-heuristic approaches (Carraco & Pato, 2004) which they used neural network for the class-teacher timetabling and harmony search used in Al-Betar and Khader (2012).

In general, the various methods described above are reported to be successfully applied in solving specific timetabling problem. However, their applicability is often only to specific institutions, making its application in all timetabling problem from various institutions unrealistic. Apart from these methods, timetabling problems are often solved by the use of commercial software. *Syllabus Plus* and *Timetabler* are *a*mong the software which is commonly employed by universities in generating their timetables.

2.6 Conclusion

In this chapter, various types of timetabling problems have been discussed. We focused on discussing the university course timetabling and the problem which arises from this type of timetabling. The problem which complicates timetabling construction is mainly due to variation of constraints. The techniques used whether an artificial intelligence or traditional operational research approaches have also been highlighted in this chapter. Among the techniques from both the categories, mathematical programming and local search techniques are observed to be the most preferred methods used in previous researches. Advances of methods are generated in order to increase the quality of the timetable, one of which is the combination of different methods.

A number of reviews on the timetabling problem are available from the literature. This includes an introduction of timetabling basic elements, the approaches of solving the problem as well as surveys of the course and examination timetabling (Carter & Laporte, 1998; Schaerf, 1999). Surveys of timetabling are also available from Hilton (1981) and Klein (1983). Additionally, a review of advances in timetabling is reported in Asratian and de Werra (2002), Burke and Petrovic (2002) and Petrovic and Burke (2004).

We are therefore able to gather the essential information to perform the current study. In this study, a general university timetable problem will be developed with the inclusion of features that have been introduced in the early years of timetabling, together with the new introduced features. All features will be formulated as mixed integer linear programming and solved using mathematical software, AIMMS.

CHAPTER 3

Modeling

3.1 Introduction

Ever since the early years, most of the researchers tend to construct their course timetabling models based of their own institution's problem. The features included are therefore limited and are unable to always be applied to other institutions apart from theirs. Hence in this study, we embrace the suggestion from Schaerf (1999) to incorporate a superset of constraints in a model. This consequently benefits timetabling construction by avoiding application to a specific institution only. Analyzing and collecting constraints employed from a number of studies are part of the steps taken towards constructing the intended model. All together there are 17 different types of requirements. In addition, we have added three new constraint types that we think should be part of the restrictions in a university based on the previous features used. A randomly generated test dataset is created, to illustrate our models. This is used as a tool for model validation before being further implemented to a larger case studies performed in the next chapter. The problem is formulated as an Integer Programming where restrictions that need to be satisfied are included in the model and further requests are incorporated into the objective function. The AIMMS mathematical software package is used to solve the course timetabling problem and obtain an optimal solution. Our results are positive in terms of the computational time. In addition, we achieved almost 100% of the lectures' preference of class meetings to the preferred time slots.

In this chapter, definition of the problem is described in Section 3.2 where all notations are given. It is then followed with the models development as illustrated in sections 3.3 to 3.6. In Section 3.3, the development of basic model is described. Section 3.4 then explains the inclusion of additional features arising in the literature.

Following that, the development of variation models and extended models are explained in Section 3.5 and 3.6 respectively, as a continuation from the basic model. The results are then discussed in Section 3.8 and concluded in the final section, Section 3.9.

3.2 Problem Definition

The university course timetabling is a bi-annual task for every university administration. It is a very difficult task as there are many criteria as well as a complex range of restrictions to consider in satisfying each university's community. In simple form, the timetabling problem can be stated as: given a set of class meetings, student groups, lecturers, timeslots and rooms, the problem is basically to assign these components to suitable timeslots and rooms subject to a set of hard (necessary) and soft (desirable) constraints. Mathematically, the problem is to optimize an objective function that reflects the value of the schedule subject to a set of constraints that relate to various operational requirements and a range of resource constraints (lecturers, rooms, etc). The developed timetable is then be used by all timetabling communities for the entire semester which usually takes up to 6 months.

The problem consists of a set of:

a. **Days or Time slots**: Number of teaching days in a week. Each day is split into a fix number of timeslot which is equal for all day.
b. **Course or Class Meetings**: Each course consist a fixed number of lectures, tutorials, labs to be scheduled. It is attended by a given number of students and is taught by a lecturer.
c. **Rooms**: Each room has its own capacity and facilities. Some rooms may not be suitable for courses.
d. **Curricula**: A curricula is a group of students taking up the same courses.

Restrictions that could arise in a timetable include:

a) Avoiding conflicts between resources such as lecturers and rooms.
b) Resources availabilities.
c) Workloads for staff members and students.
d) Class meeting patterns (parallel, precedence, etc).
e) Lunch and other desired breaks.

We assume that all timetabling information is known in advance.

Our objective is to construct a number of IP models that satisfy the hard constraints and the desirable soft constraints. Hard constraints are the types that are not meant to be violated in any situation such as the operational rules and policies. Conversely, soft constraints are the ones which can be treated as non-essential but indicates circumstances that are optional, namely preferences of students and lecturers to time and rooms.

The following notation is needed to describe our models.

3.3 Notation

Sets

C	Set of class meetings.
R	Set of room type available.
L	Set of lecturers.
S	Set of student groups.
T	Set of timeslots.
T_{slot}	Set of unavailable slots.
Day	Set of days.
C_r	Class meetings requiring type of room r, $\forall r \in R$.
C_l	Class meetings that are taught by lecturer l, $\forall l \in L$.
C_s	Class meetings that have the same group student s, $\forall s \in S$.
T_{morn}	Timeslots consisting only the morning slots for each day

T_{aft} Timeslots consisting only the evening slots for each day

T_l Set of non-available times for each lecturer l, $\forall l \in L$.

T_r Set of non-available times for each room r, $\forall r \in R$.

T_c Set of non-available times for each class meeting c, $\forall c \in C$.

F Set of class meetings in pairs (c_i,c_j) that needs to be scheduled in the same day, $(c_i,c_j) \in C$.

F' Set of class meetings in pairs (c_i,c_j) that cannot be scheduled in the same day, $(c_i,c_j) \in C$.

G Set of class meetings in pairs (c_i,c_j) that needs to occur consecutively in the same day, $(c_i,c_j) \in C$.

G' Set of class meetings in pairs (c_i,c_j) that should not be scheduled consecutively in the same day, $(c_i,c_j) \in C$.

H Set of class meetings in pairs (c_i,c_j) that needs to be scheduled in the morning and afternoon sessions, $(c_i,c_j) \in C$.

K Set of class meetings in pairs (c_i,c_j) that needs to have a day off between two of the classes, $(c_i,c_j) \in C$.

Par Set of class meetings in pairs (c_i,c_j) that needs to be scheduled parallel in one time slot, $(c_i,c_j) \in C$.

Pre Set of class meetings in pairs (c_i,c_j) that needs to be scheduled one after the other, $(c_i,c_j) \in C$.

Parameters

N_r Number of rooms available in each room type, $r \in R$.

n_d Number of timeslots in day $d \in Day$.

T_d Set of timeslots in day d.

L_{max} Maximum number of total class meetings a lecturer can teach in a day.

S_{max} Maximum number of total class meetings a student is allowed to attend each day.

mc_l Maximum consecutive classes a lecturer is allowed to teach.

mc_s Maximum consecutive classes a student is allowed to attend.

$P_{c,t}$ Preference of having class meeting c at timeslot t.

Decision Variables

$$X_{c,t} = \begin{cases} 1, \text{if a class meeting, } c \text{ is assign in time slot } t \\ 0, otherwise \end{cases}$$

Objective Function

$$\text{Maximize} \sum_{c} \sum_{t} P_{c,t} X_{c,t}$$

Here, the objective function is to maximize the timeslot preference, $P_{c,t}$ of allocating class meetings.

According to our approach of assigning values of $P_{c,t}$, all lecturers will provide different level of preferences for the time periods. This information is a pre-processing data obtain before the process of scheduling begins. In our model, these parameters are assignment values in such way to reflect the preference of allocating class meetings to the desired time slots.

3.4 Basic Model

Our basic model is a model which incorporates features that are mostly used by all researchers. Generally, these features are the rules set-up by the university which needs to be satisfied by the scheduler. Three basic rules commonly used in university course timetabling models are found in the literature. These include features such as the completeness where every element of a course or unit has to be assigned into a slot, avoiding conflict between resources (lectures, students and rooms) and the availabilities. These basic features have been considered by a number of authors such as Schmidt and Strohlein (1979), Bardadym (1996) and Avella and Vasil'ev (2005). The objective is mainly to optimize an objective function subject to these features.

Each of the mentioned features is mathematically written as follows:

a) All class meetings must be assigned to a time slot

$$\sum_{t} X_{c,t} = 1 \qquad \forall c \tag{3.1}$$

b) The room limitation restrictions

$$\sum_{c \in C_r} X_{c,t} \leq N_r \qquad \forall t \quad \forall r \in R \tag{3.2}$$

c) A lecturer must not teach more than one class meeting at a time

$$\sum_{c \in C_l} X_{c,t} \leq 1 \qquad \forall t \quad \forall l \in L \tag{3.3}$$

d) Student-clashing

$$\sum_{c \in C_s} X_{c,t} \leq 1 \qquad \forall t \quad \forall s \in S \tag{3.4}$$

e) Availability of lecturer

$$\sum_{t \in T_l} \sum_{c \in C_l} X_{c,t} = 0 \qquad \forall l \in L \tag{3.5}$$

f) Availability of room

$$\sum_{t \in T_r} \sum_{c \in C_r} X_{c,t} = 0 \qquad \forall r \in R \tag{3.6}$$

g) Availability of timeslots

$$\sum_{t \in T_{slot}} X_{c,t} = 0 \qquad \forall c \qquad (3.7)$$

Thus, we can write the basic model for the course timetabling as:

$$\text{Maximize} \sum_{c} \sum_{t} P_{c,t} X_{c,t}$$

subject to:

constraints (3.1) – (3.7)

and

$$X_{c,t} \in \{0,1\} \qquad \forall c \quad \forall t$$

3.5 Additional Features

In the following, we introduce a number of additional features to the basic model which do arise in various applications in the literature. We will also be adding some new practical restrictions motivated from the existed features. As an example, there are rules associated with the work load for lecturers and limit of daily assignments for students. These features are expressed as:

a) Maximum of total class meetings that a lecturer can teach in a day

$$\sum_{t \in Day_d} \sum_{c \in C_l} X_{c,t} \le L_{\max} \qquad \forall d \in Day \qquad \forall l \in L \qquad (3.8)$$

b) Maximum of total class meetings that a student can attend in a day

$$\sum_{t \in Day_d} \sum_{c \in C_s} X_{c,t} \leq S_{\max} \qquad \forall d \in Day \qquad \forall s \in S \qquad (3.9)$$

Certain universities limit the number of class meetings assigned consecutively. Therefore, having a maximum number of consecutive classes taught by the lecturer is also considered. This feature can be written as:

a) Maximum consecutive class meetings for a lecturer

$$\sum_{c \in C_l} (X_{c,t} + X_{c,t+1} + \ldots + X_{c,t+mc_l}) \leq mc_l$$

$$\forall t \in \{t_1, t_2 \ , \ldots, t_{n_d - mc_l}\} \qquad (3.10)$$

Apart from what we've seen in the literature, in reality this should also be applied for the students.

b) Maximum consecutive class meetings for a student

$$\sum_{c \in Cs} (X_{c,t} + X_{c,t+1} + \ldots + X_{c,t+mc_s}) \leq mc_s$$

$$\forall t \in \{t_1, t_2 \ , \ldots, t_{n_d - mc_l}\} \qquad (3.11)$$

Meeting patterns due to multiple sessions is an important feature of a specific course. Certain specific courses offered in a university semester normally consist of different elements of class meetings such as lecture, tutorials and laboratory classes. These courses often need to have the elements of class meetings scheduled in the same day or vice versa. We consider this as follows:

a) Some specific class meetings must be scheduled in the same day

$$\sum_{t \in Day_d} (X_{c_i,t} - X_{c_j,t}) = 0 \qquad \forall (c_i, c_j) \in F \quad \forall d \in Day \tag{3.12}$$

b) Some specific class meetings should not be scheduled in the same day

$$\sum_{t \in Day_d} (X_{c_i,t} + X_{c_j,t}) \leq 1 \qquad \forall (c_i, c_j) \in F' \quad \forall d \in Day \tag{3.13}$$

There are also requirements where different elements of class meetings in a specific course needs to be scheduled consecutively or must not be scheduled in that manner. In these cases, the formulations are:

a) Class meetings that need to occur consecutively

$$X_{c_i,t} = X_{c_j,t+1} \qquad \forall (c_i, c_j) \in G \quad \forall t \in \{1,2,\ldots,n_d - 1\} \tag{3.14}$$

b) Class meetings that should not occur consecutively

$$X_{c_i,t} + X_{c_j,t+1} \leq 1 \qquad \forall (c_i, c_j) \in G' \quad \forall t \in \{1,2,\ldots,n_d - 1\} \tag{3.15}$$

Having class meeting either in the morning or afternoon session is another constraint which is sometimes found in the literature. This can be concluded as having only a single class meeting in a particular day. From this observation, we believe that having an interval between two class meetings (morning and evening sessions) on the same day is sometimes demanded by certain universities. Contemplating this, we express the requirement with the formulation below with the addition of constraint (3.12) in the model.

$$\sum_{t \in T_{morn}} X_{c_i,t} = \sum_{t \in T_{aft}} X_{c_j,t} \qquad \forall (c_i, c_j) \in H \qquad (3.16)$$

In a case where a course is enrolled by a high number of student, resulting in division into multiple classes (lectures, tutorials or labs), it is sometimes required to have these classes running simultaneously. In this situation, the requirement can be formulated as a parallel constraint shown below:

$$X_{c_i,t} = X_{c_j,t} \qquad \forall t \qquad \forall (c_i, c_j) \in Par \qquad (3.17)$$

With a request from lecturers to have the students taking tutorial classes only after the lecture is conducted is also one of the meeting patterns existing in university's scheduling requirement. This meeting pattern is mainly called precedence constraint. It can be mathematically written as the following:

$$X_{c_i,t} - \sum_{t=t+1} X_{c_j,t} = 0 \qquad \forall (c_i, c_j) \in Pre$$

$$\forall t \in \{1,2,\ldots,t-1\} \qquad (3.18)$$

Having a day off between two classes of the same course is another requirement often found in universities. Below is the formulation:

$$\sum_{t \in Day_d} X_{c_i,t} + \sum_{t \in Day_d + Day_{d+1}} X_{c_j,t} \leq 1 \qquad \forall d \in Day \qquad \forall (c_i, c_j) \in K \qquad (3.19)$$

Some courses often require classes to be assigned in an equally distributed manner where lectures of each course must be spread into a given number of days. Besides having classes uniformly dispensed, we could also develop another distribution type of constraint where universities require having more classes to be assigned earlier in the week than later in the week which we believe to be very useful in some universities. This means that, the number of lecture each day is monotonically decreasing; either the same number of class meeting or less. We can formulate this constraint as:

$$\sum_{t \in Day_1} X_{c,t} \geq \sum_{t \in Day_2} X_{c,t} \geq \ldots \geq \sum_{t \in Day_d} X_{c,t} \qquad (3.20)$$

where $t \in Day_d$ is the timeslots in Day_d

From the additional features described above, 3 new constraints have been introduced.

a) Maximum consecutive class meetings for the students, which can be referred in equation (3.11).
b) Distribution of class meetings: having more class meetings earlier in the week, which can be referred in equation (3.20).
c) Gap: Having class meetings of the same course in the morning and afternoon sessions on the same day, which can be referred in equation (3.16).

3.6 Variation Model

We could define a number of variations of problems using different combination of features described earlier. The table below shows the features used by different researchers in their models that are found in the literature. In all consecutive tables presented in this thesis, constraints (3.1) to (3.20) are presented as 1 to 20.

Features	Basic							Work Load		Max Consecutive		Meeting Patterns									
								Lec	Stud	Lec	Stud										
Model	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Model 1 [83]	✓	✓	✓	✓	✓	✓	✓	✓				✓							✓	
Model 2 [13]	✓	✓	✓	✓	✓			✓	✓					✓				✓		
Model 3 [22]		✓	✓	✓	✓	✓			✓									✓		
Model 4 [80]	✓	✓	✓			✓														
Model 5 [1]			✓	✓	✓		✓						✓		✓				✓	
Model 6 [40]	✓	✓	✓	✓																
Model 7 [24]		✓	✓	✓	✓								✓		✓			✓		
Model 9 [78]		✓	✓	✓			✓													
Model 10 [10]	✓	✓	✓	✓	✓	✓		✓	✓				✓	✓						
Model 11 [74]	✓	✓	✓	✓																
Model 12 [16]	✓	✓	✓	✓				✓	✓										✓	
Model 13 [35]	✓	✓	✓	✓								✓	✓	✓						

Table 3.1(a): Summary of the features used by different researchers in the literature

Features	**Basic**							**Work Load**		**Max Consecutive**		**Meeting Patterns**								
								Lec	Stud	Lec	Stud									
Model	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Model 14 [92]		✓		✓	✓		✓											✓		
Model 15 [34]	✓	✓	✓	✓				✓				✓	✓	✓						
Model 16 [67]			✓	✓				✓	✓				✓						✓	
Model 17 [48]		✓	✓		✓			✓												
Model 18 [82]		✓	✓	✓	✓	✓		✓						✓			✓	✓	✓	
Model 19 [54]	✓	✓	✓	✓	✓															
Model 20 [23]	✓	✓	✓	✓			✓													
Model 21 [33]	✓	✓	✓	✓						✓			✓		✓					

Table 3.1(b): Summary of the features used by different researchers in the literature

Previously, models in the literature have considered only certain number of features which are relevant to the specific application. What if a university needs to consider some additional features apart from the ones mentioned? In this case, a different model needs to be generated in order to solve the timetabling problem. For this reason, we constructed variation models with different combination of features described. Some of the models consider the new set of constraints. These types of models may arise in the application of course timetabling problem which hasn't been generated before. For example, student workloads are considered in some of the models, and workloads for the teaching staffs are considered in some of the other models. In addition, we also have a number of different types of meeting requirements considered. However, all basic constraints are used in our models.
Table below shows the variety of models showing combinations of different features that may arise in the course timetabling model application.

Features	Basic							Work Load		Max Consecutive		Meeting Patterns									
								Lec	Stud	Lec	Stud									
Model	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Model A	✓	✓	✓	✓	✓	✓	✓										✓		✓	
Model B	✓	✓	✓	✓	✓	✓	✓							✓		✓		✓		
Model C	✓	✓	✓	✓	✓	✓	✓			✓	✓					✓				
Model D	✓	✓	✓	✓	✓	✓	✓	✓	✓							✓				
Model E	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓							
Model F	✓	✓	✓	✓	✓	✓	✓			✓	✓			✓	✓					
Model G	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓							
Model H	✓	✓	✓	✓	✓	✓	✓	✓	✓					✓	✓					
Model I	✓	✓	✓	✓	✓	✓	✓	✓	✓							✓				✓
Model J	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓	✓	✓					
Model K	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓				
Model L	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓				
Model M	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓					

Table 3.2: Combinations of different features that may arise in the course timetabling model application

3.7 Extended Model

Models from Schmidt and Strohlein (1979) and Schimmelpfeng and Helber (2007) are the most complete models seen in the literature which considered 11 out of the 20 collected features. Thus, for our extended or general model, we are considering a problem with all features discussed. We think that by constructing a general model including the new set of features together with all discussed features, this would be an improved model beneficial to other researchers. The list of features required is:

a) Completeness.
b) Conflicts between lecturers, student group and rooms.
c) Availabilities.
d) Working loads for both lecturer and student.
e) Maximum consecutiveness for both lecturer and student group.
f) Meeting patterns such as:
    i) Parallel constraint.
    ii) Precedence constraint.
    iii) In a day.
    iv) Not having classes in a day.
    v) Consecutively.
    vi) Not having classes consecutively.
    vii) Morning and afternoon slots.
    viii) Day-off between two classes of the same course.
    ix) Distribution constraint.

Thus, the extended IP model for a course timetabling problem can be written as:

$$\text{Maximize} \sum_{c} \sum_{t} P_{c,t} X_{c,t}$$

subject to:

constraints (3.1) – (3.20)

and

$$X_{c,t} \in \{0,1\} \qquad \forall c \quad \forall t$$

3.8 Experiments

The IP models are tested on a small generated dataset. This dataset is made of 22 courses offered which breaks up into 44 elements of class meetings. The data considers 10 lecturers, 5 student groups, 2 types of rooms with 1 room available for each type and 25 timeslots with 5 slots in each day. We use simple data for the purpose of illustrating the proposed models. Each of the models is tested on the generated problem 2 times to find:

a) Feasible solution: no soft constraints are included.
b) Solution to optimization: soft constraints are included. In particular, the soft constraint incorporated is the lecturers' preferences.

Detail information on the dataset can be referred in the appendix. The lecturers' input preferences for assigning class meetings to desired slots are also included. All of the experiments are run on AIMMS 3.11 optimization software with CPLEX 12.1 as the solver. In the following sections, the results from all the experiments will be documented.

3.8.1 Satisfaction Experiments

Satisfaction experiment aims to get a feasible solution where no soft constraints are included. For this experiment, the input preference of class meetings to slots for each lecturer is all determined to be "1". Each of the models is run on the problem instance above. As soon as a feasible solution is found, (i.e. a solution that did not violate any hard constraints) the time is recorded. The results are shown in the table below.

CPU Time	0.05 sec
Objective Function Value	44
Number of Constraints	508
Number of Variables	1101
Number of Non-Zeroes	5598
Number of Iterations	138

Table 3.3: The results of constraint satisfaction for basic model

CPU Time	0.67 sec
Objective Function Value	44
Number of Constraints	6535
Number of Variables	1101
Number of Non-Zeroes	26,139
Number of Iterations	970

Table 3.4: The results of constraint satisfaction for extended model

3.8.2 Optimization Experiments

Here the lecturers' preference of having a class meeting to a slot is taken into account. The preference parameter contains the lecturer's preference concerning assignment of class meeting to a slot. Integer values between scale 1 (least preferable) and 5 (most preferable) is used to determine these assignments.

CPU Time	0.05 sec
Best Objective Function Value	176
Number of Constraints	508
Number of Variables	1101
Number of Non-Zeroes	5598
Number of Iterations	182

Table 3.5: The results of optimization experiment for basic model

CPU Time	49.48 sec
Best Objective Function Value	168
Number of Constraints	6445
Number of Variables	1101
Number of Non-Zeroes	25,893
Number of Iterations	242,983
Number of Nodes	5202

Table 3.6: The results of optimization experiment for extended model

3.9 Discussion

Basic model consists of features that are commonly or frequently included. Features such as completeness, conflicts among resources (lecturers, students, rooms, etc) and its availabilities' are examples of basic criteria that one must have in their course timetabling model.

Whereas, the extended model or what seems to be a more general model is the extra additional features that are found in the literature. These features are basically related to the class meeting patterns. An example of these extra features is the requirement of having all class meeting in the same curricula to be scheduled on the same day or vice versa. Other types of features are the working loads for lecturers and students also the need of having lunch breaks. Hence, a general model is where all or most of these features are included in the model.

From the features gathered, varieties of other course timetabling models could also be developed by combining different features in a model. These variation models may arise in the applications.

For purpose of illustrating the models, a simple randomly generated data is employed. We tested the data to both basic and extended models. We assumed that, testing the data on to the extended model is sufficient enough in terms of model validation rather than having to test the data into the several variation models of ours. We divide the experiment into two experiments; satisfaction and optimization.

Satisfaction experiment aims to get a feasible solution. All feasible solution is considered as optimal solution. During this experiment, the input for the preference of class meetings to slots for each lecturer is determined to be 3, where no specific desirability of class meetings to slot is taken into consideration. Optimization experiment is when lecturers' preference of assigning class meetings to slots influenced the scheduling.

Successful outcomes are obtained for all the experiments in terms of the CPU time whilst satisfying all features that are included respectively. The results obtained are all under a minute. We achieved 0.05 seconds and 0.67 seconds for the satisfaction experiment for both the basic and extended model. Similar time is needed for the basic optimization experiment to get to optimize. Although a slightly longer CPU time is required for the optimization experiment for the extended model, which is 49.48 seconds yet we can still consider this a very promising result where the time needed to get the solution to optimization is not more than a minute.

Another way of assessing the timetable produced is by measuring the lecturers' satisfaction level of having their class meetings to their preferred time slots. Figure 3.1 illustrates the percentage of the class meeting assignment that corresponds to the lecturers' desired timeslots for the optimization basic model. From the figure, we can see that 93.18% obtained their class meetings to the preferred timeslots. Only 4.54% and 2.27% of lecturer obtained second and third choice respectively. Nevertheless, none of them are assigned to a least preferable timeslots.

Likewise, Figure 3.2 shows the percentage of the class meeting assignment that corresponds to the lecturers' desired timeslots for the optimization extended model. Using this model, 88.64% got to their first choice selection of their time slots and 4.54% to their second and third options equally. Only 2.27% is assigned to their fourth choice.

We attained very encouraging results for all models where the outcome is not only conflict free, but also attained in a short period of time. In addition, the determined schedules respect the soft constraint related to the preference of having class meeting to timeslot and all hard constraints listed.

In the carried out experiments, we assume that the information of the required rooms for every class meeting is known in advance. It is considered as the pre-processing data. Also excluded is the pre-assignment of class meetings to slots. However, we would consider this particular feature in Chapter 5.

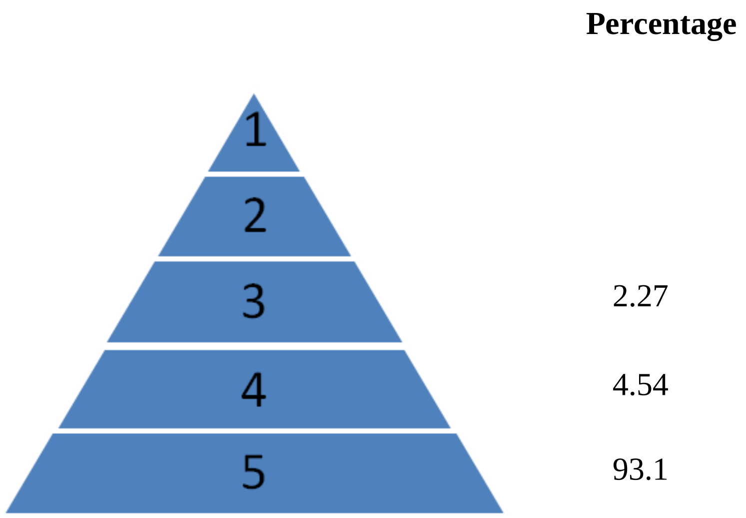

Figure 3.1: Percentage of the class meeting assignment that correspond to the lecturers' desired timeslots for the optimization basic model

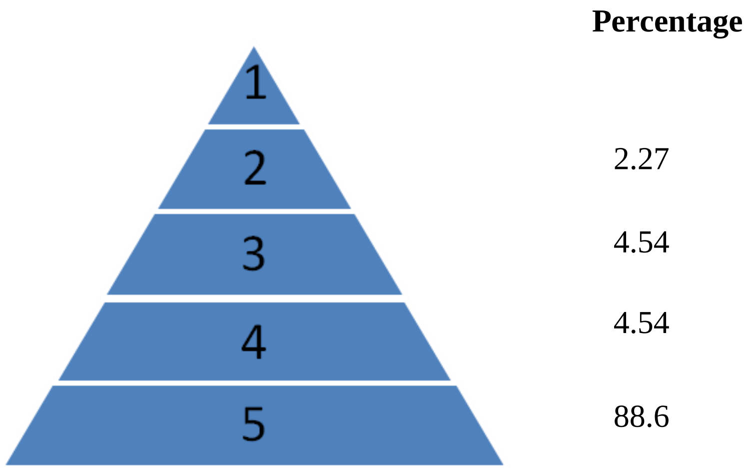

Figure 3.2: Percentage of the class meeting assignment that correspond to the lecturers' desired timeslots for the optimization extended model

3.10 Conclusion

In this chapter, we have discussed the features that are usually employed in a university course timetabling basic model. We then extended the model by adding more features found in the literature and based on our observations in university timetabling as to build one model which includes as many features as possible. From there, we created more models by extracting the features in the extended model. To illustrate all models described, a simple data is created for the purpose of testing and validating the models. The outputs obtained are analyzed.

Result from this experimental work supports the suggestions that Integer Programming (IP) is capable of generating university course timetable. The developed model from this study, which considers most of the features used in other studies, gave an optimum solution. These models are useful to be applied on the process of timetabling construction by the university administrative staffs.

Even though the problem generated at this stage is a small size problem, the model is tested to be effective. The developed model may overcome the inability of a model to be applied in a wide range of institutions. In the subsequent Chapter, 3 different case studies will be employed to further verify the models developed. Detailed description on the problems and discussions on the results will also be included. This would therefore be sufficient for validating the model.

CHAPTER 4

Computational Results for Case Studies

4.1 Introduction

In order to analyze the efficiency of the models developed in the previous chapter, we will further test these models on several problem instances that are available in the literature. Three literature data sets are taken and tested on the respective models described earlier. The first problem is taken from a Malaysian public university which is to schedule a number of class meetings for its post-graduate courses. This is then followed by a test dataset taken from Zhang and Lau (2005) which they use as a sample case study for their research involving the use of constraint satisfaction programming to solve university timetabling. The final problem is obtained from the International Timetabling Competition held in 2007. We consider only the Curriculum-based timetabling problem consisting of 21 problem instances which are based on real-world data for the Udine University. These 21 instances are divided into three categories of seven datasets (early, late and hidden datasets). As for our study, we take into account the first seven instances and labelled them in an alphabetical order. Overall, there are a total of 9 sets of problem that are implemented to validate the models in Chapter 3.

Initially, the original problem will be solved. Additional features are added which are sensible for applications in the construction of the timetables. This provides a basis for evaluating the many variations and extended models introduced. In this chapter, the results and discussions are also given from the literature test data mentioned. Below are two tables showing general statistics to literally give a picture of the size of the problems used and also the features that illustrate each problem.

This chapter is organized as follows. Case study 1, 2 and 3 are discussed in Sections 4.2, 4.3 and 4.4 respectively. Discussions on the results are given in Section 4.4, followed by Section 4.5, the conclusion.

Problem I.D	Number						
	Day	**Period**	**Course**	**Class Meeting**	**Var**	**Lec**	**Curricula**
Case Study 1	5	45	21	86	4301	20	5
Case Study 2	5	54	24	203	11,166	22	17
Case Study 3(a)	5	30	30	160	4801	24	14
Case Study 3(b)	5	25	82	283	7076	71	70
Case Study 3(c)	5	25	72	251	6276	61	68
Case Study 3(d)	5	25	79	286	7151	70	57
Case Study 3(e)	6	36	54	153	5509	47	139
Case Study 3(f)	5	25	108	361	9026	87	70
Case Study 3(g)	5	25	108	434	10,851	67	77

Table 4.1: General statistics of the size for each case study

Features	Basic							Work Load		Max Consecutive		Meeting Patterns								
								Lec	Stud	Lec	Stud									
Problem ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Case Study 1	✓	✓	✓	✓				✓	✓			✓	✓	✓	✓	✓				
Case Study 2	✓	✓	✓	✓			✓							✓		✓		✓		
Case Study 3(a)	✓	✓	✓	✓	✓															
Case Study 3(b)	✓	✓	✓	✓	✓															
Case Study 3(c)	✓	✓	✓	✓	✓															
Case Study 3(d)	✓	✓	✓	✓	✓															
Case Study 3(e)	✓	✓	✓	✓	✓															
Case Study 3(f)	✓	✓	✓	✓	✓															
Case Study 3(g)	✓	✓	✓	✓	✓															

Table 4.2: Features included in each case study

4.2 Case Study 1

This first case study is taken from one of the Malaysian University for the Mathematics Department post-graduate courses timetabling problem.

4.2.1 Problem Description

The problem consists of 21 units that breaks down into a number of class meetings to be scheduled over 45 one hour timeslots; 9 slots on each for five working days (Monday-Friday) between 8 a.m to 6 p.m.

Every unit determined by the department has 4 credit hours per week, which means that 4 hours are needed for each course in a week. Two time slots are used for every class meeting. Every unit has different students who registered. Therefore, each unit needs to be placed in the suitable lecture room that matches the course taken with the number of students. Some units needed the usage of laboratory while others needed only a standard lecture room. The list of other requirements that are needed in order to adhere to every regulation and policy that have been determined by the department are detailed below:

1. All class meetings will be allocated in one day.

2. All class meetings will be assigned to a specific time slot, which is between 8.00 a.m and 6.00 p.m.

3. Two class meetings of the same unit cannot be scheduled on the same day except for some courses.

4. There are limited capacities for lecture rooms.

5. There are a limited number of lecture rooms in each type.

6. Two class meetings in the same group/curricula cannot be scheduled at the same time slot.

7. Two units taught by the same lecturer cannot conflict with one another, that is, cannot be taught at the same time.

8. Each lecturer cannot teach more than 4 hours a day.

9. A student can only attend as long as 8 hours of class meetings.

10. All class meetings need to be placed in a suitable lecture room.

11. Some of the units needed the class meetings to be scheduled in the same day (morning and afternoon sessions).

4.2.2 IP formulation

We will be using the model below as to represent and solve the problem defined above:

$$\text{Maximize} \sum_{c} \sum_{t} P_{c,t} X_{c,t}$$

subject to:

constraints (3.1) – (3.4)

constraints (3.8) – (3.9)

constraints (3.12) – (3.16)

and

$$X_{c,t} \in \{0,1\} \qquad \forall c \quad \forall t$$

4.2.3 Problem Extension

We then extend the original problem by incorporating more features which have been introduced in the previous chapter. The additional features incorporated are:

a) Precedence.
b) Parallel.
c) Distribution.
d) Day off.

However, the data used will remain the same. We solve the problem by using the extended model shown below:

$$\text{Maximize} \sum_{c} \sum_{t} P_{c,t} X_{c,t}$$

subject to:

constraints (3.1) – (3.20);

and

$$X_{c,t} \in \{0,1\} \qquad \forall c \quad \forall t$$

With the same data of lecturers’ preference used, following are the results attained. Detail information on the dataset can be referred in the appendix together with the lecturers’ input preferences of assigning class meetings to desired slots.

4.2.4 Results

Below are the results obtained using AIMMS mathematical software with CPLEX 12.1 as the solver. As in the previous chapter, we will run the model 2 times:

a) Feasible solution.
b) Solution to optimization.

Satisfaction Experiments

Satisfaction experiment aims to get a feasible solution where no soft constraints are included. For this experiment, the input preference of class meetings to slots for each lecturer is all determined to be "1". Each of the models is run on the problem instance above. As soon as a feasible solution is found, (i.e. a solution that did not violate any hard constraints) the time is recorded. The results are shown in the table below:

CPU Time	0.30sec
Objective Function Value	86
Number of Constraints	4891
Number of Variables	4301
Number of Non-Zeroes	53586
Number of Iterations	703

Table 4.3: The results of constraint satisfaction for the original problem for case study 1 (without additional features)

CPU Time	0.67 sec
Objective Function Value	86
Number of Constraints	6,684
Number of Variables	4,301
Number of Non-Zeroes	86,372
Number of Iterations	1186
Number of Nodes	32

Table 4.4: The results of constraint satisfaction with the additional features for case study 1

Optimization Experiments

This is when the lecturers' preference of having a class meeting to a slot is taken into account. The preference parameter used contains the lecturer's preference concerning assignment of class meeting to a slot. Integer values between scale 1 (least preferable) and 5 (most preferable) is used to determine these assignments.

CPU Time	0.31 sec
Best Objective Function Value	317
Number of Constraints	4891
Number of Variables	4301
Number of Non-Zeroes	53586
Number of Iterations	599

Table 4.5: The results of optimization experiment for the original problem for case study 1 (without additional features)

CPU Time	0.44 sec
Best Objective Function Value	310
Number of Constraints	6,728
Number of Variables	4,301
Number of Non-Zeroes	86,636
Number of Iterations	850

Table 4.6: The results of optimization experiment with additional features for case study 1

4.3 Case Study 2

Our second case study is a problem taken from the literature data described by Zhang and Lau (2005).

4.3.1 Problem Description

This sample case study is to assign a number of 203 timetable items (class meetings) made up from 24 subjects to be scheduled in 54 one hour timeslots of five working days (Monday – Friday). The timetable items are referred to lectures and tutorials class meetings. A subject on offer is always made up of weekly lecture and tutorial. One or more lecturers are allowed to teach a subject. Each lecture usually runs for two hours. However a lecturer can request for a one and half hour lecture. There are two types of tutorials; classroom based tutorial and laboratory based tutorial. Both types can be either one or two hour duration.

Other constraints are in the form of regulations:

a) Class meetings can only be scheduled between 8 a.m to 6 p.m.
b) No lecture or tutorial can be scheduled from 1 p.m – 2 p.m on Wednesday to allow teaching staffs to attend seminars.

Lecturers' requests (pre-specified requirements):

a) In addition, certain lecturers can make special requests of the days they are able to teach and time they prefer due to the nature of employment such as part-time lecturer.
b) Students can only take tutorial class after the lecture is conducted.
c) Repeat lectures which cater mainly for the part-time students must be held in the evening.
d) If a subject can only be taught by one lecturer then different tutorial groups cannot be scheduled concurrently.

The input data consist of:

- Five working days = {Monday, Tuesday, Wednesday, Thursday and Friday}
- Eleven timeslots for each day = {0800, 0900, 1000, 1100, 1200, 1300, 1400, 1500, 1600, 1700, 1800}
- Six rooms types r, each having a specified number of room available = {lecture hall1, lecture hall2, tutorial room1, tutorial room2, laboratory1, laboratory2}

We also consider:

- 22 lecturers that hold responsible for their class meetings.
- 203 class meetings of 24 courses.

- 28 student groups that are enrolled for the same subject throughout the semester.
- Some meeting patterns.
- Fixed parameter such as the working load of class meetings for lecturers/students.

All the assignments are required to meet the rules determined by the university. Among the rules are:

a) Completeness.
b) Non-contradictoriness of the resources.
c) Availabilities of rooms, lecturers and time slots.
d) Meeting patterns:
   i) Precedence.
   ii) Allocating class meetings of the same course to morning and afternoon sessions.
   iii) Consecutive.

4.3.2 IP formulation

Below is the model to represent the problem defined above.

$$\text{Maximize} \sum_{c} \sum_{t} P_{c,t} X_{c,t}$$

subject to:

constraints (3.1) – (3.4)

constraints (3.7); (3.14); (3.16); (3.18);

and

$$X_{c,t} \in \{0,1\} \qquad \forall c \quad \forall t$$

4.3.3 Problem Extension

We then extend the original problem by incorporating more features which have been introduced in the previous chapter. The additional features incorporated:

e) Work load for lecturers and students.
f) Maximum number of class meeting consecutiveness.
g) Class meetings to be scheduled in the same day.
h) Parallel.
i) Distribution.
j) Day off.

However, the data used will remain the same. We will solve the problem by using the extended model shown below:

$$\text{Maximize} \sum_{c} \sum_{t} P_{c,t} X_{c,t}$$

subject to:

constraints (3.1) – (3.20);

and

$$X_{c,t} \in \{0,1\} \qquad \forall c \quad \forall t$$

With the same data of lecturers' preference used, following are the results attained. Detail information on the dataset can be referred in Zhang and Lau (2005).

4.3.4 Results

Below are the results obtained using AIMMS mathematical software with CPLEX 12.1 as the solver. As in the previous chapter, we run the model 2 times to find:

a) Feasible solution.
b) Solution to optimization.

Satisfaction Experiments

Satisfaction experiment aims to get a feasible solution where no soft constraints are included. For this experiment, the input preference of class meetings to slots for each lecturer is determined to be all 1. Each of the models is run on the problem instance above. As soon as a feasible solution is found, (i.e. a solution that did not violate any hard constraints) the time is recorded. The results are shown in the table below.

CPU Time	1.47sec
Objective Function Value	203
Number of Constraints	6326
Number of Variables	11166
Number of Non-Zeroes	104290
Number of Iterations	1112

Table 4.7: The results of constraint satisfaction for the original problem for case study 2 (without additional features)

CPU Time	5.93sec
Objective Function Value	203
Number of Constraints	10132
Number of Variables	11166
Number of Non-Zeroes	213728
Number of Iterations	6344

Table 4.8: The results of constraint satisfaction with additional features for case study 2

Optimization Experiment

This is when the lecturers' preference of having a class meeting to a slot is taken into account. The preference parameter used contains the lecturer's preference concerning assignment of class meeting to a slot. Integer values between scale 1 (least preferable) and 5 (most preferable) is used to determine these assignments.

CPU Time	1.62sec
Best Objective Function Value	923
Number of Constraints	6326
Number of Variables	11166
Number of Non-Zeroes	104290
Number of Iterations	146

Table 4.9: The results of optimization experiment for the original problem for case study 2 (without additional features)

CPU Time	246.25sec
Best Objective Function Value	902
Number of Constraints	10132
Number of Variables	11166
Number of Non-Zeroes	213728
Number of Iterations	484882
Number of Nodes	760

Table 4.10: The results of optimization experiment with additional features for case study 2

4.4 Case Study 3

The following problem is taken from the International Timetabling Competition 2007 (http://www.cs.qub.ac.uk/itc2007). The competition is divided into three different timetabling problems, and one of the tracks concerns the course timetabling formulation that applies to Italian universities (called Curriculum-Based Course

Timetabling). The dataset is composed from real-world instances provided by the University of Udine. As for our third case study, we describe one of the competition tracks namely the “Curriculum-Based Course Timetabling” as reported in Di Gaspero et al. (2007).

4.4.1 Problem Description

The Curriculum-based timetabling problem consists of the weekly scheduling of the lectures for several university courses within a given number of rooms and time periods, where conflicts between courses are set according to the curricula published by the University and not on the basis of enrolment data. This formulation applies to University of Udine (Italy) and to many Italian and indeed International Universities, although it is slightly simplified with respect to the real problem to maintain a certain level of generality. The problem consists of the following entities:

Days, Timeslots, and Periods

We are given a number of teaching days in the week (typically 5 or 6). Each day is split into a fixed number of timeslots, which is equal for all days. A period is a pair composed of a day and a timeslot. The total number of scheduling periods is the product of the days times the day timeslots.

Courses and Teachers

Each course consists of a fixed number of lectures to be scheduled in distinct periods, it is attended by given number of students, and is taught by a teacher. For each course there is a minimum number of days that the lectures of the course should be spread in, moreover there are some periods in which the course cannot be scheduled.

Rooms

Each room has a limited capacity, expressed in terms of number of available seats. All rooms are equally suitable for all courses (if large enough).

Curricula

A curriculum is a group of courses such that any pair of courses in the group have students in common. Based on curricula, we have the conflicts between courses and other soft constraints. The solution of the problem is an assignment of a period (day and timeslot) and a room to all lectures of each course.

The hard constraints are the following:

a) **Lectures**: All lectures of a course must be scheduled, and they must be assigned to distinct periods. A violation occurs if a lecture is not scheduled.

b) **Room Occupancy**: Two lectures cannot take place in the same room in the same period. Two lectures in the same room at the same period represent one violation. Any extra lecture in the same period and room counts as one more violation.

c) **Conflicts**: Lectures of courses in the same curriculum or taught by the same teacher must be all scheduled in different periods. Two conflicting lectures in the same period represent one violation. Three conflicting lectures count as 3 violations: one for each pair.

d) **Availabilities**: If the teacher of the course is not available to teach that course at a given period, then no lectures of the course can be scheduled at that period. Each lecture in a period unavailable for that course is one violation.

The soft constraints are the following:

a) **Room Capacity**: For each lecture, the number of students that attend the course must be less or equal than the number of seats of all the rooms that host its lectures. Each student above the capacity counts as 1 point of penalty.

b) **Minimum Working Days**: The lectures of each course must be spread into the given minimum number of days. Each day below the minimum counts as 5 points of penalty.

c) **Curriculum Compactness**: Lectures belonging to a curriculum should be adjacent to each other (i.e., in consecutive periods). For a given curriculum we account for a violation every time there is one lecture not adjacent to any other lecture within the same day. Each isolated lecture in a curriculum counts as 2 points of penalty.

d) **Room Stability**: All lectures of a course should be given in the same room. Each distinct room used for the lectures of a course, but the first, counts as 1 point of penalty.

4.4.2 IP Formulation

We will be using the basic model to represent the problem defined above.

$$\text{Maximize} \sum_{c} \sum_{t} P_{c,t} X_{c,t}$$

subject to:

constraints (3.1) – (3.4);

and

$$X_{c,t} \in \{0,1\} \qquad \forall c \quad \forall t$$

4.4.3 Problem Extension

We then extend the original problem by incorporating other features which have been introduced in the previous chapter. The additional features incorporated for this particular problem:

a) Work load for lecturers and students.
b) Maximum number of class meeting consecutiveness.
c) Class meetings to be scheduled in the same day.
d) Class meetings to be scheduled consecutively.
e) Parallel.
f) Precedence.
g) Distribution.
h) Day off.

However, all features listed will be implemented only for the first three instances (3a, 3b and 3c) of case study 3. As for the remainder of the instances, we will randomly choose the additional features that will be included. We will solve the problems by using models introduced in chapter 3 accordingly. The table below shows the features that will be included.

Case Study Features	3(a)	3(b)	3(c)	3(d)	3(e)	3(f)	3(g)
1	✓	✓	✓	✓	✓	✓	✓
2	✓	✓	✓	✓	✓	✓	✓
3	✓	✓	✓	✓	✓	✓	✓
4	✓	✓	✓	✓	✓	✓	✓
5	✓	✓	✓	✓	✓	✓	✓
6	✓	✓	✓	✓	✓	✓	✓
7	✓	✓	✓	✓	✓	✓	✓
8	✓	✓	✓	✓			
9	✓	✓	✓	✓			
10	✓	✓	✓	✓	✓		
11	✓	✓	✓	✓	✓		
12	✓	✓	✓	✓	✓		
13	✓	✓	✓		✓		
14	✓	✓	✓		✓	✓	
15	✓	✓	✓		✓	✓	
16	✓	✓	✓			✓	
17	✓	✓	✓			✓	✓
18	✓	✓	✓			✓	✓
19	✓	✓	✓				✓
20	✓	✓	✓				✓

Table 4.11: Features that will be included for each problem instances

With the same data of lecturers' preference used, following are the results attained. Detail information on the dataset can be referred in the website of International Timetabling Competition 2007 (http://www.cs.qub.ac.uk/itc2007).

4.4.4 Experiments

There are 21 instances available: 7 for each set (early, late, and hidden). They are all of the form described in Section 4.4.2. All instances are real data from the University of Udine consisting between 150 to 450 class meetings, 9-18 rooms, 5-300 number of students and 4 features. As for our study, we will only be analyzing the first seven instances which is the early datasets. The 7 datasets are labelled as “Case Study 3a”, “Case Study 3b”, “Case Study 3c” and so forth.

4.4.5 Results

Below are the results obtained using AIMMS mathematical software with CPLEX 12.1 as the solver. The models are tested on each of the 7 problems instances 2 times to find:

a) Feasible solution.
b) Solution to optimization.

Satisfaction Experiments

Satisfaction experiment aims to get a feasible solution where no soft constraints are included. For this experiment, the input preference of class meetings to slots for each lecturer is determined to be all 1. Each of the models is run on the problem instance above. As soon as a feasible solution is found, (i.e. a solution that did not violate any hard constraints) the time is recorded. The results are shown in the table below.

Instances	3(a)	3(b)	3(c)	3(d)	3(e)	3(f)	3(g)
CPU Time (sec)	0.22	1.33	0.78	0.30	0.59	1.28	2.32
Objective Function Value	160	283	251	286	152	361	434
Number of Constraints	1501	4375	3949	4041	7307	5035	5635
Number of Variables	4801	7076	6276	7151	5473	9026	10851
Number of Non-Zeroes	26147	52537	46604	44499	77986	59140	68145
Number of Iterations	1094	1834	1386	1173	1141	2194	3647
Number of Nodes	-	-	-	-	-	-	-

Table 4.12: The results of constraint satisfaction for the original problem for case study 3

Instances	3(a)	3(b)	3(c)	3(d)	3(e)	3(f)	3(g)
CPU Time (sec)	1.39	4.15	2.54	1.56	6.52	5.96	12.62
Objective Function Value	160	283	251	286	152	361	434
Number of Constraints	2927	6097	5533	5735	9861	6767	7323
Number of Variables	4801	7076	6276	7151	5473	9026	10851
Number of Non-Zeroes	61348	105266	93489	88299	160476	115835	129950
Number of Iterations	1660	4221	3884	3316	4982	5376	9607
Number of Nodes	-	-	-	-	-	-	-

Table 4.13: The results of constraint satisfaction with additional features for case study 3

Optimization Experiment

This is when the lecturers' preference of having a class meeting to a slot takes into account. The preference parameter used contains the lecturer's preference concerning assignment of class meeting to a slot. Integer values between scale 1 (least preferable) and 5 (most preferable) is used to determine these assignments.

Instances	3(a)	3(b)	3(c)	3(d)	3(e)	3(f)	3(g)
CPU Time (sec)	0.16	7.77	2.61	1.87	7.80	394.26	5820.21
Best Objective Function Value	171	1353	1196	1380	716	1722	2083
Number of Constraints	1503	4375	3949	4041	7307	5035	5635
Number of Variables	4801	7076	6276	7151	5473	9026	10851
Number of Non-Zeroes	26159	52537	46604	44499	77986	59140	68145
Number of Iterations	614	29209	8462	1769	36054	1183101	13860529
Number of Nodes	-	257	62	-	450	12151	116879

Table 4.14: The results of optimization experiment for the original problem for case study 3

Instances	3(a)	3(b)	3(c)	3(d)	3(e)	3(f)	3(g)
CPU Time (sec)	2.62	460.09	18.70	28.27	21.84	275.50	5903.61
Best Objective Funtion Value	205	1319	1165	1374	708	1700	2068
Number of Constraints	2240	6097	5533	5296	8561	5297	5768
Number of Variables	4801	7076	6276	7151	5473	9026	10851
Number of Non-Zeroes	48263	105266	93489	75259	91504	60140	86015
Number of Iterations	4372	1204400	52987	71661	88282	777377	11543853
Number of Nodes	14	7811	468	708	733	6551	77559

Table 4.15: The results of optimization experiment with additional features for case study 3

4.5 Discussion

Two entities that we should be looking at from a derived solution: CPU time on getting a solution and the satisfaction level of the timetabling communities. In this case, the timetabling community satisfaction level is the lecturers' preference in having class meetings to a slot. As for the CPU time, the faster time to obtain a solution the better it is. However, we have to consider the size of the problem to be solved. The CPU time is also influenced by the requirements needed.

As for the satisfaction level, we analyze each assignment of class meetings to slots whether it has satisfied the lecturer's preference. According to our approach of assigning values to the cost coefficients in the objective function, teachers provide different levels of preferences for all the time periods that each of them is available for teaching.

Three different case studies found in the literature are used to further verify our models developed in the previous chapter. The first case study is taken from a Malaysian University. It involves 86 class meetings to be scheduled into 50 slots. A literature problem from Zhang and Lau (2005) is our second case study. The last problem is obtained from a competition held by in 2007, where the data are inspired by the real world problem.

Initially, the original problem is solved. Additional features are added accordingly to which are sensible for applications in the construction of the timetable. We include all other features introduced for case study 1, 2 and the first three instances of case study 3. As for the remainder of the instances, we will randomly choose the additional features that will be included. This is to evaluate the variation and extended models introduced. Similar to chapter 3, the experiment is divided into two; satisfaction and optimization. We discuss the outcomes accordingly.

As it is shown in Table 4.3 and 4.4, we achieved computational time of 0.30 and 0.67 seconds for the satisfaction experiment to both the original problem (without any additional features) and the problem which includes more additional features respectively. There is not much difference in the computational time when the desirability of each lecturer having to teach in their preferred time slots is being considered. These are shown in Table 4.5 and 4.6. Both attained the solution to optimality in under a minute.

Continuing for case study 2, the computational time of the satisfaction experiment for both the original problem introduced in the literature and the problem that are added additional requirements are 1.47 and 5.93 seconds, respectively. Slightly longer time is needed for the optimization experiment 1.62 seconds and 246.25 seconds. Similar to the previous outcomes, the results for 7 instances in case study 3 came out successfully for all experiments. These are summarized in Table 4.12, 4.13, 4.14 and 4.15. As we move further down the table, the CPU time changes in an ascending order. This does not indicate an inefficiency of the models, instead it portrays the influence of problem size. Moreover, the number of requirements being considered in the model also makes the computation longer. To further assess the effectiveness, we calculate the percentage of each preference level for the lecturers to the desired time slot as shown in figures 4.1 to 4.9.

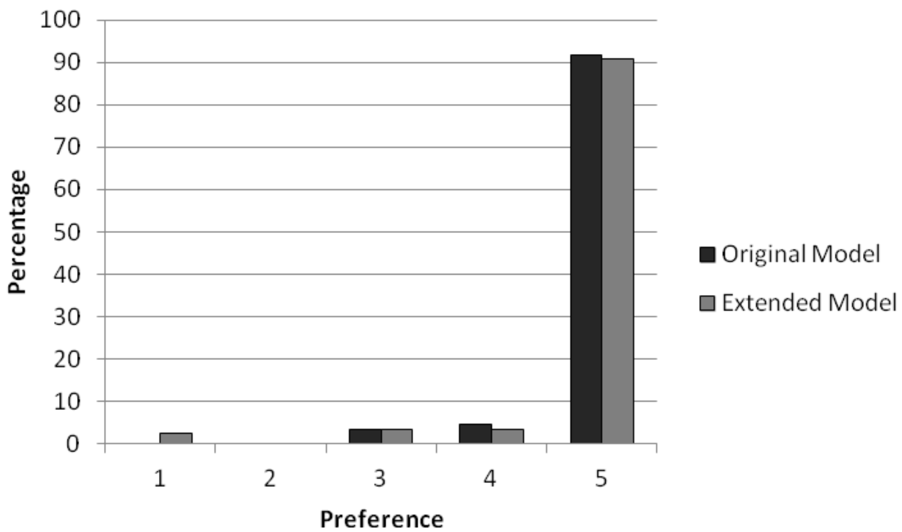

Figure 4.1 Percentage level of satisfaction for the optimization experiment in case study 1

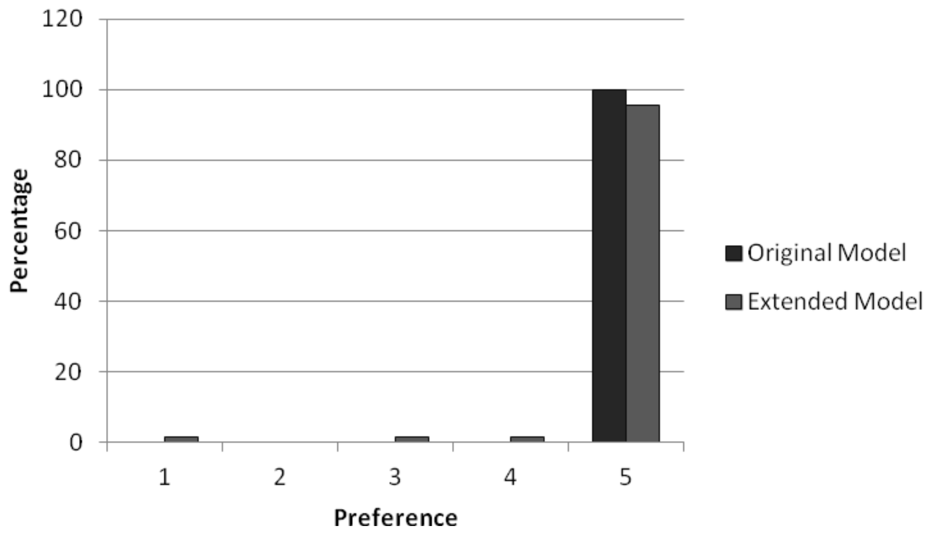

Figure 4.2: Percentage level of satisfaction for the optimization experiment in case study 2

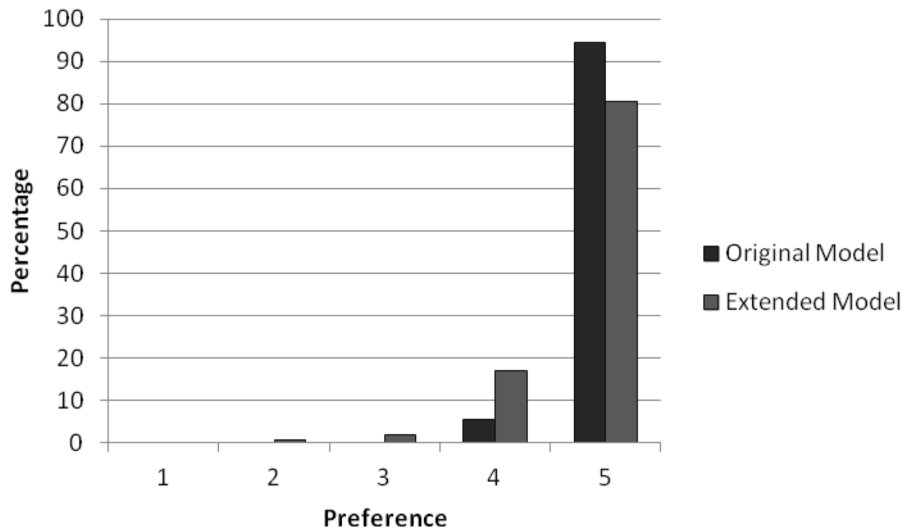

Figure 4.3: Percentage level of satisfaction for the optimization experiment in case study 3(a)

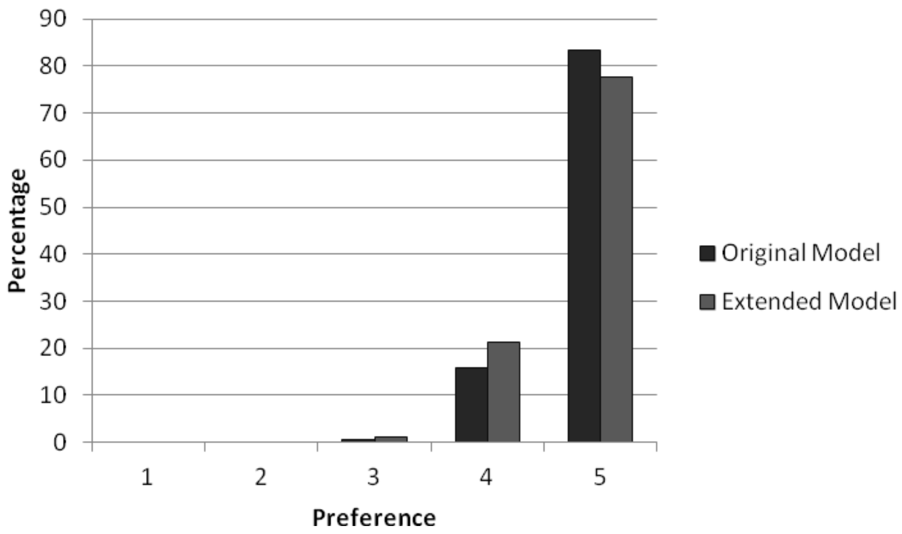

Figure 4.4: Percentage level of satisfaction for the optimization experiment in case study 3(b)

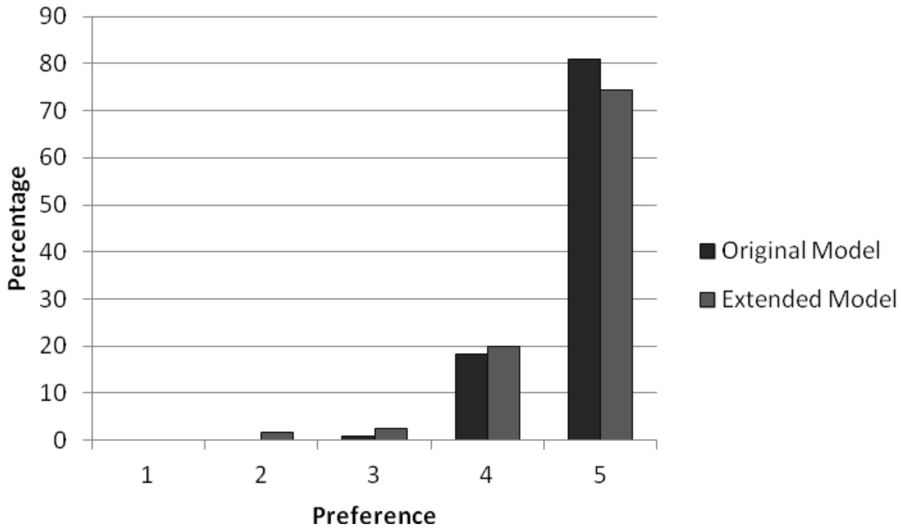

Figure 4.5: Percentage level of satisfaction for the optimization experiment in case study 3(c)

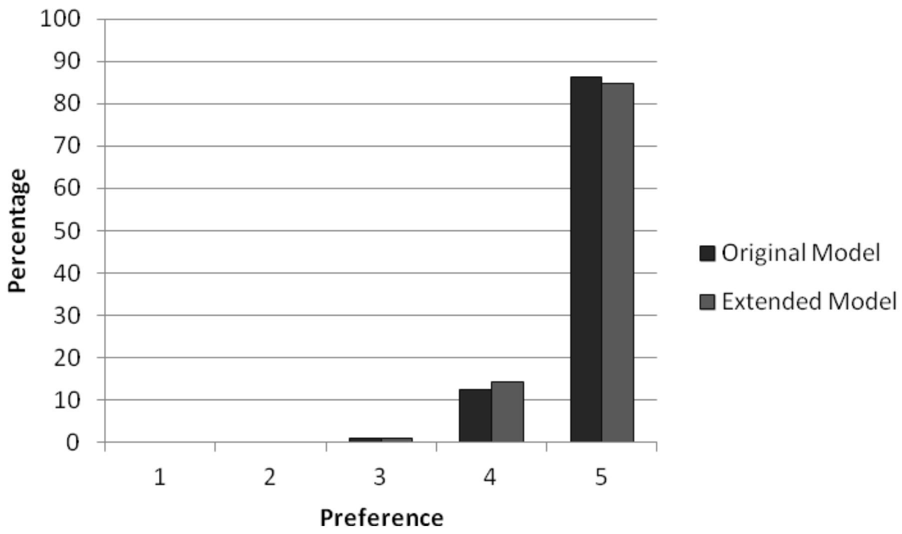

Figure 4.6: Percentage level of satisfaction for the optimization experiment in case study 3(d)

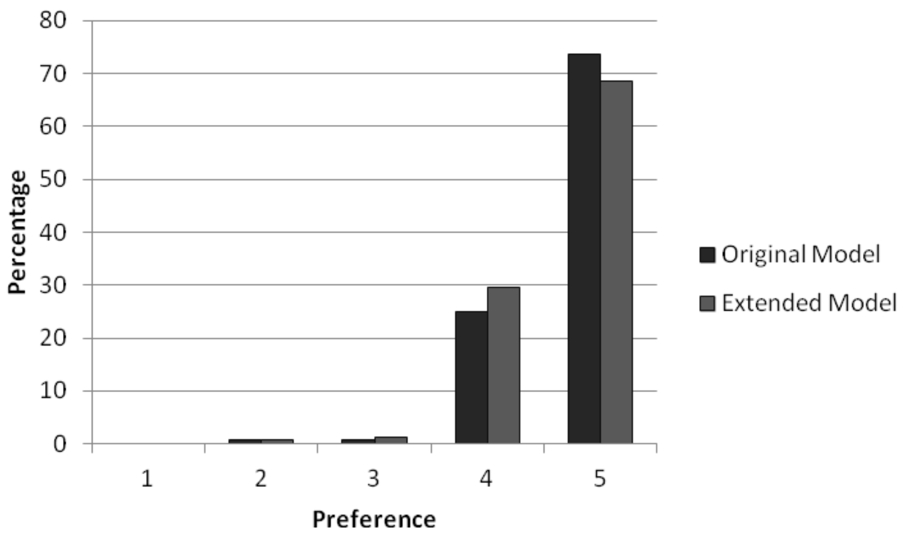

Figure 4.7: Percentage level of satisfaction for the optimization experiment in case study 3(e)

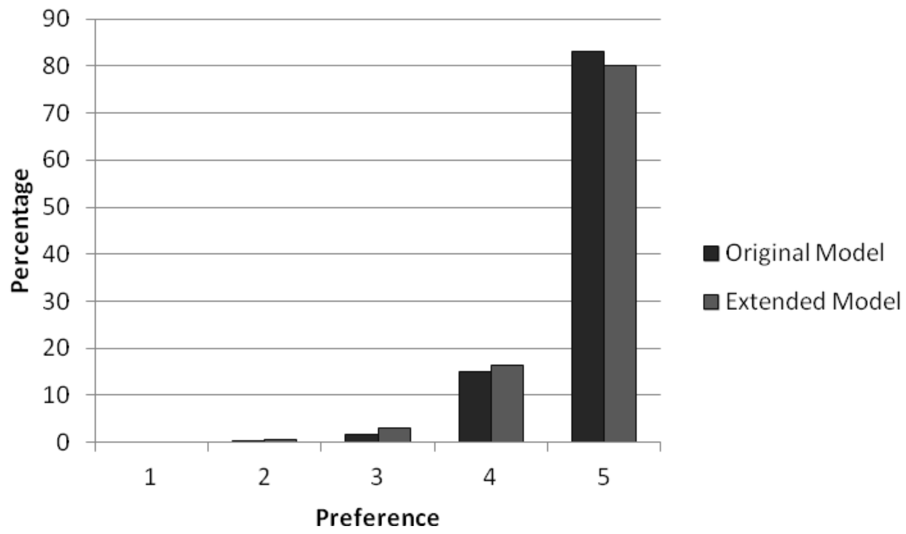

Figure 4.8: Percentage level of satisfaction for the optimization experiment in case study 3(f)

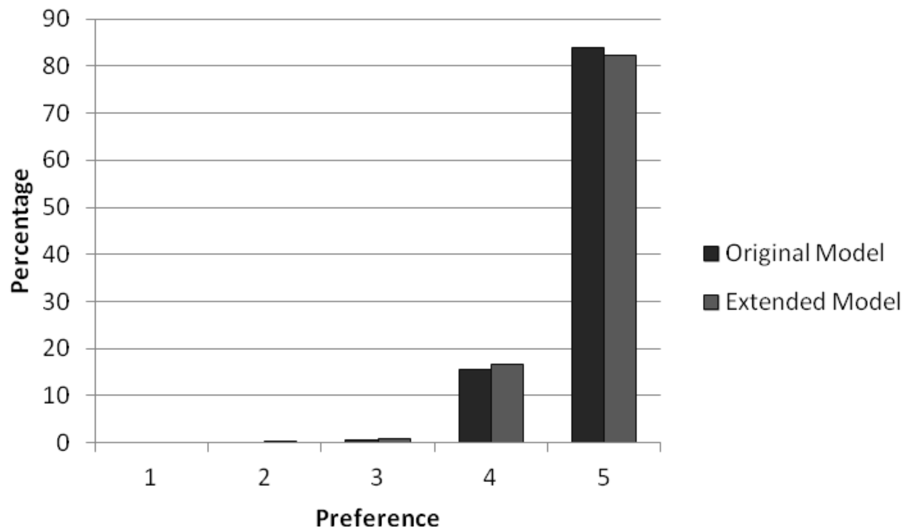

Figure 4.9: Percentage level of satisfaction for the optimization experiment in case study 3(g)

From the above figures, we can conclude by stating that for the optimization experiment for both the problems, the original and extension models, for all instances the results are remarkably good. Results from both original and extension models are satisfying where most of the assignments (70% - 100%) are placed on the first choice of preference. While the assignments to the last choice of preference only compass not more than 5% for each problem.

It is shown that the original problem has a higher percentage for the first choice of preference when compared to the extension problem. However, this is expected since a larger number of requirements will result in the difficulty of assigning all of them into their first choice of preference. Nonetheless, if not assigned to their first choice, the assignments would mostly go to the second choice which is considered as satisfactory.

There are a few things which are being left out, thus preventing us to compare the results obtained from the solutions attained from the competition. We focused our study on the hard constraints that we did not include the soft constraints listed in the competition website.

Four soft constraints described are:

a) Room capacity.
b) Room stability.
c) Compactness.
d) Minimum working days.

However, as mentioned earlier, we assume that the information of the required rooms for every class meeting is known in advance. Since we are using a work load type of constraint in our model, incorporating the compactness of class meetings belonging to the same course will result in inconsistency that restricts the number of class meetings of a lecturer and student in a day. Minimum working days could be included in the model although it will require a longer time. We would like to address this for future work.

4.6 Conclusion

In this chapter, we conclude that the application of developed models to three bigger problem cases adapted from literature is successful. The problems are applied in the variation models that are generated for the purpose of efficiency testing. To further assess the efficiency of our extended model, we included additional features in the three problems. From both of the assessments, results obtained are in fact considered excellent. From this testing, it is highlighted that the application of our derived models towards most, if not all problem, seems realistic. It therefore pinpoints the importance of having a general model for the use of any timetabling problem in different institutions. From the results obtained so far in this study, further addition of features to the model appears to be practical.

CHAPTER 5

Pre-Scheduling University Course Timetabling

5.1 Introduction

One of the many variations in solving timetabling problem of courses in universities is the pre-assignment scheduling. This involves an initial consideration of certain units which normally comprise of basic units for first year students. These units that cover a number of courses can be pre-schedule on their own. Following the pre-assignment of these core units at the beginning of a timetabling process, the rest of the units are assigned. The pre-assignments of the core units may be considered as a simplification tool in solving timetabling problem. Reduction of a number of resources (lecturers, rooms and slots) can be a problem resulting from pre-assigning the core units. However this scenario on the other hand can assist with the assignment of the remaining units given that fewer factors have to be considered in finalizing the timetabling. Furthermore, this sort of simplification is crucial due to the potential benefit it has on reducing computational time used in solving timetabling problem.

The chapter is arranged as follows. Problem definition is given in Section 5.2. The IP formulation is given the following section, Section 5.3. Results from the experiments are illustrated in Section 5.4 and discussed in Section 5.5. The final section, Section 5.6 gives some conclusion remarks of the chapter.

5.2 Problem Definition

We will use the first case study, referred to in Chapter 4 to demonstrate this problem with few modifications. We determine the core units and the slots desired. The core units chosen are based on:

a) Most number of students enrol
b) Most number of different courses requiring that unit
c) Important units

Below are the listings of units and elements offered:

Unit	Element	Number of Student
Unit A	L, L, T, T	10
Unit B	L, L, T, T	18
Unit C	L, L, T, T	12
Unit D	L, L, T, T	2
Unit E	L, L, T, T	11
Unit F	L, L, T, T	12
Unit G	L, L, T, T	3
Unit H	L, L, T, T	3
Unit I	L, L, T, T	2
Unit J	L, L, T, T	3
Unit K	L, L, T, T	20
Unit L	L, L, T, T	27
Unit M	L, L, T, T	14
Unit N	L, L, T, T	23
Unit O	L, L, T, T	42
Unit P	L, L, T, T	27
Unit Q	L, L, T, T	21
Unit S	L, L, T, T	17
Unit T	L, L, T, T	13
Unit U	L, L, T, T	12
Unit V	L, L, T, T	9
Unit W	L, L, T, T	12

Table 5.1: Listing of units offered

In stage 1, based on the listing, we determine the core units that will be scheduled to the prime timeslots which is the most desirable slots. From the determination of core units, 5 units are selected for the initial assignment. These units are:

i) Unit A.
ii) Unit B.
iii) Unit L.
iv) Unit O.

The 4 units consisting of 8 class meetings involving only lectures are first assigned to the prime time slots which are usually the morning slots in each day. The assignment of all other elements in the core units will then follow according to the requirements and restrictions determined. Subsequently, a timetable is set up consisting of limited number of rooms following the pre-assignment of elements in stage 1. The remainder units are then scheduled subject to the availability in the existing timetable.

The input data consists of:

- Five working days = {Monday, Tuesday, Wednesday, Thursday and Friday}
- Nine timeslots for each day = {0800 - 0900, 0900 - 1000, 1000 - 1100, 1100 - 1200, 1300 - 1400, 1400 - 1500, 1500 - 1600, 1600 - 1700, 1700 - 1800}
- Four rooms types r, for each having a number of room available for each type = {lecture hall1, lecture hall2, tutorial room1, tutorial room2}
- 20 lecturers
- 5 student groups which enrolled for the same subject throughout the semester.
- Some meeting patterns.
- Fixed parameter or the working load for lecturers/students consecutiveness of class meetings.

5.3 IP formulation

As discussed in the earlier section, this problem involves two-phase solution. We use the model below as to represent and solve the problem in both stages:

$$\text{Maximize} \sum_{c} \sum_{t} P_{c,t} X_{c,t}$$

subject to:

constraints (3.1) – (3.4)

constraints (3.8) – (3.9)

constraints (3.12) – (3.16)

and

$$X_{c,t} \in \{0,1\} \qquad \forall c \quad \forall t$$

With the same data of lecturers' preference used, following are the results attained. Detail information on the dataset can be referred in the appendix together with the lecturers' input preferences of assigning class meetings to desired slots.

The initial stage involves scheduling of the units that are considered priority, which is then followed by scheduling of all the remainder courses offered (according to these pre-scheduled units). The rest of the units are then scheduled based on the output of the first stage. Both stages involve assignments of courses based on the requirements specified by the university. Similar to the model presented in Chapter 4, the features considered in both the stages are:

a) Completeness
b) Conflicts of resources (lecturers, rooms and slots)

c) Work load for lecturers and students

d) Meeting patterns:

 i) Some specific class meetings must be scheduled in the same day

 ii) Some specific class meetings should not be scheduled in the same day

 iii) Class meetings that need to occur consecutively

 iv) Class meetings that should not occur consecutively

 v) Having class meeting either in the morning or afternoon session

5.4 Results

Below are the results obtained using AIMMS 3.10 mathematical software with CPLEX 12.1 as the solver. As in the previous chapter, we run the model two times:

a) Feasible solution.

b) Solution to optimization.

Satisfaction Experiment

Satisfaction experiment aims to get a feasible solution where no soft constraints are included. For this experiment, the input preference of class meetings to slots for each lecturer is determined to be all 1. Each of the models is run on the problem instance above. As soon as a feasible solution is found, (i.e. a solution that did not violate any hard constraints) the time is recorded. The results are shown in the table below.

CPU Time	0.0 sec
Optimal Solution Value	16
Number of Constraints	997
Number of Variables	801
Number of Non-Zeroes	8414
Number of Iterations	0

Table 5.2: The results of constraint satisfaction for the pre-scheduling problem in stage 1

CPU Time	0.09 sec
Optimal Solution Value	86
Number of Constraints	4908
Number of Variables	4301
Number of Non-Zeroes	54032
Number of Iterations	119

Table 5.3: The results of constraint satisfaction for the pre-scheduling problem in stage 2

Optimization Experiment

This is when the lecturers' preference of having a class meeting to a slot is taken into account. The preference parameter used contains the lecturer's preference concerning assignment of class meeting to a slot. Integer values between scale 1 (least preferable) and 5 (most preferable) is used to determine these assignments.

CPU Time	0.0 sec
Optimal Solution Value	64
Number of Constraints	997
Number of Variables	801
Number of Non-Zeroes	8414
Number of Iterations	0

Table 5.4: The results of optimization experiment for the pre-scheduling problem in stage 1

CPU Time	0.11 sec
Optimal Solution Value	317
Number of Constraints	4908
Number of Variables	4301
Number of Non-Zeroes	54032
Number of Iterations	115

Table 5.5: The results of optimization experiment for the pre-scheduling problem in stage 2

Comparison between Normal and Pre-Scheduling

We compare results obtained using the pre-scheduling approach to the results from normal scheduling done in Chapter 4.

	Satisfaction Experiment		**Optimization Experiment**	
Solution Approaches	CPU Time	Optimal Solution Value	CPU Time	Optimal Solution Value
Normal Scheduling	0.30 sec	86	0.31 sec	317
Pre-scheduling	0.09 sec	86	0.11 sec	317

Table 5.6: Computation times for the two solution approaches

	Percentage Level of Preferences (%)				
Solution Approaches	**1**	**2**	**3**	**4**	**5**
Normal Scheduling	0	0	3.49	4.65	91.86
Pre-scheduling	0	0	3.49	4.65	91.86

Table 5.7: Satisfaction levels achieved with the two different solution approaches

5.5 Discussion

In this chapter, we used the approach of pre-scheduling to solve the same case study which is solved in Chapter 4. This approach is a simplification of solving a timetabling problem in which priority of courses assignment is given to the core units involved in a university timetabling. Similarly to the previous chapters, we carried out two experiments to test the effectiveness of this model towards solving problem of the specific case study, satisfaction and optimization experiment.

The solution involves two stages; with stage 1 considering assignment of elements of the core units into prime time slots which then follows with the assignment of the remainder units in stage 2. Results from the satisfaction experiment of pre-scheduling problem in stage 1 and 2 are shown in Table 5.2 and Table 5.3 respectively. Successful results is achieved in terms of the computational time for the satisfaction experiment for both stage 1 and stage 2 in the approach of pre-scheduling, which is 0.0 and 0.09 seconds. Also, from this experiment, most of the class meetings are successfully assigned to their desired timeslots.

Table 5.4 and 5.5 shows the results from the optimization experiment of pre-scheduling problem in stage 1 and 2. The results from this experiment illustrates a very good computational time for both stage 1 and stage 2, which are 0.0 and 0.11 seconds respectively. This experiment also proven that majority class meetings are effectively scheduled to their desired timeslots.

To further assess the effectiveness of the pre-scheduling approach in solving the case study, a comparison between the results obtained using the pre-assignment approach and results from normal scheduling done in Chapter 4 are performed (Table 5.6). The comparison is carried out for both satisfaction and optimization experiments. From this assessment, we observed that the pre-scheduling approach had a better computational time (0.09 seconds) than the normal scheduling (0.30 seconds) for satisfaction experiment. The same case is seen in the optimization experiment with pre-scheduling having only 0.11 seconds and normal scheduling with 0.31 seconds for their computational time. We also observed that pre-scheduling had the same ability to assign the courses to their preferred time slots as the normal scheduling (Table 5.7), which suggests that this approach is a promising simplified approach in solving timetabling problem.

5.6 Conclusion

This chapter discussed a simplified approach towards solving timetabling problem. We have applied this approach using the model that is generated and discussed in previous chapter of this thesis. The pre-assignment of core units does not only prove it's' usefulness in solving timetabling problem, but also indirectly illustrates that the model generated is in fact applicable to be used with this approach. Although, we have applied the pre-assignment approach on only one chosen case study, it is highly possible that the generated model can be applied in other case studies used in previous chapters using pre-assignment way. The successful application of courses pre-assignment in solving timetabling problem would certainly help timetabling process become a simpler task.

CHAPTER 6

Conclusion Remarks and Future Work

In this thesis, we have successfully constructed a more general university course timetabling model that includes features that are essential. These features are the requirements needed in a university. There is variety of features, one of which is how the class meeting is specifically organized. These models may also be applied to all university courses timetabling development according to their requirements. In detail, we summarize our main contributions below and suggest directions for future work based on this study.

In Chapter 2, as an initial step to our study, we have reviewed the features used by other key researchers in the literature. A total of 17 features were observed. These features were the operational rules and requirements of a specific university. Operational rules such as workloads for lecturers and student groups need to be considered. An example of a requirement is to have class meeting to be assigned to a specific slot. We have gathered and formulated all essential features into a single model where it will be more general towards the university course timetabling problem. This was one of the problems encountered in university course timetabling, where models were developed only for the intended problem. Many approaches have been used in solving the timetabling problem, however we have chosen to employ IP and AIMMS mathematical software to solve our models.

In Chapter 3, based on the information obtained in the previous chapter, we have introduced a basic model for university course timetabling problems. The basic model incorporates features that mostly arise in applications. Three basic features that were commonly used were the completeness constraints, ensuring all class meetings or events to be scheduled in a time slot; the conflict constraints between the resources (lecturers, student groups and rooms) and also the resources availability at each time slot. Subsequently, we added all features considered in the literature to develop one extended model. This was the aim of our study, to develop a model which incorporates as many features as possible that have been employed by researchers, as it would benefit timetabling construction by avoiding application to a specific institution only. In addition, three new requirements that we think should be part of the restrictions in a model were added. These added features were:

a) Maximum consecutive of class meetings for the students.
b) Distribution of class meetings: having more class meetings earlier in the week.
c) Gap: Having class meetings of the same course in the morning and afternoon sessions on the same day.

Different combinations of the features which form the extended model were extracted to produce a range of models that may arise in the course timetabling model application. We evaluated our models with a randomly generated dataset. All results obtained were shown to be positive in terms of the computational time and lecturers' satisfaction of assigning classes taught to desirable time slots. We achieved almost 100% of the lectures' preference of class meetings to the preferred time slots.

In Chapter 4, more evaluation and testing of the developed models were carried out. We verified our models on bigger case studies from the literature. Three case studies were used, with totally different problems. The first case study was taken from one of the Malaysian University to schedule a timetable for postgraduate students. This was followed by the case study of Zhang and Lau (2005). Our final problem was Track 3 in the International Timetabling Competition-2 held in 2007. This was the curriculum based timetabling problem based on real world data for the Udine University, Italy. A total of 9 data sets of problems were implemented. Originally the main problem was solved using one of the variation models introduced in Chapter 3. Following this, we extend the problem by including more additional features, which were sensible for applications in the construction of the timetable. Remarkable outcomes were achieved in terms of the CPU time and satisfaction level of the lecturers' preferences of their class meetings to slots. Thus, we can conclude that the models developed are applicable to different institutions and may overcome the inability of a model to be applied in a wide range of institutions.

Chapter 5 provides a different type of approach that is being used in practice these days in certain universities. In this chapter, we have applied our models to the process of solving timetabling problem of a chosen case study using the pre-scheduling approach. In pre-scheduling approach, core units were scheduled first followed by the remainder units. Using the models developed, once more the problem was solved successfully, especially in terms of reducing computational time. This illustrates the flexibility of the developed models to be used in solving timetabling problem, even using a simplified approach.

Overall, in this thesis we have observed, gathered and discussed the features normally used in a university course timetabling model. Each feature was formulated into Integer Programming and form into a single general model. Moving to another level, we have added three new requirements that we think could be incorporated in the model. A small randomly generated data set was created to illustrate the models. To support our research ideas we have applied our models to three case studies where they imposed different requirements. This was to analyze on how well the application of our models to be able to solve other problems.

From this testing, it was highlighted that the application of our derived models towards most, if not all problem, seems realistic. It therefore pinpoints the importance of having a general model for the use of any timetabling problem in different institutions. From the results obtained so far in this thesis, further addition of features to the model appears to be practical.

6.1 Future Work

In addition to the outcomes obtained from the studies in this thesis, more work needs to be done to further strengthen the models. Many other additional features could be introduced in future work. The inclusion of these potential additional features in our model would create a better generalized model towards solving timetabling problem of most universities.

We have been focusing on the hard constraints, constraints which need to be satisfied. Realistically, some of the hard constraints could be considered as soft constraints as to create alternative solution. Note that, if we could solve a problem with the hard constraints, it is likely to solve a model where the hard constraints are considered as soft constraints (preferential). Apart from the soft constraints involving lecturer's preferences, other soft constraints were not tested in this thesis. However, given that successful outcomes were reported in terms of preference satisfaction and computational time with all the considered hard constraints, this thesis provides a foundation for further research on consideration of other soft constraints.

In this thesis, we tested the developed models on three case studies. Albeit having various requirements for each case study, we managed to report successful outcomes from the application of the developed models. As a prospect, the application of the models on a real case study of a university is interesting. However, this is expected to be a very challenging problem to solve. In reality, the automation of a university course timetabling process does not only involve scheduling, but many other processes that would have to be considered. Therefore, the application of the developed models reported in this thesis onto a real case study of a university in future work would generate a very useful knowledge in this area.

APPENDIX

SMALL GENERATED DATASET

Course	Course Code	Teacher	Teacher Code	Num. of Class Meetings	Formation
Course 1	1	L1	1	2	cm1, cm2
Course 2	2	L1	1	2	cm3, cm4
Course 3	3	L2	2	2	cm5, cm6
Course 4	4	L2	2	2	cm7, cm8
Course 5	5	L3	3	2	cm9, cm10
Course 6	6	L3	3	2	cm11, cm12
Course 7	7	L4	4	2	cm13, cm14
Course 8	8	L4	4	2	cm15, cm16
Course 9	9	L5	5	2	cm17, cm18
Course 10	10	L5	5	2	cm19, cm20
Course 11	11	L6	6	2	cm21, cm22
Course 12	12	L6	6	2	cm23, cm24
Course 13	13	L7	7	2	cm25, cm26
Course 14	14	L7	7	2	cm27, cm28
Course 15	15	L8	8	2	cm29, cm30
Course 16	16	L8	8	2	cm31, cm32
Course 17	17	L9	9	2	cm33, cm34
Course 18	18	L9	9	2	cm35, cm36
Course 19	19	L10	10	2	cm37, cm38
Course 20	20	L10	10	2	cm39, cm40
Course 21	21	L10	10	2	cm41, cm42
Course 22	22	L1	1	2	cm43, cm44

Group	Course	Class Meeting
1	course 1, course 2, course 11, course 16, course 17, course 18	cm1, cm2, cm3, cm4, cm21, cm22, cm31, cm32, cm33, cm34, cm35, cm36
2	course 3, course 4, course 12, course 22	cm5, cm6, cm7, cm8, cm23, cm24, cm43, cm44
3	course 5, course 6, course 13, course 20, course 21	cm9, cm10, cm11, cm12, cm25, cm26, cm39, cm40, cm41, cm42
4	course 7, course 8, course 14	cm13, cm14, cm15, cm16, cm27, cm28
5	course 9, course10, course 15, course 19	cm17, cm18, cm19, cm20, cm29, cm30, cm37, cm38
6	course 17, course 18, course 21	cm33, cm34, cm35, cm36, cm41, cm42

Teacher	**Teacher Code**	**Class Meeting**
L1	1	cm1, cm2, cm3, cm4, cm43, cm44
L2	2	cm5, cm6, cm7, cm8
L3	3	cm9, cm10, cm11, cm12
L4	4	cm13, cm4, cm15, cm16
L5	5	cm17, cm18, cm19, cm20
L6	6	cm21, cm22, cm23, cm24
L7	7	cm25, cm26, cm27, cm28
L8	8	cm29, cm30, cm31, cm32
L9	9	cm33, cm34, cm35, cm36
L10	10	cm37, cm38, cm39, cm40, cm41, cm42

Room	Class Meeting
Lecture Hall	cm1, cm3, cm5, cm7, cm9, cm11, cm13, cm15, cm17, cm19, cm21, cm23, cm25, cm27, cm29, cm31, cm33, cm35, cm37, cm39, cm41, cm43, cm2, cm4, cm6
Lab	cm8, cm10,cm12, cm14, cm16, cm18, cm20, cm22, cm24, cm26, cm28, cm30, cm32, cm34, cm36, cm38, cm40, cm42, cm44

Class Meeting	Day	Slot
cm5, cm6, cm7, cm8	Monday	1 to 5
cm9, cm10, cm11, cm12	Friday	1 to 5
cm8, cm10,cm12, cm14, cm16, cm18, cm20, cm22, cm24, cm26, cm28, cm30, cm32, cm34, cm36, cm38, cm40, cm42, cm44	Monday, Wednesday, Friday	1

CASE STUDY 1

Course	Course code	Teacher	teacher code	# class meeting	# Student	Formation			
Unit A	1	L1	1	4	10	cm1	cm2	cm3	cm4
Unit B	2	L2	2	4	18	cm5	cm6	cm7	cm8
Unit C	3	L2	2	4	12	cm9	cm10	cm11	cm12
Unit D	4	L3	3	4	2	cm13	cm14	cm15	cm16
Unit E	5	L4	4	4	11	cm17	cm18	cm19	cm20
Unit F	6	L5	5	4	12	cm21	cm22	cm23	cm24
Unit G	7	L6	6	4	3	cm25	cm26	cm27	cm28
Unit H	8	L7	7	4	3	cm29	cm30	cm31	cm32
Unit I	9	L8	8	4	2	cm33	cm34	cm35	cm36
Unit J	10	L9	9	4	3	cm37	cm38	cm39	cm40
Unit K	11	L10	10	4	20	cm41	cm42	cm43	cm44
Unit L	12	L11	11	4	27	cm45	cm46	cm47	cm48
Unit M	13	L12 & L13	12	4	14	cm49	cm50	cm51	cm52
Unit N	14	L14	14	4	23	cm53	cm54	cm55	cm56
Unit O	15	L15	15	4	42	cm57	cm58	cm59	cm60
Unit P	16	L16	16	4	27	cm61	cm62	cm63	cm64
Unit Q	17	L17	17	4	21	cm65	cm66	cm67	cm68
Unit R	18	L18	18	4	17	cm69	cm70	cm71	cm72
Unit S	19	L18	18	4	13	cm73	cm74	cm75	cm76
Unit T	20	L14	14	4	12	cm77	cm78	cm79	cm80
Unit U	21	L19	19	4	9	cm81	cm82	cm83	cm84
Unit V	22	L20	20	2	12	cm85	cm86		

Teacher	teacher code	Class meetings							
L1	1	cm1	cm2	cm3	cm4				
L2	2	cm5	cm6	cm7	cm8	cm9	cm10	cm11	cm12
L3	3	cm13	cm14	cm15	cm16				
L4	4	cm17	cm18	cm19	cm20				
L5	5	cm21	cm22	cm23	cm24				
L6	6	cm25	cm26	cm27	cm28				
L7	7	cm29	cm30	cm31	cm32				
L8	8	cm33	cm34	cm35	cm36				
L9	9	cm37	cm38	cm39	cm40				
L10	10	cm41	cm42	cm43	cm44				
L11	11	cm45	cm46	cm47	cm48				
L12 & L13	12	cm49	cm50	cm51	cm52				
L14	14	cm53	cm54	cm55	cm56	cm77	cm78	cm79	cm80
L15	15	cm57	cm58	cm59	cm60				
L16	16	cm61	cm62	cm63	cm64				
L17	17	cm65	cm66	cm67	cm68				
L18	18	cm69	cm70	cm71	cm72	cm73	cm74	cm75	cm76
L19	19	cm81	cm82	cm83	cm84				
L20	20	cm85	cm86						

Rooms	Class Meeting											
1	cm21	cm22	cm23	cm24	cm25	cm26	cm27	cm28	cm29	cm30	cm31	cm32
	cm37	cm38	cm39	cm40								
2	cm1	cm2	cm3	cm4	cm5	cm6	cm7	cm8	cm9	cm10	cm11	cm12
	cm13	cm14	cm15	cm16	cm17	cm18	cm19	cm20	cm33	cm34	cm35	cm36
	cm41	cm42	cm43	cm44	cm45	cm46	cm47	cm48	cm49	cm50	cm51	cm52
	cm73	cm74	cm77									
3	cm53	cm54	cm55	cm56	cm57	cm58	cm59	cm60	cm61	cm62	cm63	cm64
	cm65	cm66	cm67	cm68	cm69	cm70	cm81	cm82				
4	cm71	cm72	cm75	cm76	cm79	cm80	cm83	cm84	cm85	cm86		

Curricula	Group	Course	Class Meetings
Curricula 1	1	Unit A, Unit B, Unit C, Unit E, Unit F	cm1, cm2, cm3, cm4, cm5, cm6, cm7,cm8, cm9, cm10,cm11, cm12, cm13, cm14, cm15, cm16, cm17, cm18, cm19, cm20, cm21, cm22, cm23, cm24
Curricula 2	2	Unit B, Unit D, Unit G, Unit H, Unit J, Unit I, Unit L	cm5, cm6, cm7, cm8, cm13, cm14, cm15, cm16, cm25, cm26, cm27, cm28, cm29, cm30, cm31, cm32, cm33, cm34, cm35, cm36, cm37, cm38, cm39, cm40, cm45, cm46, cm47, cm48
Curricula 3	3	Unit B, Unit D, Unit L, Unit M, Unit O	cm5, cm6, cm7, cm8, cm13, cm14, cm15, cm16, cm45, cm46, cm47, cm48, cm49, cm50, cm51, cm52, cm57, cm58, cm59, cm60
Curricula 4	4	Unit N, Unit O, Unit P, Unit Q	cm53, cm54, cm55, cm56, cm57, cm58, cm59, cm60, cm61, cm62, cm63, cm64, cm65, cm66, cm67, cm68
Curricula 5	5	Unit R, Unit S, Unit T, Unit U, Unit V	cm69, cm70, cm71, cm72, cm73, cm74, cm75, cm76, cm77, cm78, cm79, cm80, cm81, cm82, cm83, cm84, cm85, cm86

LECTURERS' INPUT PREFERENCES PARAMETER FOR OPTIMIZATION EXPERIMENTS FOR CASE STUDY 1

Rows represent timeslots and columns represent class meetings.

5	5	5	4	4	1	1	1	1	1	5	5	5	4	4	1	1	1	1	1	5	5	5	4	4	1	1	1	1	1	5	5	5	4	4	1	1	1	1	1	5	5	5	4	4	1	1	1	1	1
5	5	5	4	4	1	1	1	1	1	5	5	5	4	4	1	1	1	1	1	5	5	5	4	4	1	1	1	1	1	5	5	5	4	4	1	1	1	1	1	5	5	5	4	4	1	1	1	1	1
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LECTURERS’ INPUT PREFERENCES PARAMETER FOR OPTIMIZATION EXPERIMENTS FOR CASE STUDY 2

Rows represent timeslots and columns represent class meetings.

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LECTURERS' INPUT PREFERENCES PARAMETER FOR OPTIMIZATION EXPERIMENTS FOR CASE STUDY 3(a)

Rows represent timeslots and columns represent class meetings. Preference parameters (1 to 5) are uniformly distributed.

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LECTURERS' INPUT PREFERENCES PARAMETER FOR OPTIMIZATION EXPERIMENTS FOR CASE STUDY 3(b)

Rows represent timeslots and columns represent class meetings. Preference parameters (1 to 5) are uniformly distributed.

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LECTURERS’ INPUT PREFERENCES PARAMETER FOR OPTIMIZATION EXPERIMENTS FOR CASE STUDY 3(c)

Rows represent timeslots and columns represent class meetings. Preference parameters (1 to 5) are uniformly distributed.

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LECTURERS' INPUT PREFERENCES PARAMETER FOR OPTIMIZATION EXPERIMENTS FOR CASE STUDY 3(d)

Rows represent timeslots and columns represent class meetings. Preference parameters (1 to 5) are uniformly distributed.

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LECTURERS' INPUT PREFERENCES PARAMETER FOR OPTIMIZATION EXPERIMENTS FOR CASE STUDY 3(e)

Rows represent timeslots and columns represent class meetings. Preference parameters (1 to 5) are uniformly distributed.

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LECTURERS' INPUT PREFERENCES PARAMETER FOR OPTIMIZATION EXPERIMENTS FOR CASE STUDY 3(f)

Rows represent timeslots and columns represent class meetings. Preference parameters (1 to 5) are uniformly distributed.

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LECTURERS' INPUT PREFERENCES PARAMETER FOR OPTIMIZATION EXPERIMENTS FOR CASE STUDY 3(g)

Rows represent timeslots and columns represent class meetings. Preference parameters (1 to 5) are uniformly distributed.

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