



**AN ANALYTIC HIERARCHY PROCESS BASED MATHEMATICAL
PROGRAMMING MODEL FOR UNIVERSITY TIMETABLING PROBLEM**

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SEPTEMBER 2019

AN ANALYTIC HIERARCHY PROCESS BASED MATHEMATICAL
PROGRAMMING MODEL FOR UNIVERSITY TIMETABLING PROBLEM

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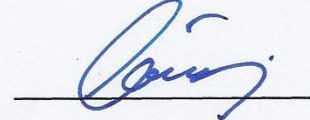
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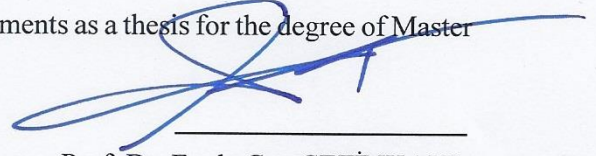
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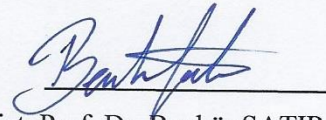
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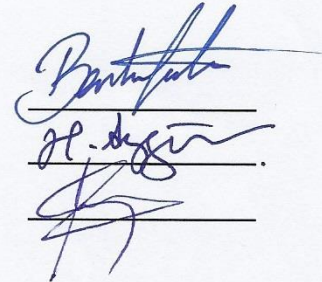
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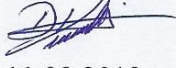
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ABSTRACT

AN ANALYTIC HIERARCHY PROCESS BASED MATHEMATICAL PROGRAMMING MODEL FOR UNIVERSITY TIMETABLING PROBLEM

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Today, timetabling becomes a widespread problem in all educational institutions. In existing systems once course selection is made, options are reviewed and changed according to the request of instructors. Instructors timetables are scheduled without prioritizing the views and priorities of the instructors. In this study, a Mathematical Programming Model (MPM) has been developed for solving a case of timetabling problem at Çankaya University. The weight of preferences, i.e. the objective function coefficients of the MPM Model will be based on AHP. The model proposed in this study has two main categories of objectives: instructor preferences and student preferences. The data used to calculate weights of preferences were collected via instructors' and students' questionnaires. The results obtained from the weighting approach used for the two main objectives were used in the mathematical model and timetables have been generated.

Keywords: Analytic Hierarchy Process, Mathematical Programming, University Timetabling Problem

ÖZ

ÜNİVERSİTE DERS PROGRAMI PROBLEMI İÇİN ANALİTİK HİYERARŞİ
YÖNTEMİ TABANLI BİR MATEMATİKSEL MODEL

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Zaman çizelgeleme problemi günümüzde tüm eğitim kurumlarında yıllardır süregelen yaygın bir problem olmaktadır. Mevcut sistemlerde ders seçimleri yapıldıktan sonra, hocaların isteği üzerine seçimler tekrar gözden geçirilip değiştirilmektedir. Ders ve derslik atamaları, en başta öğretim üyelerinin öncelikleri ve görüşleri alınmaksızın yapılmaktadır. Bu çalışmada, bir üniversitede ders çizelgeleme problemi için bir matematik programlama (MPM) modeli geliştirilmiştir. MPM'nin amaç fonksiyon katsayıları gibi tercih ağırlıkları, Analitik Hiyerarşi Prosesi ile belirlenmiştir. Bu çalışmada önerilen modelde iki ana hedef kategorisi vardır: öğretim elemanı tercihleri ve öğrenci tercihleri. Tercih ağırlıklarını hesaplamak için kullanılan veriler, öğrencilere ve öğretim elemanlarına yapılan anketlerle toplanmıştır. İki ana hedef için kullanılan ağırlıklandırma yaklaşımından elde edilen sonuçlar, matematik modelde kullanılmış ve bir zaman çizelgelemesi oluşturulmuştur.

Anahtar Kelimeler: Analitik Hiyerarşi Prosesi, Matematiksel Programlama, Üniversite ders çizelgeleme problemi

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LIST OF ABBREVIATIONS

AHP: Analytic Hierarchy Process

MPM: Mathematical Programming Model

CI: Consistency Index

CR: Consistency Ratio

RI: Random Index

CHAPTER 1.

INTRODUCTION

Timetabling is the act of scheduling something to happen or do something at a particular time [10]. Gasimov et al. [10] introduces timetabling problem for educational institutions as; “ *A classical combinatorial problem that requires finding a schedule to determine which courses will be given in which classrooms, by which instructors and during which time slots.* ”

Timetabling problems were studied over the decades by different authors such as Gasimov et al.[10] , Even et al.[11], Werra [12], Cooper and Kingston [13], Daskalaki et al. [14]. In timetabling problems, due to the complexity of its nature; it is very hard to find a solution. There are many constraints that influence these problems which can be either individual or organizational.

A min-max approach considering faculty preferences was presented by Kara and Özdemir [15]. Hertz and Robert [16] proposed an approach focusing on dividing the problem into a series of sub-problems. Daskalaki and Birbas [14] developed a two-stage relaxation procedure to solve a university timetabling problem. A 0-1 linear programming model considering both the administration’s and instructors’ preferences was presented by Gasimov et al. [10].

According to Kochetov et al.[18], “who consider the well known NP–hard teacher/class timetabling problem” mentioned timetabling problem as; “The optimization problem is NP–hard. Moreover, the decision problem on existence of a feasible solution is NP–complete. [18]

Also Francis et al.[19], introduce their study about timetabling problem as; “Timetabling problem belongs to the NP-hard class combinational optimization problem whereby its computational time grows exponentially with an increase in the number of variables involved”[19]

In this study we propose a Mathematical Programming Model approach which uses weights calculated by Analytic Hierarchy Process, derived from instructor and student preferences. The data used to calculate weights of preferences were collected via instructors’ and students’ questionnaires.

The results obtained from the weighting approach used for the two main objectives were used in the mathematical model and timetables have been generated. One of the main advantages of this approach is to solve of the problem, by using weights for preferences. Another one is decreasing the number of steps followed in constructing schedules by the university. Because of the nature of the problem, the solution process has been considered as two stages; defining weights by the use of AHP process, and then solving the mathematical model by the use of these weights in GAMS/CPLEX solver.

CHAPTER 2. METHODOLOGY

In this chapter, the methodology used in this study will be explained. Details about the overall approach and the main idea for applying this method are given. We used a mathematical programming model to solve the timetabling problem in GAMS/CPLEX solver which is explained in section 2.1. The weights used for instructor and student preferences were calculated with the Analytic Hierarchy Process which is mentioned in section 2.2.

2.1. MATHEMATICAL PROGRAMMING MODEL

Mathematical programming model problems are used in many fields of science, engineering, economics and logistics where optimal decisions need to be taken in the presence of trade-offs between two or more conflicting objectives [6]. “In mathematical programming there can be more than one objectives, and in general, there is no single optimal solution that simultaneously optimizes all the objectives. In these cases, the decision makers are looking for the most preferred solution, in contrast to the optimal solution.” [5].

“According to Hwang and Masud (1979) the methods of solving MPM problems can be classified into three categories, based on the phase that the decision maker involves in the decision-making process expressing their preferences” [6]. Which are;

Priori methods: In this method the decision maker expresses his/her preferences before the solution process [9].

Interactive methods: In this method, phases of dialog with the decision maker are interchanged with phases of calculation. And the process usually converges [9].

Posteriori methods: “Efficient solutions of the problem are generated, after that the decision maker selects among them” [9].

According to the given information Priori Method was used in this study.

Our problem is NP-Hard by its nature. In the result part of this study, we have shared examples for 24-hour GAMS/CPLEX runs without reaching an acceptable gap percentage compared to optimal objective function value. In mathematical programming, if any feasible solution is accepted without optimizing w.r.t. an objective function, any feasible solution is called a “satisficing” solution. Kan [17] implies that “all NP problems are reducible to the so-called satisfiability problem...”[17] When we run the “satisficing model” of our problem, we observe very quick solutions, as expected.

Williams [20] define the “hard constraints” as the constraints which cannot be violated and “soft constraints” which can be violated at a certain cost. In our problem, the university allows a student to have clashing courses. We allow this in our formulation by penalizing clashes. For an instructor, having two class meetings at the same time is impossible, so we assume that constraint as a hard one. Using soft constraints instead of hard constraints makes the problem easier, but still the problem is NP-Hard. For deciding weight for penalties, we use AHP method and obtain weights for violations of instructor and student preferences. The key point is that the weight obtained from AHP must be consistent to be used in the mathematical model. AHP can be considered as the backbone of the formation of the objective function of this problem. This study therefore, benefits from two main methods, which are the usage of AHP and the mathematical model, to solve the timetabling problem.

2.2. ANALYTIC HIERARCHY PROCESS

In today's world, making the best decisions is very hard due to the growing complexity. For a long time, managers and decision makers that had authority, decided based on analytic and quantitative facts. In fact, there were important subjective

aspects such as tacit experience, thoughts or feelings. Due to be non-measurability, these aspects were not taken into consideration.

“Many methods stemming from applied mathematics and operations research have proved useful to help decision makers making informed decisions, and among these methods there are also those requiring, as inputs, subjective judgments from a decision maker or an expert” [1].

AHP is a theory and methodology for relative measurement [1]. In classical measurement, the main aim is to find out the exact measures of the pairs that are compared. However, in AHP which is a relative measurement, “the decision maker is not interested in the exact measurement of some quantities, but rather on the proportions between them”.

Analytic Hierarchy Process (AHP) is a very useful tool for analyzing subjective judgements while making decisions. As this study is focused on using AHP, it is vital to clarify the steps and all the aspects of the process.

Relative measurements are suitable for cases in which the best criteria must be chosen [1]. In this case, the important point is to find the best among criteria, rather than knowing the precise scores of them. Also, when the attributes are intangible, it is difficult to design a measurement scale. For this reason, AHP can be used in order to simplify the analysis. Now let's look at the steps of AHP, to better understand the process.

2.2.1. Steps of AHP

A decision maker could run into troubles when rating in the form of a numerical vector for many criteria. This is a matter of fact and originates from our cognitive limits and the impossibility of effectively comparing several criteria at the same time [1]. In order to split the problem into smaller pieces, makes the decision maker easier to compare among criteria. There are three main steps to follow in AHP which are [1];

1. Problem structuring and definition of the hierarchy
2. Elicitation of pairwise comparisons

3. Derivation of priority vectors and their linear combinations.

These three main steps can be finished by making the calculations explained in the following subsections.

2.2.1.1. Pairwise Comparison Matrix

As it is mentioned before, in case of many criteria, it is hard to make a comparison and give the best decision for the decision maker. That's why the decision maker compares the criteria as pairs each time. This way, it is easy to define which criterion is better than the other. By selecting among each pair, the pairwise comparison matrix is constructed, which gives a ratio between degrees of preferences among all criteria (Figure 1).

$$A = \begin{bmatrix} & \textit{Criterion 1} & \textit{Criterion 2} & \textit{Criterion 3} & \textit{Criterion n} \\ \textit{Criterion 1} & a_{11} & a_{12} & a_{13} & a_{1n} \\ \textit{Criterion 2} & a_{21} & a_{22} & a_{23} & a_{2n} \\ \textit{Criterion 3} & \vdots & \vdots & \vdots & \vdots \\ \textit{Criterion n} & a_{n1} & a_{n2} & a_{n3} & a_{nn} \end{bmatrix}$$

Figure 1: Pairwise comparison matrix [1]

The values in the pairwise comparison matrix express the ratio of degree of preference among each alternative. For example, if we consider a_{12} , it gives us the preference ratio of x_1 over x_2 . If the value is, let's say 2, it means that x_1 is likely to be preferred two times more than x_2 .

In the same manner, it means that x_2 is preferred $\frac{1}{2}$ rather than x_1 and the corresponding value for this situation will be a_{21} . Note that the multiplication of these values equal to 1. So, if one alternative is x times better then the other alternative, it means that the second alternative is $1/x$ better than the first one. This ratio is called also the weight ratio between criteria where;

$$a_{ij} = w_i/w_j$$

2.2.1.2. Normalizing the Matrix

In order to find the priority vector, the matrix must be normalized. Normalizing the matrix means that for each alternative x_i , all the values of a_{ij} must be summed and each a_{ij} must be divided into that sum. By doing so, we obtain a new matrix where the new values of a_{ij} are c_{ij} calculated with the formula below.

$$c_{ij} = \frac{a_{ij}}{\sum_i a_{ij}}$$

After normalizing the matrix, the average of $c_{i,j}$ values corresponding for each x_i is calculated and written into the matrix, to obtain the priority vector w .

$$w = \begin{bmatrix} w_1 \\ w_2 \\ w_3 \end{bmatrix}$$

2.2.1.3. Calculating lambda (λ) coefficient

To calculate the lambda (λ) coefficient, the eigenvector method [1] introduced by Brunelli (2014) was used. The results of the questionnaires are were put in a pairwise comparison matrix, normalized and the lambda (λ) coefficient was calculated. Brunelli (2014), explains that there will be several roots for lambda (λ) and the one that has the maximum value λ_{max} is used in the Consistency Index (CI) calculation. Here we took lambda (λ) directly as λ_{max} in our calculations.

The lambda coefficient is calculated by the formula;

$$\lambda = \frac{E_i}{n}$$

Where E_i is the Eigen value and is calculated by,

$$E_i = \frac{d}{w}$$

and d is the column vector and is calculated by multiplying the A matrix with the priority vector w_i ;

$$d = A . w$$

2.2.1.4. Consistency index

According to the result that given a pairwise comparison matrix A , its maximum eigenvalue, λ_{max} , is equal to n if and only if the matrix is consistent [1]. The consistency index was first introduced by Thomas L. Saaty in the late 80's [3]. As it was mentioned in 2.2.1.3., we took lambda (λ) directly as λ_{max} in our calculations.

$$CI(A) = \frac{\lambda_{max} - n}{n - 1}$$

2.2.1.5. Consistency Ratio

The consistency ratio is the ratio found by dividing the CI by RI (A predefined random index). It can be thought as a rescaled version of CI . In other words, an estimation of the average CI is obtained from a large enough set of randomly generated matrices of size n .

$$CR(A) = \frac{CI(A)}{RI_n}$$

According to Saaty [4], in practice matrices with values $CR \leq 0.1$ should be accepted and values greater than 0.1 should be rejected. A value of $CR = 0.1$ means that the judgments are 10% as inconsistent as if they had been given randomly. You can see the random index values calculated (Table 1).

Table 1: Random Index Values [1]

n	3	4	5	6	7	8	9	10
RI_n	0.5247	0.8816	1.1086	1.2479	1.3417	1.4057	1.4499	1.4854



CHAPTER 3. UNIVERSITY TIMETABLING PROBLEM

In this chapter, a case study is made using AHP and a MOMP, in order to solve a university time-tabling problem. All the steps of AHP defined prior this chapter have been followed step by step and calculations have been made. The results obtained are put into GAMS/CPLEX, to solve the mathematical model constructed for the problem. In the following sections you can find the details about the study.

3.1. CURRENT SYSTEM

In this section, the current time-tabling system used at Çankaya University will be explained. After understanding the current system, it will be easier to evaluate the new approach used in this study. In the current scheduling system used by the university, the main problem is that the notification of problems related to course schedules (class request, day time change, etc.) are shared with the Registrars' Office at step 7 (Figure 5). So, the office must go over the schedule again, spending time to arrange the notified requests.

The change notifications are made by the department chairs of each department. Prior the notifications, instructors make their requests to the chair, and the chair arranges the departments' schedule. Afterwards, the notification is sent to the Registrar's Office. As you can see, a lot of process is done behind the stage in order to fulfill instructor requests, because of not considering their preferences at the beginning. Also, one more insufficiency of the current system is that, while constructing the schedule, students' preferences are not taken into consideration either.

3.1.1. Steps in the Current System

In the current system used in Çankaya University, the following steps are followed in order to define the final course schedules;

1. The departments deliver their courses and data related to these courses to their department coordinators.
2. The Mathematics Department places the weekly syllabus of the mathematics courses on the table by specifying day-hours and forwards them to the Registrar's Office.
3. The Department of Basic Engineering submits the weekly schedule of Physics courses on the table to the Department of Basic Engineering and submits them to the Student Affairs Department.
4. The Department of Foreign Languages to place the weekly course schedule of the English courses on the table by specifying day-hours and forwards them to the Department of Student Affairs.
5. All departments to place their courses appropriately on the syllabus delivered to them.
6. Course entries take place from Course Data Entry System and are approved by advisors.
7. Notification of problems related to course schedules (class request, day time change, etc.) are shared with the Registrars' Office.
8. Course registration of students for Semester.

As we can see, in the current system after collecting course related information from all departments in a specific order, the Registrars' Office constructs the overall schedule. The tasks defined above can be seen in an order in timeline (Appendix 1).

3.1.2. Problems of the Current System

In this system, the main problem is that the notification of problems related to course schedules (class request, day time change, etc.) are shared with the Registrars' Office at step 7 (Figure 2). So, the office must go over the schedule again, spending time to arrange the notified requests.

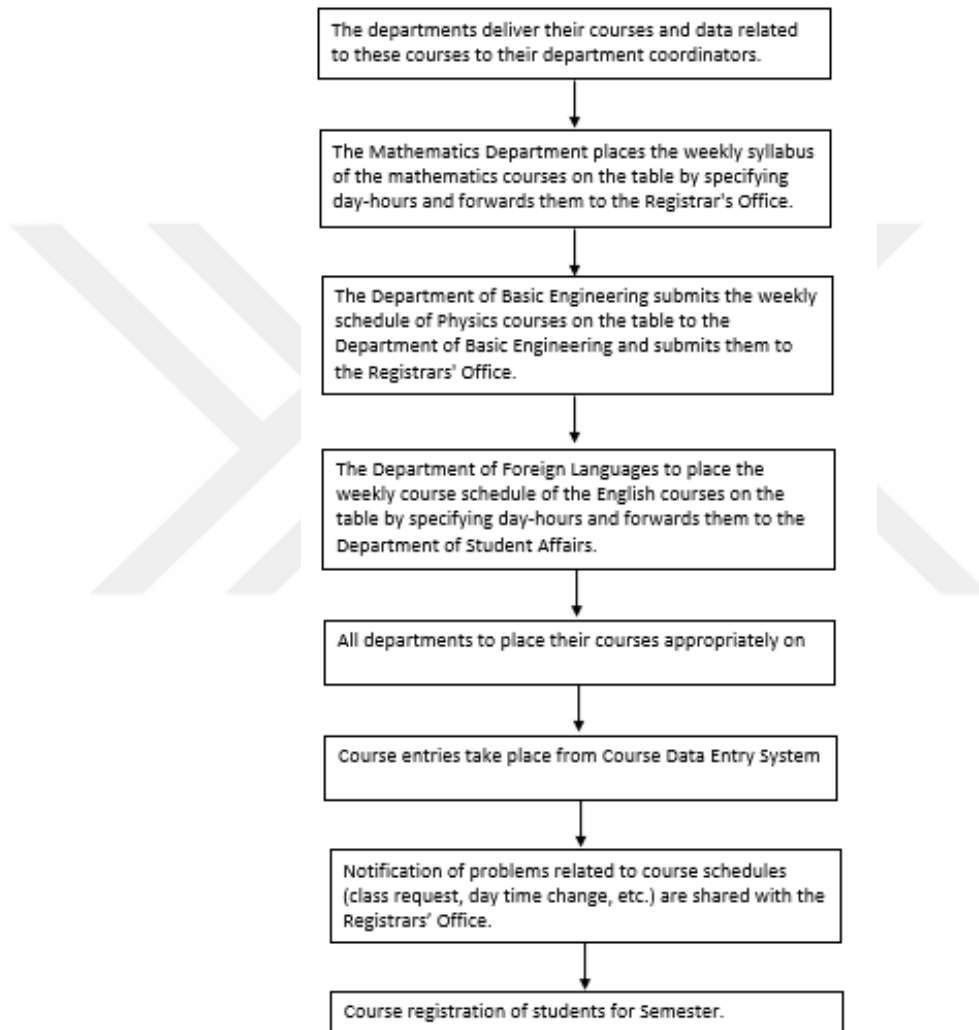


Figure 2: Flowchart of Current System

The change notifications are made by the department chairs of each department. Prior the notifications, instructors make their requests to the chair, and the chair arranges the departments' schedule. Afterwards, the notification is sent to the Registrar's Office. As you can see, a lot of process is done behind the stage in order to fulfill instructor

requests, because of not considering their preferences at the beginning. Also, one more disadvantage of the current system is that, while constructing the schedule, students' preferences are not taken into consideration either.

3.2. OUR APPROACH

In the new approach that we instruct, the most important difference is using AHP at the beginning to determine preferences of instructors and students via questionnaires and use the information in the basis of constructing the schedule. In the new system introduced, the timetabling problem will take weights which are calculated in AHP. The weights refer to instructor and student preferences which are collected using two different questionnaires filled by the instructors and students respectively. By this way, the overall process will take less time and obtain a better solution with less effort. In the next chapter, information about methodology used is explained and details are given.

3.2.1. Phases of Our Approach

There are four phases in the new approach, which can be seen below in figure 3, in order to see clearly a wide copy of it has been added to appendix 2;

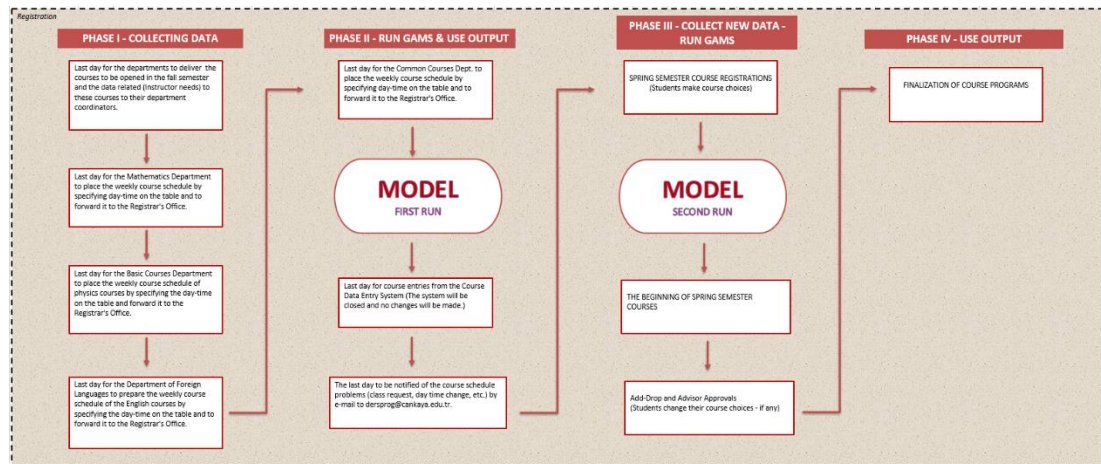


Figure 3: Flowchart of the new approach

The new approach consists of four phases;

1. Phase I. Collecting Data
2. Phase II. Model First Run & Use Output
3. Phase III. Collect New Data & Model Second Run
4. Phase IV. Use the Output

Phase I. Collecting Data

Phase I is focusing on collecting data where the following steps take place;

1. Departments deliver the courses to be opened in the fall semester and the data related (Instructor needs) to these courses to their department coordinators.
2. The Mathematics Department places the weekly course schedule by specifying day-time on the table and to forward it to the Registrar's Office.
3. The Basic Courses Department places the weekly course schedule of physics courses by specifying the day-time on the table and forwards it to the Registrar's Office.
4. The Department of Foreign Languages prepares the weekly course schedule of the English courses by specifying the day-time on the table and forwards it to the Registrar's Office.

Here, instructor and student questionnaires are distributed to collect information about preferences, in order to be used in AHP.

Phase II. Model First Run & Use Output

In Phase II, while further steps go on in collecting data, the first run of the model takes place and the output is used for the first time. Here the preferences of instructors have been already collected and taken into consideration while constructing a feasible course schedule. Phase II contains the following steps;

1. The Common Courses Department places weekly course schedule by specifying day-time on the table and forwards it to the Registrar's Office.
2. “*MODEL FIRST RUN*” takes place at this step.

3. The course entries are made from the Course Data Entry System (The system will be closed, and no changes will be made.)
4. The course schedule problems (class request, day time change, etc.) have been notified to the Registrar's Office.

Here, the main aim is to obtain zero problems at step 4. If the collected data is consistent and is used in the model, it is expected to obtain a feasible solution where all the instructors are pleased with the resulting schedule. The expected income is, of course to have less problems when compared to the current system.

Phase III. Collect New Data & Model Second Run

At the beginning of Phase III, there is already a schedule in hand, which has been obtained as the model has been run in the previous phase. But as the students make course choices in Phase III, a second run must be made. The following actions take place in the third phase;

1. Semester course registrations (Students make course choices)
2. "MODEL SECOND RUN" takes place at this step.
3. The beginning of semester courses.
4. Add-Drop and Advisor Approvals (students change course choices – if any)

In this phase, the schedule is completed, and the semester has begun. In fact the only need for phase IV is because of the add-drop period.

Phase IV. Use the Output

This phase has only one step which is the finalization of the course programs. In the previous steps the preferences data of instructors are collected, the first run has been made, the course choices have been made by the students, the second run has been made, add-drops have been made, and lastly the final schedule is released.

3.2.2. Instructor Questionnaire

In order to collect preference data for instructors, a questionnaire has been prepared and distributed to each instructor. In the questionnaire, there are three conditions, where the instructor must choose among, and select the relevant importance between every pair (Table 2).

Table 2: Selection Criteria (Instructor Questionnaire)

CRITERIA	UNWANTED SITUATION
A: REGULAR DISTRIBUTION OF COURSES (BALANCEDNESS)	For example; the teacher has 3 hours on Mondays and Tuesdays and 6 hours on Wednesdays and Thursdays; no homogeneous distribution throughout the week.
B: HAVING A DAY-OFF	That the instructor doesn't have any free days without lessons.
C: HAVING AT LEAST ONE HOUR BREAK BETWEEN COURSES	There is no gap of at least 1 hour between the courses given by the teacher on the same day.

The selection is made by giving numerical values corresponding to importance relevancy between the criteria. The values are from 1 to 9, where the odd numbers can be considered as main values and even numbers as intermediate values (Table 3).

Table 3: Values corresponding to importance relevancy

Verbal Scale	Main Values
Equally Important	1
Somewhat More Important	3
More Important	5
Much More Important	7
Significantly More Important	9

For example;

If instructor thinks that *A* is “Significantly More Important” than *B*; he/she should write *A 9 B* for “*A & B*”;

But he/she thinks that, *B* is “More Important” than *A*; for *A & B*, writing *B first*: he/she should write *B 5 A*.

For another option, if *C* is “Somewhat More Important “*than B*; For *B & C*, writing *C first*: *C 3 B* must be written.

3.2.3. Student Questionnaire

In order to collect preference data for students, a questionnaire has been prepared and distributed to forty students. In the questionnaire, there are five conditions, where each student must choose among, and select the relevant importance between every pair (Table 4).

Table 4: Selection Criteria (Instructor Questionnaire)

CRITERIA	UNWANTED SITUATION
A: CLASH OF COURSES	The situation that different courses clash at the same meeting hour.
B: REGULAR DISTRIBUTION OF COURSES (BALANCEDNESS)	For example; the student has 3 hours on Mondays and Tuesdays and 6 hours on Wednesdays and Thursdays; no homogeneous distribution throughout the week.
C: HAVING MORE THAN THREE HOURS BREAK BETWEEN COURSES	For example; There is more than 3 hours break between courses IE376 and IE343 taken by the student.
D: HAVING A DAY OFF	That the student doesn't have any free days without lessons.
E: HAVING AT LEAST ONE HOUR BREAK BETWEEN COURSES	There is no gap of at least 1 hour between the courses taken by the student on the same day.

The selection is made by giving numerical values corresponding to importance relevancy between the criteria which is exactly the same in the instructor questionnaire. The values are from 1 to 9, where the odd numbers can be considered as main values and even numbers as intermediate values (Table 3).

3.3. AHP CALCULATIONS FOR QUESTIONNAIRES

In this section, the aim is to explain the questionnaires applied to both instructors and students to collect relevant data of their preferences. The results of the questionnaires led us to weights which are the main reason to use AHP and were used in the mathematical model.

3.3.1. Calculation for Instructor Questionnaire

In this part the calculation of the weights for instructor questionnaire is explained. A total of 10 instructors attended the questionnaire. At the end the result is checked by Consistency Ratio (*CR*) calculation, and the weights are obtained to be used for instructor preferences.

3.3.1.1. Pairwise Comparison Matrix

By selecting among each pair, the pairwise comparison matrix was constructed, which had given a ratio between degrees of preferences among all criteria according to the instructor questionnaires.

		A	B	C
A=	A	1.00	0.26	0.31
	B	3.86	1.00	3.26
	C	3.09	0.31	1.00
TOTAL		7.95	1.57	4.57

3.3.1.2. Normalizing the Matrix

After the pairwise comparison is constructed, it is normalized by dividing each cell to the column total. The normalized matrix can be seen in table below.

		A	B	C
C=	A	0.13	0.17	0.07
	B	0.49	0.64	0.71
	C	0.39	0.20	0.22

The W_i priority vector is calculated from the normalized matrix, by taking the averages of each row corresponding to the criteria A, B, and C respectively.

3.3.1.3. Calculating lambda (λ) coefficient

In order to find out the lambda (λ) coefficient, firstly the column vector D_l and Eigen vector E_l have been calculated.

$$D_l = A.W$$

$$D_l = \begin{bmatrix} 1 & 0.26 & 0.31 \\ 3.86 & 1 & 3.26 \\ 3.09 & 0.31 & 1 \end{bmatrix} \cdot \begin{bmatrix} 0.12 \\ 0.61 \\ 0.27 \end{bmatrix}$$

$$E_l = \frac{D_l}{W} = \begin{bmatrix} 3.02 \\ 3.18 \\ 3.08 \end{bmatrix}$$

$$\lambda = \frac{E_l}{n} = 3.09$$

3.3.1.4. Calculating CI & CR

The λ coefficient has been used to find Consistency Index (*CI*) and calculate the Consistency Ratio (*CR*).

$$CI = \frac{\lambda - n}{n - 1} = \frac{3.09 - 3}{3 - 1} = 0.05$$

$$CR = \frac{CI}{RI} = \frac{0.05}{0.58} = 0.08 \leq 0.1 \quad (\text{Consistent then accept})$$

As *CR* is smaller than 0.1 so the weights that are obtained are accepted to be used in the model.

3.3.1.5. Objective Weights for Instructors

After the calculations and consistency controls were made, the following weights were eligible to be used in the model for instructor preferences.

$$W_t = \begin{bmatrix} 0.12 \\ 0.61 \\ 0.27 \end{bmatrix}$$

3.3.2. Calculation for Student Questionnaire

In this part the first attempt made for calculation of the weights for student questionnaires are explained. A total of 50 students attended the questionnaire. At the end you will see that the result is checked by Consistency Ratio (*CR*) calculation, and the weights obtained are refused to be used. Therefore, a second attempt has been made after applying the same questionnaire to same students. Although the results in the first

attempt were inapplicable, it was important to show you the overall work and steps followed consequently to find applicable results.

3.3.2.1. Pairwise Comparison Matrix

By selecting among each pair, the pairwise comparison matrix was constructed, which had given a ratio between degrees of preferences among all criteria according to the student questionnaires.

A=	A	1.00	4.96	4.07	4.57	5.04
	B	0.20	1.00	4.90	4.85	4.81
	C	0.25	0.20	1.00	4.73	4.47
	D	0.22	0.21	0.21	1.00	6.26
	E	0.20	0.21	0.22	0.16	1.00
	Total	1.86	6.58	10.41	15.32	21.58

3.3.2.2. Normalizing the Matrix

After the pairwise comparison is constructed, it is normalized by dividing each cell to the column total. The normalized matrix can be seen below.

		A	B	C	D	E
C=	A	0.54	0.75	0.39	0.30	0.23
	B	0.11	0.15	0.47	0.32	0.22
	C	0.13	0.03	0.10	0.31	0.21
	D	0.12	0.03	0.02	0.07	0.29
	E	0.11	0.03	0.02	0.01	0.05
	Total	1	1	1	1	1

The W priority vector is calculated from the normalized matrix, by taking the averages of each row corresponding to the criteria A, B, C, D and E respectively.

$$W = \begin{bmatrix} 0.44 \\ 0.25 \\ 0.16 \\ 0.10 \\ 0.04 \end{bmatrix}$$

3.3.2.3. Calculating lambda (λ) coefficient

In order to find out the lambda (λ) coefficient, firstly the column vector D_s and Eigen vector E_s have been calculated.

$$D_s = A.W$$

$$D_s = \begin{bmatrix} 1 & 4.96 & 4.07 & 4.57 & 5.04 \\ 0.20 & 1 & 4.90 & 4.85 & 4.81 \\ 0.25 & 0.20 & 1 & 4.73 & 4.47 \\ 0.22 & 0.21 & 0.21 & 1 & 6.26 \\ 0.20 & 2.21 & 0.22 & 0.16 & 1 \end{bmatrix} \cdot \begin{bmatrix} 0.44 \\ 0.25 \\ 0.16 \\ 0.10 \\ 0.04 \end{bmatrix} = \begin{bmatrix} 3.03 \\ 1.82 \\ 1.01 \\ 0.56 \\ 0.24 \end{bmatrix}$$

$$E_s = \frac{D_s}{W} = \begin{bmatrix} 6.85 \\ 7.16 \\ 6.48 \\ 5.32 \\ 5.44 \end{bmatrix}$$

$$\lambda = \frac{E_s}{n} = 6.25$$

3.3.2.4. Calculating CI & CR

The λ coefficient has been used to find Consistency Index (CI) and Consistency Ratio (CR).

$$CI = \frac{\lambda - n}{n - 1} = \frac{6.25 - 5}{5 - 1} = 0.31$$

$$CR = \frac{CI}{RI} = \frac{0.31}{1.1086} = 0.28 \geq 0.1 \quad (\text{Not consistent then reject})$$

As CR is greater than 0.1, the weights that are obtained could not be used in the model.

3.3.3. Calculation for Student Questionnaire (Second attempt)

As the first attempt had not driven results suitable to be used in the model, a second questionnaire has been delivered to the same students. The gathered data is used to calculate the CR value. The same steps in section 3.3.2 were followed.

3.3.3.1. Pairwise Comparison Matrix

By selecting among each pair, the pairwise comparison matrix was constructed, which had given a ratio between degrees of preferences among all criteria according to the student questionnaires.

	A	B	C	D	E
A	1.00	2.52	3.08	6.72	9.00
B	0.40	1.00	2.39	4.01	6.79
C	0.32	0.42	1.00	4.73	4.47
D	0.15	0.25	0.21	1.00	4.95
E	0.11	0.15	0.22	0.20	1.00
Total	1.98	4.34	6.91	16.67	26.22

3.3.3.2. Normalizing the Matrix

After the pairwise comparison for the second attempt was constructed, it was normalized by dividing each cell to the column total.

	A	B	C	D	E
A	0.50	0.58	0.45	0.40	0.34
B	0.20	0.23	0.35	0.24	0.26
C	0.16	0.10	0.14	0.28	0.17
D	0.08	0.06	0.03	0.06	0.19
E	0.06	0.03	0.03	0.01	0.04
Total	1.00	1.00	1.00	1.00	1.00

The W priority vector is calculated from the normalized matrix, by taking the averages of each row corresponding to the criteria A, B, C, D and E respectively.

$$W = \begin{bmatrix} 0.46 \\ 0.26 \\ 0.17 \\ 0.08 \\ 0.03 \end{bmatrix}$$

3.3.3.3. Calculating lambda (λ) coefficient

In order to find out the lambda (λ) coefficient, firstly the column vector D_s and Eigen vector E_s have been calculated.

$$D_s = A.W$$

$$D_s = \begin{bmatrix} 1 & 2.52 & 3.08 & 6.72 & 9 \\ 0.40 & 1 & 2.39 & 4.01 & 6.79 \\ 0.32 & 0.42 & 1 & 4.73 & 4.47 \\ 0.15 & 0.25 & 0.21 & 1 & 4.95 \\ 0.11 & 0.15 & 0.22 & 0.20 & 1 \end{bmatrix} \cdot \begin{bmatrix} 0.46 \\ 0.26 \\ 0.17 \\ 0.08 \\ 0.03 \end{bmatrix} = \begin{bmatrix} 2.49 \\ 1.41 \\ 0.97 \\ 0.42 \\ 0.18 \end{bmatrix}$$

$$E_s = \frac{D_s}{W} = \begin{bmatrix} 5.47 \\ 5.53 \\ 5.65 \\ 5.11 \\ 5.15 \end{bmatrix}$$

$$\lambda = \frac{E_s}{n} = 5.38$$

3.3.3.4. Calculating CI & CR

The λ coefficient has been used to find Consistency Index (*CI*) and Consistency Ratio (*CR*).

$$CI = \frac{\lambda - n}{n - 1} = \frac{5.38 - 5}{5 - 1} = 0.10$$

$$CR = \frac{CI}{RI} = \frac{0.10}{1.1086} = 0.09 \leq 0.1 \quad (\text{Consistent then accept})$$

As *CR* is smaller than 0.1, the weights that are obtained were suitable to be used in the model.

3.3.3.5. Objective Weights for Students

After the calculations and consistency controls were made, the following weights were eligible to be used in the model for student preferences.

$$W_s = \begin{bmatrix} 0.46 \\ 0.26 \\ 0.17 \\ 0.08 \\ 0.03 \end{bmatrix}$$

3.3.4. Results Obtained from AHP

As it is explained in the previous subsections, the AHP calculations for the instructor and student preferences were completed and the weights W_i and W_s are obtained to be used in the mathematical model. The values are given below.

$$W_i = \begin{bmatrix} 0.12 \\ 0.61 \\ 0.27 \end{bmatrix} \quad W_s = \begin{bmatrix} 0.46 \\ 0.26 \\ 0.17 \\ 0.08 \\ 0.03 \end{bmatrix}$$

CHAPTER 4.
MATHEMATICAL MODEL

In order to solve the problem, a mathematical model is constructed, verification and validation of the model are performed.

4.1. THE MODEL

The sets, parameters, decision variables, constraints and objective function are as follows.

SETS

S^l the set of instructors

$$S^l = \{l: l = BS, FCC, MAE, GY, HA, NK, OK, AK, HO, AKK\}$$

S^d the set of days

$$S^d = \{d: d = 1, 2, \dots, 5\}$$

S^h set of starting hour of class meetings

$$S^h = \{h: h = 09, 10, \dots, 16\}$$

S^t set that defines time for meeting hours for each day and is a combination of day & hour

$$S^t = S^d \times S^h$$

S_h^t is the subset of S^t where t belongs to meeting starting hour
 $S_h^t = \{109, 209, 309, 409, 509\}$ where $h = 1$

S_d^t is the subset of S^t where t belongs to meeting day
 $S_d^t = \{109, 110, 111, 112, 113, 114, 115, 116, \}$ where $d = 1$

S^m is the set for the class meetings, which are formed by the combination of courses, their types (Theory or Practice) and section number
 $S^m = \{m: m = IE333T2, IE334P1, \dots\}$

S_e^m subset of S^m defining external class meetings (belonging to other departments)
 $S_e^m = \{\tilde{m}: \tilde{m} = CENGxxxLx, \dots\}$

S^g The set of students who take same courses at same time (defines student groups)
 $S^g = \{g: g = 1, 2, \dots, G\}$

S^i is the set of criteria that instructors select upon
 $S^i = \{i: i = 1, 2, 3\}$

S^j is the set of criteria that students select upon
 $S^j = \{j: j = 1, 2, 3, 4, 5\}$

The elements of the set indicate the name and surname of each instructor. Ten instructors in the Industrial Engineering Department are defined as elements of set S^l . S^d is the set of days. Beginning from Monday to Friday, five consecutive days are the elements of this set.

S^t is the set that defines the time for meeting hours for each day and is constructed by a combination of day & hour. The first digit is for the day where the meeting is held and the second and third digits imply the hour of that specific day. For example, if we consider 10 o'clock on Tuesday, it is denoted as 210, whereas 14 o'clock on Friday is denoted as 514.

S^m is the set for the class meetings, which are formed by the combination of courses, their types (such as lecture or recitation) and section number. For example, IE407L9 indicates that, it is the IE407 courses Lecture for section 9, where IE232R1 indicates that it is the first section of recitation for course IE232.

PARAMETERS

$BigM$	A large number
k_m	Total duration of class meeting m (in hours)
n_g	number of students in student group g
$GM_{g,m}$	$= \begin{cases} 1 & \text{if student group } g \text{ takes class meeting } m \\ 0 & \text{otherwise} \end{cases}$
$LM_{l,m}$	$= \begin{cases} 1 & \text{if instructor } l \text{ is assigned to class meeting } m \\ 0 & \text{otherwise} \end{cases}$
$F_{l,t}$	$= \begin{cases} 1 & \text{if time } t \text{ is feasible for instructor } l \\ 0 & \text{otherwise} \end{cases}$
WI_1	weight of balancedness objective for instructors (I_1)
WI_2	weight of day-off objective for instructors (I_2)
WI_3	weight of break between meetings objective for instructors (I_3)
WS_1	weight of balancedness objective for students (S_1)

WS_2	weight of day-off objective for students (S_2)
WS_3	weight of break between meetings objective for students (S_3)
WS_4	weight of no long-break objective for students (S_4)
WS_5	weight of no clash objective for students (S_5)
SI_1	scale of balancedness objective for instructors (I_1)
SI_2	scale of day-off objective for instructors (I_2)
SI_3	scale of break between meetings objective for instructors (I_3)
SS_1	scale of balancedness objective for students (S_1)
SS_2	scale of day-off objective for students (S_2)
SS_3	scale of break between meetings objective for students (S_3)
SS_4	scale of no long-break objective for students (S_4)
SS_5	scale of no clash objective for students (S_5)
$X_{t,\tilde{m}}^e$	$= \begin{cases} \text{where external class meeting } \tilde{m} \text{ starts at time} \\ 0 \text{ otherwise} \end{cases}$
$Y_{t,\tilde{m}}^e$	$= \begin{cases} \text{where external class meeting } \tilde{m} \text{ occurs at time } t \\ 0 \text{ otherwise} \end{cases}$

Weight parameters are obtained from AHP. Scale parameters (from SI_1 to SS_5) are used to balance objective function components. Derivation of the numerical values of these parameters will be explained in the following parts of this section.

As it was mentioned in section 3.2.1. "Phases of Our Approach", there are four phases. In the first phase data is collected and both the instructor and student preference weights are calculated. In the second phase, model's first run took place.

At the third phase data is collected again but the weights for preferences remain same. Lastly, at the fourth phase the model's second run has been made to obtain the final schedule.

So, only the values of the parameters below do change in Phase III;

- n_g
- $GM_{g,m}$
- $LM_{l,m}$

Where the other parameters remain the same (Table 5).

Table 5: Data Collection & Parameter Calculation for Phases

<u>PHASE I</u>	<u>PHASE II</u>	<u>PHASE III</u>	<u>PHASE IV</u>
$BigM$	No Data Collection	No Change in Data	No Data Collection
k_m	No Data Collection	No Change in Data	No Data Collection
n_g	No Data Collection	n_g	No Data Collection
$GM_{g,m}$	No Data Collection	$GM_{g,m}$	No Data Collection
$LM_{l,m}$	No Data Collection	$LM_{l,m}$	No Data Collection
$F_{l,t}$	No Data Collection	No Change in Data	No Change in Data
WI_1 to WI_3	No Data Collection	No Change in Data	No Change in Data
WS_1 to WS_5	No Data Collection	No Change in Data	No Change in Data
$X_{t,\tilde{m}}^e$	No Data Collection	No Change in Data	No Data Collection
$Y_{t,\tilde{m}}^e$	No Data Collection	No Change in Data	No Data Collection
SI_1 to SI_3	No Data Collection	No Change in Data	No Change in Data
SS_1 to SS_5	No Data Collection	No Change in Data	No Change in Data

DECISION VARIABLES

$$X_{t,m} = \begin{cases} 1 & \text{if class meeting } m \text{ starts at time } t \\ 0 & \text{otherwise} \end{cases}$$

$$Y_{t,m} = \begin{cases} 1 & \text{if class meeting } m \text{ occurs at time } t \\ 0 & \text{otherwise} \end{cases}$$

$$U_{t,g} = \begin{cases} 1 & \text{if student group } g \text{ has any class meeting at time } t \\ 0 & \text{otherwise} \end{cases}$$

$$TID_{l,d} = \text{Total meeting hours of Instructor } l \text{ on day } d$$

$$BID_{l,d} = \begin{cases} 1 & \text{if instructor } l \text{ has meeting on day } d \\ 0 & \text{otherwise} \end{cases}$$

$$DID_{l,d,d'}^+ = \text{Positive difference between total meeting hours of Instructor } l \text{ on days } d \text{ and } d'$$

$$DID_{l,d,d'}^- = \text{Negative difference between total meeting hours of Instructor } l \text{ on days } d \text{ and } d'$$

$$NBI_{l,m} = \begin{cases} 1 & \text{if there is no break after meeting } m \text{ for instructor } l \\ 0 & \text{otherwise} \end{cases}$$

$$TSD_{g,d} = \text{Total meeting hours of student group } g \text{ on day } d$$

$$BSD_{g,d} = \begin{cases} 1 & \text{if student group } g \text{ has meeting on day } d \\ 0 & \text{otherwise} \end{cases}$$

$$DSD_{g,d,d'}^+ = \text{Positive difference between total meeting hours of student group } g \text{ on days } d \text{ and } d'$$

$$DSD_{g,d,d'}^- = \text{Negative difference between total meeting hours of student group } g \text{ on days } d \text{ and } d'$$

$$NBS_{g,m} = \begin{cases} 1 & \text{if no break after meeting } m \text{ for student group } g \\ 0 & \text{otherwise} \end{cases}$$

$$LBS_{g,m} = \begin{cases} 1 & \text{if break } \geq 3 \text{ hrs after meeting } m \text{ for student group } g \\ 0 & \text{otherwise} \end{cases}$$

$NCS_{g,t}$ = Number of clashing meetings at time t for student group g

I_1 Total time and daily differences between total meeting hour for all instructors.

I_2 Total days that instructors have meetings.

I_3 Total meetings of instructors that there is no at least one-hour break after meeting.

S_1 Total time and daily differences between total meeting hour for all students, weighted by group size.

S_2 Total days that student group has meetings, weighted by group size.

S_3 Total meetings of student group that there is no at least one-hour break after meeting, weighted by group size.

S_4 Total meetings of student group that has at least three hours break between meetings, weighted by group size.

S_5 Total number of clashes for student groups, weighted by group size.

CONSTRAINTS

$$X_{t,m} = X_{t,m}^e ; \forall t, m \text{ where } m \in S_e^m \quad (1)$$

$$Y_{t,m} = Y_{t,m}^e ; \forall t, m \text{ where } m \in S_e^m \quad (2)$$

$$\sum_{\forall t} X_{t,m} = 1 ; \forall m \quad (3)$$

$$\sum_{\forall t} Y_{t,m} = k_m ; \forall m \quad (4)$$

$$X_{t,m} = 0 ; t \in S_d^t, t > 8d - k_m + 1 \quad (5)$$

$$Y_{t',m} \geq X_{t,m} ; t \& t' \in S_d^t, t + k_m - 1 \geq t' \geq t \quad (6)$$

$$\sum_{\forall m, m \notin S_e^m} Y_{t,m} LM_{l,m} \leq F_{l,t} ; \forall l, t \quad (7)$$

$$TID_{l,d} = \sum_{t \in S_d^t} \sum_{\forall m} Y_{t,m} LM_{l,m} ; \forall l, d \quad (8)$$

$$BigM \times BID_{l,d} \geq TID_{l,d} ; \forall l, d \quad (9)$$

$$DID_{l,d,d'}^+ \geq TID_{l,d} - TID_{l,d'} - BigM \times (1 - BID_{l,d'}) \quad \forall l, d, d' \quad (10)$$

$$DID_{l,d,d'}^- \geq TID_{l,d'} - TID_{l,d} - BigM \times (1 - BID_{l,d}) \quad \forall l, d, d' \quad (11)$$

$$I_1 = \sum_{\forall d} \sum_{\forall d'} \sum_{\forall t} DID_{l,d,d'}^- + DID_{l,d,d'}^+ \quad (12)$$

$$I_2 = \sum_{\forall d} \sum_{\forall l} BID_{l,d} \quad (13)$$

$$Y_{t,m} LM_{l,m} \sum_{\forall m'} Y_{t+1,m'} LM_{l,m'} - 1 \leq NBI_{l,m} \quad \forall l, m, m', t \quad (14)$$

$$I_3 = \sum_{\forall m} \sum_{\forall l} NBI_{l,m} \quad (15)$$

$$TSD_{g,d} = \sum_{t \in S_d^t} \sum_{\forall m} Y_{t,m} GM_{g,m}; \quad \forall g, d \quad (16)$$

$$BigM \times BSD_{g,d} \geq TSD_{g,d}; \quad \forall g, d \quad (17)$$

$$DSD_{g,d,d'}^+ \geq TSD_{g,d} - TSD_{g,d'} - BigM \times (1 - BSD_{g,d'}) \quad \forall g, d, d' \quad (18)$$

$$DSD_{g,d,d'}^- \geq TSD_{g,d'} - TSD_{g,d} - BigM \times (1 - BSD_{g,d}) \quad \forall g, d, d' \quad (19)$$

$$S_1 = \sum_{\forall d} \sum_{\forall d'} \sum_{\forall g} n_g \times (DSD_{g,d,d'}^- + DSD_{g,d,d'}^+) \quad (20)$$

$$S_2 = \sum_{\forall d} \sum_{\forall g} n_g \times BSD_{g,d} \quad (21)$$

$$\sum_{\forall m} Y_{t,m} GM_{g,m} \leq M \cdot U_{t,g} \quad \forall g, t \quad (22)$$

$$X_{t,m}GM_{g,m} + U_{t',g} - 1 \leq NBS_{g,m} \quad \forall g, m, t, t', \text{ where } t' = t + k(m) \text{ and } t, t' \in S_d^t \quad (23)$$

$$S_3 = \sum_{\forall m} \sum_{\forall g} n_g \times NBS_{g,m} \quad (24)$$

$$X_{t,m}GM_{g,m} \leq LBS_{g,m} + \sum_{\forall m'; m \neq m'} \sum_{t'=t+k_m}^{t+k_m+2} Y_{t',m'}GM_{g,m'} \quad \forall t, g, m \quad (25)$$

$$S_4 = \sum_{\forall m} \sum_{\forall g} n_g \times LBS_{g,m} \quad (26)$$

$$NCS_{g,t} \geq \sum_{\forall m} Y_{t,m}GM_{g,m} - 1 \quad \forall g, t \quad (27)$$

$$S_5 = \sum_{\forall t} \sum_{\forall g} n_g \times NCS_{g,t} \quad (28)$$

$$ZI = WI_1SI_1I_1 + WI_2SI_2I_2 + WI_3SI_3I_3 \quad (29)$$

$$ZS = WS_1SS_1S_1 + WS_2SS_2S_2 + WS_3SS_3S_3 + WS_4SS_4S_4 + WS_5SS_5S_5 \quad (30)$$

OBJECTIVE FUNCTION

$$Z = \alpha ZI + (1 - \alpha)ZS \quad (31)$$

Here, constraints (1) and (2) are used for the external courses taken from other departments. Constraint (3) defines the beginning hour of a meeting, where constraint (4) defines the duration hours of a meeting. Constraint (5) implies that the last hour of a meeting cannot exceed the last hour of a day. Constraint (6) says that a specific meeting's occurrence time should begin or must be after its starting time. Constraint (7) ensures that an instructor cannot have more than one meeting at the same time. Constraint (8) expresses that an instructor's total meeting hours in a day is defined as the total lecture hours he/she gives. Constraint (9) is used to find whether the instructor has meeting on the specified day. Constraints (10) and (11) together make a balance of daily meeting hours of assigned meetings throughout the week, meaning that there will be not much difference in total daily meeting hours between days. Here the values of "0" are neglected and not taken into consideration. Constraint (12) gives, I_1 which is the regular distribution of courses (balancedness) for instructors. Constraint (13) gives, I_2 which shows that the instructor has a day-off. Constraint (14) shows that there is at least one-hour break between meetings hours for the instructor, by the help of constraint (15) indicating I_3 which corresponds to occurrence of a break after meeting. Constraint (16) expresses that an instructor's total meeting hours in a day is defined as the total meeting hours of a student group takes. Constraint (17) ensures that the instructor has meeting on the specified day. Constraints (18) and (19) together make a balance of daily meeting hours of assigned meetings throughout the week, meaning that there will be not much difference in total daily meeting hours between days. Constraint (20) gives, S_1 which is the regular distribution of courses (balancedness) for students. Constraint (21) gives total days of the week that student group has meetings weighting by group size. Constraint (22) defines if student group has any meeting at that time. Constraint (23) shows that if there is no at least one-hour break between meeting hours for the student group. Constraint (24) assigns value of S_3 using no one-hour breaks after meetings weighting by group size. Constraint (25) expresses that there are at least 3 hours between two different meetings. Constraint (26) expresses, S_4 which means that there are at least three hours break between courses for students, where constraint (27) indicates there is no clash of different courses at the same meeting hour, by the help of, S_5 , defined in constraint (28).

The instructor objective function (29) calculates the total value for instructors. Each component has three parts, viz., weight, scale and function value. For example, the

first component $WI_1SI_1I_1$ is composed of weight parameter obtained from AHP, scale parameter to balance this component with others and the first objective function of instructors (the total time and daily differences between total meeting hour). Usage and finding values of scale parameters is explained in the next paragraph. The student objective function (30) calculates the total value for students similar to (29). The overall objective function (31) is the sum of linear combination of instructor and student objective functions with factor α , where $0 \leq \alpha \leq 1$. $\alpha = 1$ means only the instructors' objectives are considered in optimization, $\alpha = 0$ means just the opposite (means only the students' objectives are considered), $\alpha = 1/2$ means objective functions of instructors and students are treated equally, and so on.

Scale parameter is used as follows. Consider \tilde{I}_1 and \tilde{I}_2 values for a specific solution (i.e., $\tilde{X}_{t,m}$ and $\tilde{Y}_{t,m}$ values) and also assume that $\tilde{I}_1 = c$ (c is a number), $\tilde{I}_2 = 1000c$. In this case, the effect of second objective function of instructors will be more than the first one. If this happens in general, optimal solution will be biased to meet the second objective function component more than the first one. Actually, the weight parameters of AHP is for this purpose, but the value difference between objective function components deteriorate this effect. If we use scale values as 1000 and 1 for SI_1 and SI_2 , respectively, first two components of the objective function will be $WI_11000I_1 + WI_2I_2$. Using weight parameters, the purpose of AHP is achieved without any scale effect of numerical values of the objective function coefficients.

Scale parameters are found as follows. We solve the mathematical model for the schedules used at fall and spring semesters of 2018-2019 Academic Year (see Section 5.1 for detailed explanation of data sets). In other words, all courses are assumed as external courses and consequently there is no decision variable in the model. Only the values of objective function components are calculated in this fashion. The model is solved for both fall and spring semester data and average values of objective function components are used in finding scales. Scales are found in such a way that average values multiplied by scales would be equal, and this value is selected to be 500. Then, average values multiplied by scales for all three objective function components will be the same and it is 500.

In Tables 6 and 7, values used are obtained by solving the mathematical model. Average implies the average of values obtained from fall and spring semester data results. LB and UB are the lower and upper bounds indicating the values that each objective component can take and are calculated by using the formulas for each component. The column “Likely” indicates the outcome that is mostly expected.

Since weight factors are summed up to 1, *ZI* will be 500, as well. For students, similar approach is used but since *ZS* is composed of five objective function components, 300 is used as the number for multiplying average values with scales.

Table 6: Scales Calculations for Instructor Objectives

Objective Function Component	Value with Fall	Value with Spring	Average	Scale
I1	98	26	62	8.0645
I2	29	20	24.5	20.4082
I3	24	24	24	20.8333

Table 7: Scale calculations for Student Group Objectives

Objective Function Component	Value with Fall	Value with Spring	Average	Scale
S1	3824	2548	3186	0.0941
S2	848	829	838.5	0.3577
S3	216	109	162.5	1.8461
S4	1192	1097	1144.5	0.2621
S5	204	175	189.5	1.5831

4.2. Verification

The model constructed has been used in GAMS/CPLEX and syntax error checks were made. After that all the syntax errors were resolved and the verification of the model has been completed. This was important to be sure that the model we constructed was put into GAMS/CPLEX correctly.

4.3. Validation

After constructing the model, a sample data named “TOY” has been used to validate the model (Table 8). The TOY data was a small sample, taken from the full data obtained from Çankaya University. The results were as expected, and the validation process was successful. Further step to be taken was using the verified mathematical model with the full data set in the experimentation phase.

Table 8: Sets of data set TOY

t	M	g	l	d	h	TD		TH		me	mi
						t	d	t	h		
109,	CENG128L1,	1,	BS	1	9	109 . 1	109 . 9	CENG128L1,			
110,	CENG128T1,	2,	FCC	2	10	110 . 1	110 . 10	CENG128T1			
111,	IE227P1,	3,	MAE		11	111 . 1	111 . 11				IE227P1,
112,	IE227P2,	4,			12	112 . 1	112 . 12				IE227P2,
113,	IE227T1,	5			13	113 . 1	113 . 13				IE227T1,
114,	IE227T2,				14	114 . 1	114 . 14				IE227T2,
115,	IE232P1,				15	115 . 1	115 . 15				IE232P1,
209,	IE232T1,					209 . 2	209 . 9				IE232T1,
210,	IE334P1,					210 . 2	210 . 10				IE334P1,
211,	IE334P2,					211 . 2	211 . 11				IE334P2,
212,	IE334T1,					212 . 2	212 . 12				IE334T1,
213,	IE334T2					213 . 2	213 . 13				IE334T2
214,						214 . 2	214 . 14				
215						215 . 2	215 . 15				

The TOY data set, and the steps followed while solving the problem will be explained with the help of tables. This will help the readers better understand the constraints, objectives and how the model works. As mentioned above, the sample data “TOY”, has been driven from the actual data set. The elements of the set were selected for; 2 days, 7 hours, 12 meetings, 5 student groups and 3 instructors given in table 8 above.

The k_m values which describes each courses total weekly hour, was listed in order to be used in the model. The twelve courses and their weekly hours can be seen in table 9 below.

Table 9: The list of k_m used in TOY data

m	k
CENG128L1	2
CENG128T1	3
IE227P1	2
IE227P2	2
IE227T1	3
IE227T2	3
IE232P1	2
IE232T1	3
IE334P1	2
IE334P2	2
IE334T1	3
IE334T2	3

The five different student groups, and the number of students of each group are defined in n_g which is shown below in table 10.

Table 10: n_g used in TOY data

Group No	Number of Students
1	3
2	5
3	10
4	2
5	7

The meetings assigned to student groups are defined in the $GM_{g,m}$ data sheet, which can be seen below in table 11.

Table 11: $GM_{g,m}$ used in TOY data

	CENG128L1	CENG128T1	IE227P1	IE227P2	IE227T1	IE227T2	IE232P1	IE232T1	IE334P1	IE334P2	IE334T1	IE334T2
1			1		1				1		1	
2	1	1		1	1		1	1				
3										1		1
4							1	1	1		1	
5	1	1								1		1

The instructors assigned to meetings are defined in the $LM_{l,m}$ data sheet, which can be seen below in table 12.

Table 12: $LM_{l,m}$ used in TOY data

	CENG 128L1	CENG 128T1	IE227 P1	IE227 P2	IE227 T1	IE227 T2	IE232 P1	IE232 T1	IE334 P1	IE334 P2	IE334 T1	IE334 T2
BS			0	0	0	0	0	0	1	1	1	1
FCC			0	0	0	0	1	1	0	0	0	0
MAE			1	1	1	1	0	0	0	0	0	0

The specific times available for each instructor is defined in $F_{l,t}$ data sheet, for each of the three instructors for 14 hours (table 13).

Table 13: $F_{l,t}$ used in TOY data

	109	110	111	112	113	114	115	209	210	211	212	213	214	215
BS	1	1	1	1	1	1	1	1	1	1	1	1	1	1
FCC	1	1	1	1	1	1	1	1	1	1	1	1	1	1
MAE	1	1	1	1	0	0	1	1	1	1	1	0	0	1

The WI values calculated for instructor preference weights used in TOY data can be seen below in table 14. There are three weights for three instructors.

Table 14: WI used in TOY data

weight of balancedness objective for instructors	WI1	0.12
weight of day-off objective for instructors	WI2	0.61
weight of break between meetings objective for instructors	WI3	0.27

The WS values for five different students are entered in TOY data sheet which can be seen in table 15.

Table 15: WS used in TOY data

weight of balancedness objective for students	WS1	0.46
weight of day-off objective for students	WS2	0.26
weight of break between meetings objective for students	WS3	0.17
weight of no long breaks objective for students	WS4	0.08
weight of no clash objective for students	WS5	0.03

$X_{t,m}^e$ is given in table 16, which is used for the external class meeting in TOY data sheet. As it was introduced before, it shows at what time the meeting starts.

Table 16: $X_{t,m}^e$ used in TOY data

	CENG128L1	CENG128T1
109	1	1
110		
111		
112		
113		
114		
115		
⋮		
215		

$Y_{t,m}^e$ is given in table 17, which is used for the external class meeting in TOY data sheet. The $Y_{t,m}^e$ data shows at which time t , an external class meeting occurs.

Table 17: $Y_{t,m}^e$ used in TOY data

	CENG128L1	CENG128T1
109	1	1
110	1	1
111		1
112		
113		
114		
115		
209		
210		
211		
212		
213		
214		
215		

After the data and the model has been entered, GAMS/CPLEX has been used to run the mode in order to find a result. The GAMS/CPLEX results are shown below. Schedules were constructed for each instructors. The schedules for instructors BS, FCC and MAE can be seen in tables 18, 19 and 20 respectively.

Table 18: The schedule for instructor BS

	Monday	Tuesday
9	IE334T1	IE334T2
10	IE334T1	IE334T2
11	IE334T1	IE334T2
12		
13		IE334P2
14	334P1	IE334P2
15	334P1	

Table 19: The schedule for instructor FCC

	Monday	Tuesday
9		IE232P1
10		IE232P1
11		IE232P1
12		
13		IE232T1
14		IE232T1
15		IE232T1

Table 20: The schedule for instructor MAE

	Monday	Tuesday
9		IE227T1
10	IE227T2	IE227T1
11	IE227T2	IE227T1
12	IE227T2	
13	IE227P2	
14	IE227P2	IE227P1
15		IE227P1

After the results obtained above, we had the opportunity to check whether our model was working properly or not. To check the results, we looked at the preferences of instructors. Instructor MAE had not preferred one option over another significantly. His selections were not pointing on a special will. That's why his schedule was constructed as it was shown in table 20. As you can see, there are no break hours on Monday between meetings IE227T2 and IE227P2, where there is a one-hour break on Tuesday between meetings IE227T1 and IE227P1. According to MAE's preferences, the resulting schedule obtained for him was accurate.

Instructor BS made his preferences more likely to have at least one-hour breaks between his course meetings. The resulting schedule for him in table 18 was constructed by the model in order to have at least one-hour break, which is pretty aligned with his preferences. As you can see, on Monday there are two off hours between meetings IE334T1 and IE334P1. Also there is a one-hour break between meetings IE334T2 and IE334P2 on Tuesday.

Lastly, instructor FCC made his preference to have a day-off. The resulting schedule obtained for him as shown in table 19, exactly satisfied his choice. As you can see he has no course meetings on Monday, and both course meetings he attends are on Tuesday. As discussed above, the model we constructed to solve the timetabling problem by the use of AHP has given results parallel to the weights of instructor preferences. Further studies can be; applying this approach to other real-life problems where subjective thoughts or opinions of people should have been taken in consideration.



CHAPTER 5. EXPERIMENTATION AND RESULTS

We solve the mathematical programming model under different scenarios. The results show that the solutions are much better than the current timetable. These are explained in the following sections.

5.1. EXPERIMENTATION

After finishing the verification and validation of the model by the use of TOY data, the full data taken from Çankaya University was used in GAMS/CPLEX to obtain the real-life results. Two sets of data is obtained for the fall and spring semesters of 2018-2019 Academic Year. We use them for scales of the objective function (as explained in Section 4.1) and only solve the model for fall semester. Fall semester data consists of 10 instructors, 104 course meetings, 292 student groups, 5 days and 8 hours a day. A specific setting of the model has been run for 24 hours and the gap between the best solution and the optimal one is about 68% as seen in Figure 4. Therefore, we made some simplifications on the data to reduce the problem size. Since the run durations were very long, the reduction made according to the student groups which were taking at least five courses in that semester has been taken. The resulting “reduced” fall semester data consists of 10 instructors, 17 course meetings, 13 student groups, 5 days and 8 hours a day.

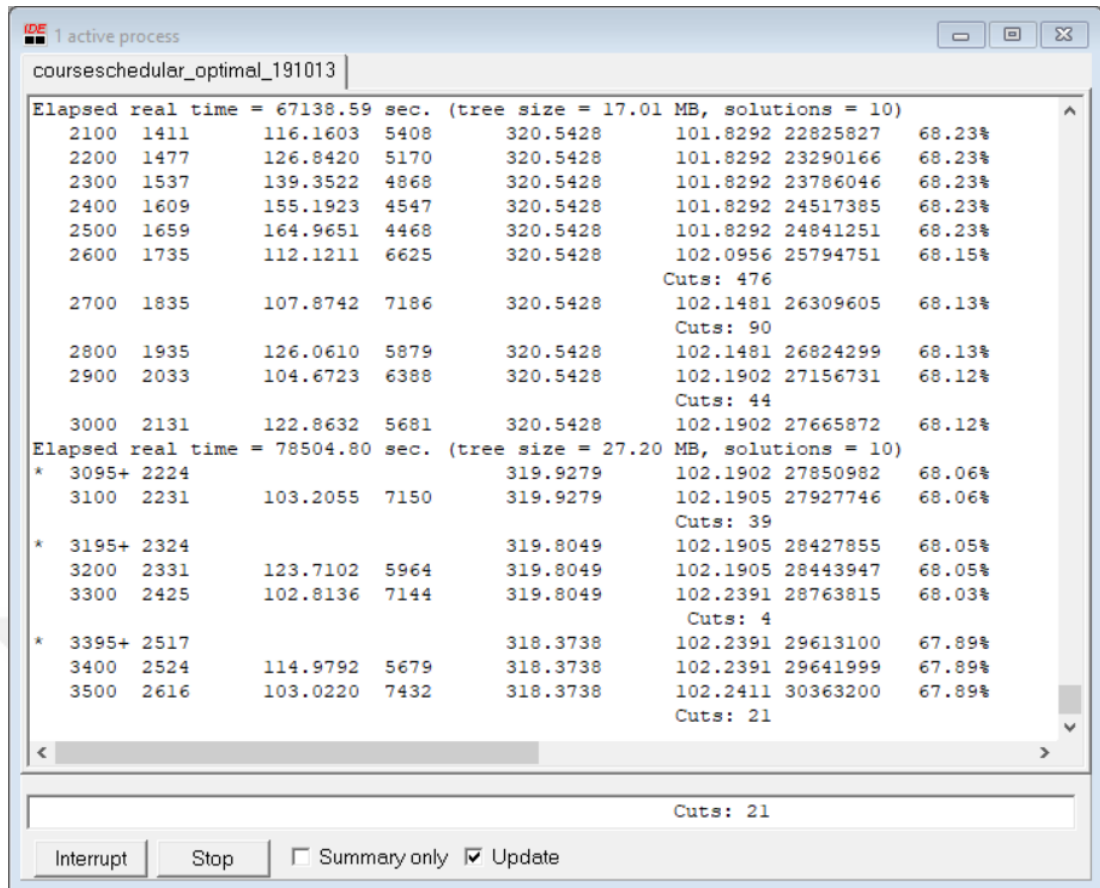


Figure 4: Screenshot for run of full data in GAMS/CPLEX

The runs were made for different alpha (α) levels for the data set with a gap of 20%. A gap of 20% means that GAMS/CPLEX will stop when it finds a solution with proximity of 20% to the optimal solution. Afterwards the results were compared to the current solution in order to determine the improvement achieved on the objectives. The run times spent for different alpha levels in GAMS/CPLEX for the reduced data set can be seen below in table (21). In the next section, the results obtained for different alpha (α) levels are shown.

Table 21: Time durations of runs for different alpha levels

Alpha Values	Duration (sec)	Duration (min)
$\alpha = 0.25$	2910	48.5
$\alpha = 0.50$	1340	22.33333333
$\alpha = 0.75$	182	3.033333333
$\alpha = 1.00$	8	0.133333333

5.2. RESULTS

The results obtained for Z^c , Z^α and improvement in the overall objective function can be seen in table 22. The improvement in the overall objective function for a specific α value is calculated as follows:

$$\frac{Z^c - Z^\alpha}{Z^c} \times 100$$

Table 22: Z^c , Z^α and improvement results

	Fall	Optimal (according to α values 0.25 to 1)				Improvement (%) (according to α values 0.25 to 1)			
	Current	0.25	.50	0.75	1	0.25	0.50	0.75	1
Z^α	---	50.89	92	141.69	177.69	87	80	73	70
Z^c	---	406.68	468.07	529.47	590.86	---	---	---	---
ZI	590.86	176.31	171	183.32	177.69	70	71	69	70
ZS	345.28	9.08	13	16.80	75.32	97	96	95	78
I_1	98	0	2	6	6	100	98	94	94
I_2	29	11	10	12	12	62	66	59	59
I_3	24	7	8	5	4	71	67	79	83
S_1	3824	60	180	202	1044	98	95	95	73
S_2	848	27	41	58	65	97	95	93	92
S_3	212	3	1	2	63	99	100	99	70
S_4	1169	14	36	56	65	99	97	95	94
S_5	204	51	21	18	58	75	90	91	72

As it is show in table 22, although the model has been run with a 20% gap, a significant improvement has been achieved related to the current solution. The alpha values change the participation rate of the instructor and student preference weights. As α value gets closer to 1, the preferences of instructors are considered more than the student preferences. In the same manner, as α value gets closer to 0, the preferences of instructors are considered less according to student preferences.

In the table the improvements are given according to each four cases that imply different importance situations. The results show that the model achieved an improvement in objective function in the range of 70-87%.



CHAPTER 6. CONCLUSION

In this study, the aim was to construct a mathematical model in order to solve university timetabling problem. As it was mentioned in the previous sections, a sample data has been taken and run in GAMS/CPLEX to be able to check the accuracy of the model.

The important aspect of this study is to solve a mathematical programming model for the university timetabling problem and incorporating Analytic Hierarchy Process to calculate the weights of instructor and student preferences to handle the objective function. In order to weight instructor and student preferences, we use five levels of linear combination, where the extremes are considering only the instructor preferences and only the student preferences, and the middle combination is treating those preferences equally.

Our problem is an NP-Hard problem. In our sample data set, the run time was not a serious problem. But with real data set, it was harder to solve. We first reduced the real data set and then sacrificed from gap percentage of best solution to optimal solution. Even with 20% gap, we obtained significant improvements (up to 87%) in the objective function value.

Our main contribution to timetabling problem is using AHP to determine preference weights. This problem can be solved by using a metaheuristic approach, which is expected to find a much better solution than optimization with 20% gap, but this approach is beyond our the scope of our work and can be considered as future work of this study.

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APPENDICES

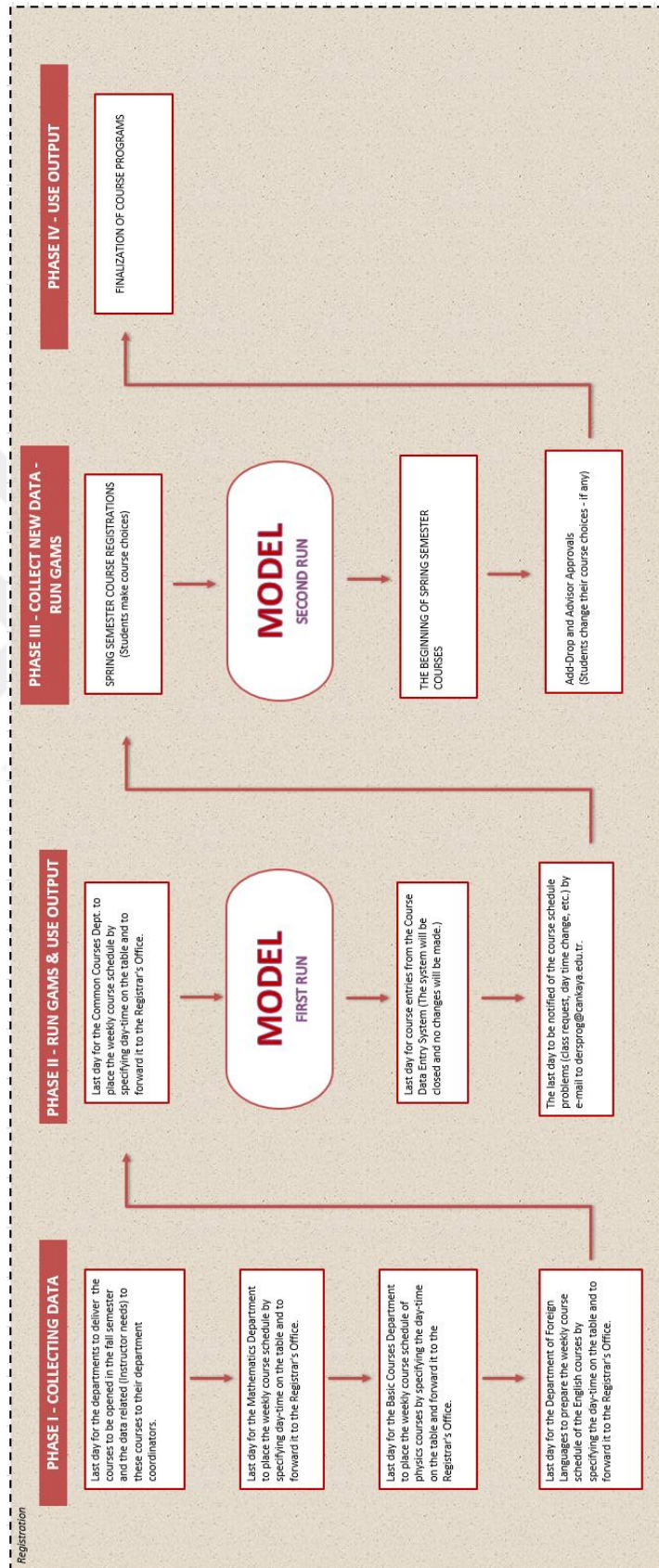


APPENDIX 1

8.1.2018	1. The departments deliver their courses and data related to these courses to their department coordinators. (Until 10.1.2018)
10.1.2018	2. The Mathematics Department places the weekly syllabus of the mathematics courses on the table by specifying day-hours and forwards them to the Registrar's Office. (Until 12.1.2018)
12.1.2018	3. The Department of Basic Engineering submits the weekly schedule of Physics courses on the table to the Department of Basic Engineering and submits them to the Student Affairs Department.
16.1.2018	4. The Department of Foreign Languages to place the weekly course schedule of the English courses on the table by specifying day-hours and forwards them to the Department of Student Affairs.
19.1.2018	5. All departments to place their courses appropriately on the syllabus delivered to them. (Until 28.1.2018)
28.1.2018	6. Course entries take place from Course Data Entry System and are approved by advisors. (Until 3.2.2018)
3.2.2018	7. Notification of problems related to course schedules (class request, day time change, etc.) are shared with the Registrars' Office. (Until 9.2.2018)
9.2.2018	8. Course registration of students for Semester. (Until 10.2.2018)
10.2.2018	
11.2.2018	
12.2.2018	
13.2.2018	
14.2.2018	
15.2.2018	
16.2.2018	
17.2.2018	
18.2.2018	
19.2.2018	
20.2.2018	
21.2.2018	
22.2.2018	
23.2.2018	

Each task starts under their relevant dates and are indicated with the same color.

APPENDIX 2



APPENDIX 3

Example three pages of data for the class meeting registration data according to student for fall 2018 semester. (Total rows 2096 approximately 53 pages)

Student NO	Course	Code	Course Name	T	Section
201312069	ECON	213	Principles of Economics	4	2
201412013	ECON	213	Principles of Economics	4	1
201412052	ECON	213	Principles of Economics	4	2
201512002	ECON	213	Principles of Economics	4	1
201512032	ECON	213	Principles of Economics	4	1
201512063	ECON	213	Principles of Economics	4	1
201512407	ECON	213	Principles of Economics	4	1
201612009	ECON	213	Principles of Economics	4	2
201612014	ECON	213	Principles of Economics	4	1
201612026	ECON	213	Principles of Economics	4	1
201612029	ECON	213	Principles of Economics	4	2
201612039	ECON	213	Principles of Economics	4	1
201612041	ECON	213	Principles of Economics	4	2
201612042	ECON	213	Principles of Economics	4	2
201612048	ECON	213	Principles of Economics	4	2
201612657	ECON	213	Principles of Economics	4	1
201712001	ECON	213	Principles of Economics	4	2
201712002	ECON	213	Principles of Economics	4	1
201712003	ECON	213	Principles of Economics	4	1
201712004	ECON	213	Principles of Economics	4	2
201712005	ECON	213	Principles of Economics	4	2
201712007	ECON	213	Principles of Economics	4	2
201712009	ECON	213	Principles of Economics	4	1
201712010	ECON	213	Principles of Economics	4	1
201712011	ECON	213	Principles of Economics	4	1
201712012	ECON	213	Principles of Economics	4	2
201712014	ECON	213	Principles of Economics	4	2
201712015	ECON	213	Principles of Economics	4	1
201712016	ECON	213	Principles of Economics	4	1
201712017	ECON	213	Principles of Economics	4	2
201712018	ECON	213	Principles of Economics	4	2
201712019	ECON	213	Principles of Economics	4	2
201712021	ECON	213	Principles of Economics	4	2
201712022	ECON	213	Principles of Economics	4	2
201712023	ECON	213	Principles of Economics	4	2
201712024	ECON	213	Principles of Economics	4	2

201712025	ECON	213	Principles of Economics	4	2
201712028	ECON	213	Principles of Economics	4	2
201712029	ECON	213	Principles of Economics	4	1
201712030	ECON	213	Principles of Economics	4	1
201712031	ECON	213	Principles of Economics	4	1
201712033	ECON	213	Principles of Economics	4	1
201712034	ECON	213	Principles of Economics	4	1
201712035	ECON	213	Principles of Economics	4	1
201712037	ECON	213	Principles of Economics	4	2
201712038	ECON	213	Principles of Economics	4	1
201712039	ECON	213	Principles of Economics	4	1
201712040	ECON	213	Principles of Economics	4	1
201712041	ECON	213	Principles of Economics	4	1
201712042	ECON	213	Principles of Economics	4	1
201712043	ECON	213	Principles of Economics	4	2
201712044	ECON	213	Principles of Economics	4	1
201712045	ECON	213	Principles of Economics	4	2
201712046	ECON	213	Principles of Economics	4	2
201712047	ECON	213	Principles of Economics	4	2
201712048	ECON	213	Principles of Economics	4	2
201712050	ECON	213	Principles of Economics	4	2
201712051	ECON	213	Principles of Economics	4	2
201712052	ECON	213	Principles of Economics	4	2
201712053	ECON	213	Principles of Economics	4	1
201712054	ECON	213	Principles of Economics	4	2
201712055	ECON	213	Principles of Economics	4	1
201712057	ECON	213	Principles of Economics	4	2
201712058	ECON	213	Principles of Economics	4	1
201712059	ECON	213	Principles of Economics	4	1
201712060	ECON	213	Principles of Economics	4	2
201712061	ECON	213	Principles of Economics	4	2
201712062	ECON	213	Principles of Economics	4	1
201712064	ECON	213	Principles of Economics	4	2
201712065	ECON	213	Principles of Economics	4	2
201712066	ECON	213	Principles of Economics	4	2
201712067	ECON	213	Principles of Economics	4	1
201712068	ECON	213	Principles of Economics	4	1
201712069	ECON	213	Principles of Economics	4	1
201712070	ECON	213	Principles of Economics	4	2
201712071	ECON	213	Principles of Economics	4	2

201312001	IE	227	Introduction to Probability	3	1
200912001	IE	227	Introduction to Probability	3	2
201012003	IE	227	Introduction to Probability	3	2
201012035	IE	227	Introduction to Probability	3	1
201012501	IE	227	Introduction to Probability	3	2
201212036	IE	227	Introduction to Probability	3	1
201412020	IE	227	Introduction to Probability	3	2
201412017	IE	227	Introduction to Probability	3	1
201512053	IE	227	Introduction to Probability	3	1
201512067	IE	227	Introduction to Probability	3	1
201512040	IE	227	Introduction to Probability	3	1
201512033	IE	227	Introduction to Probability	3	1
201412056	IE	227	Introduction to Probability	3	1
201512014	IE	227	Introduction to Probability	3	1
201712013	IE	227	Introduction to Probability	3	2
201712006	IE	227	Introduction to Probability	3	2
201712008	IE	227	Introduction to Probability	3	1
201612405	IE	227	Introduction to Probability	3	1
201612667	IE	227	Introduction to Probability	3	2
201612058	IE	227	Introduction to Probability	3	1
201612056	IE	227	Introduction to Probability	3	1
201612055	IE	227	Introduction to Probability	3	1
201612062	IE	227	Introduction to Probability	3	1
201612063	IE	227	Introduction to Probability	3	1
201612064	IE	227	Introduction to Probability	3	2
201612065	IE	227	Introduction to Probability	3	2
201612066	IE	227	Introduction to Probability	3	1
201612067	IE	227	Introduction to Probability	3	2
201612040	IE	227	Introduction to Probability	3	2
201612037	IE	227	Introduction to Probability	3	2
201612035	IE	227	Introduction to Probability	3	2
201612036	IE	227	Introduction to Probability	3	1
201612031	IE	227	Introduction to Probability	3	1
201612032	IE	227	Introduction to Probability	3	1
201612034	IE	227	Introduction to Probability	3	2
201612054	IE	227	Introduction to Probability	3	2
201612049	IE	227	Introduction to Probability	3	2
201612050	IE	227	Introduction to Probability	3	1
201612051	IE	227	Introduction to Probability	3	2

APPENDIX 4

Example one page for data of courses opened in fall 2018 semester. (Total rows 70772 approximately 1814 pages)

Corse	Code	Section	Day	Hour	Theoretical/Practical
ALM	102	1	Çarşamba	09:00/09:20	T
ALM	102	1	Çarşamba	10:00/10:20	T
ALM	102	1	Çarşamba	11:00/11:20	P
ALM	102	1	Çarşamba	12:00/12:20	P
ALM	102	1	Çarşamba	13:00/13:20	T
ALM	102	1	Çarşamba	13:00/13:20	T
ALM	102	1	Çarşamba	14:00/14:20	T
ALM	102	1	Çarşamba	14:00/14:20	T
ALM	102	1	Çarşamba	15:00/15:20	P
ALM	102	1	Çarşamba	15:00/15:20	P
ALM	102	1	Çarşamba	16:00/16:20	P
ALM	102	1	Çarşamba	16:00/16:20	P
ALM	102	1	Perşembe	13:00/13:20	T
ALM	102	1	Perşembe	14:00/14:20	T
ALM	102	1	Perşembe	15:00/15:20	P
ALM	102	1	Perşembe	16:00/16:20	P
ALM	102	2	Çarşamba	09:00/09:20	T
ALM	102	2	Çarşamba	10:00/10:20	T
ALM	102	2	Çarşamba	11:00/11:20	P
ALM	102	2	Çarşamba	12:00/12:20	P
ALM	102	2	Çarşamba	13:00/13:20	T
ALM	102	2	Çarşamba	13:00/13:20	T
ALM	102	2	Çarşamba	14:00/14:20	T
ALM	102	2	Çarşamba	14:00/14:20	T
ALM	102	2	Çarşamba	15:00/15:20	P
ALM	102	2	Çarşamba	15:00/15:20	P
ALM	102	2	Çarşamba	16:00/16:20	P
ALM	102	2	Çarşamba	16:00/16:20	P
ALM	102	2	Perşembe	13:00/13:20	T
ALM	102	2	Perşembe	14:00/14:20	T