Case Study

# Reducing Class-Scheduling Conflicts Using Linear Programming

Melissa Humphrey[1] and Amarjit Singh, F.ASCE[2]

**Abstract:** The scheduling of college courses within a given semester plays a crucial role in a student's daily life, educational and professional pursuits, and future successes. Inadequate class scheduling has the potential to delay student graduation. There is no standardized system for scheduling classes for the Department of Civil and Environmental Engineering at University of Hawaii (UH) at Manoa, which generates numerous class conflicts every semester. This article proposes an optimization model combining visual modeling and linear programming software that can be used to identify and eliminate conflicts when scheduling both undergraduate-level and graduate-level courses within an individual department. Constraints for this model were created to ensure that prerequisites are enforced, overlapping classes are minimized or eliminated, and maximum numbers of classes are available to the students every semester. Schedules for eight semesters were tested by the model, and then compared to the newly optimized version to determine if class conflicts could be reduced. Results showed that the proposed modeling methodology improved every semester's schedule by an average of 83.46%, with a minimum confidence of 95.14%, thereby attesting to the validity of this model, allowing students more class options and the ability to graduate sooner. **DOI: 10.1061/(ASCE)EI.1943-5541.0000336.** 



## Background and Introduction

It is becoming increasingly common for a 4-year college education to span the course of 6–8 years. According to the U.S. Department of Education, less than 40% of recent college graduates were able to complete a bachelor's degree in 4 years, with closer to 60% completing it in 6 years (Luckerson 2013). At the University of Hawaii at Manoa, that 40% shrinks even smaller still, to 27.9% of traditional students graduating in 4 years (Terrell 2015). These additional years can take a toll on students both financially and emotionally.

The University of Hawaii (UH) at Manoa had over 20,000 students enrolled in the 2015–2016 calendar year. Within that 20,000, approximately 1.75% belong to the Department of Civil and Environmental Engineering—300 undergraduates and 40–60 graduate students. There are currently 18 professors (current, assistant, and emeritus) serving the Department of Civil and Environmental Engineering (henceforth, CEE), all contributing to an average of 44 classes—36 undergraduate and 9 graduate classes. Classes generally are taught between the hours of 7:30 a.m. and 5:30 p.m. with some graduate classes extending until 9:00 p.m.

The way in which the resources are structured needs to be looked at closely to ensure that the available resources deliver the desired optimal outcomes. Based upon previous studies and the research performed in this article, it is recommended that a more structured and scientific method would be able to better serve the students of any Civil Engineering department in particular, and any department in general, in their academic pursuits.

[1]Project Engineer, Layton Construction Co., 733 Bishop St. 1820, Honolulu, HI 96813. E-mail: melissahumphrey2013@gmail.com

[2]Professor, Dept. of Civil and Environmental Engineering, Univ. of Hawaii at Manoa, 2540 Dole St., Honolulu, HI 96822 (corresponding author). E-mail: amsingh00@gmail.com

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## Problem

The problem is that there are numerous class conflicts where classes overlap each other in time slots, disallowing students from taking classes they want and/or need. In a sample survey of civil engineering students ($n = 30$), 10% were delayed in graduation by 1 year as a result of scheduling overlaps, and an additional 33% had to sacrifice their preferred class choices for other options (Truong 2011). This sample is taken to represent the population of students; 77% of students believed that the class schedules have conflicts, and that the conflicts mess up the schedule of working students, whereas 67% believe that the conflicts can be resolved. The most common way in which a schedule with fewer conflicts can benefit the students was reported as allowing timely graduation. This whole problem as perceived is important as it affects individual students both personally and academically, as limited class availability can delay graduation dates, affect work schedule and income, incur greater student loans, and ultimately deter students from continuing their education altogether if it becomes too difficult.

Delayed college graduation can be costly for students. Although there are several factors that contribute to a college student's overall workload, it is believed that minimizing scheduling conflicts would alleviate the overall stresses on students and aid them in their pursuits for timely graduation dates.

## Objective

The objective of this research is to present a workable scheduling model that maximizes the educational opportunities available to students, which will minimize costs to the students and facilitate timely graduations.

### *Purpose*

The purpose of the linear optimization and visual models are to eliminate class conflicts and to provide students with the maximum number of course selections possible within a semester. Eliminating class overlaps and conflicts will grant students the ability to choose their schedule according to the requirements they need to graduate. By considering a variety of constraints, such as room availability, professor availability, and time preferences, the linear program and system presented in this model will address the conflicts in draft schedules created by the department chair and minimize them.

### Scope

The scope of this article was to analyze the course schedules for both undergraduate-level and graduate-level courses within the Department of Civil and Environmental Engineering at the UH Manoa campus only. Eight semester schedules were chosen for analysis; six semesters were previously analyzed by Truong (2011). This article is an extension of his research, which contributed several improvements and clarifications to the overall process. The *LINGO* software was used for the linear programming analysis.

## Literature Review

There have been several cases of automated or electronic schedule generation in different universities, all with the intent of creating a perceived better schedule. However, in several cases, improvement or change to the schedule is based upon different criteria, depending on the needs and challenges presented by the specific university.

In a study performed at Worcester Polytechnic Institute (Worcester, Massachusetts), a linear programming model was created to schedule classes to classrooms based on capacity and function, as it is said to affect the overall quality of the class (Wormald and Guimond 2012). For example, music classes needed to be scheduled in rooms with supporting acoustical quality, and lectures of 15 people should not have been scheduled for lecture halls with a capacity of over 300. The timing of classes was only adjusted based upon the schedule for individual rooms, with no attention to overlaps or professor schedules.

In two other studies, at Chin-Min University in Taiwan (Chen 2008) and the University of Patras in Greece (Daskalaki et al. 2004), constraints similar to those in this study were created and used regarding class overlaps and professors' time preferences. However, in the Chin-Min University case, professors' seniority was considered when accounting for their preferences and was entered into a separate matrix before composing the linear program. In the University of Patras case, students' schedules were also accounted for, in terms of compacting schedules and minimizing room changes. Although both of those considerations were very helpful to students, they were not considered in this research.

In a study done at Kuwait University, a two-stage linear programming model was created to schedule facilities and faculty for the 50,000 person university. For the first stage, the facilities were scheduled considering various factors such as available classrooms and labs, parking locations and availability, and traffic/commute times. The second stage was assigning professors to the class schedule, as Kuwait University was one of the first to enact a gender-based policy, meaning female professors would teach all-female classes and vice-versa for males (Al-Yakoob and Sherali 2006). Several of the constraints applied to that program were similarly used in this research, such as the professor's time preferences, not forcing a professor to teach back-to-back classes, and ensuring that their lectures and labs all occurred at different times. The Kuwait University study was very successful in considering both the student's limitations (i.e., parking and time of day with traffic), as well as the professors.

A similar study was performed at Osmangazi University in Turkey using 0–1 linear programming. Ismayilova et al. (2005) also used analytic hierarchy process (AHP) and analytic network process (ANP) to develop a standardized class-scheduling model. The model incorporated the administration's preferences in tandem with the professor's preferences in regards to teaching classes.

Truong (2011) undertook studies using linear programming for class scheduling. He used specific assumptions and criteria that are particularly applicable to a civil engineering program in the United States. This study applies and extends the methodology he used and expands the database by applying it to two more semesters. Some clarifications to his process were made during this study, which will be explained in later sections.

## Assumptions Made in Linear Model

Certain assumptions were made from the data provided, which contributed in the formulation of the linear program regarding constraint selection and formulation. They must be stated for the clarity of the process, and were assumed (rather than articulated through constraints) as a way to keep the program simplified.

### Monday–Wednesday–Friday or Tuesday–Thursday Categories

The classes assigned during Monday–Wednesday–Friday (MWF) or Tuesday–Thursday (TR) categories were honored and left on the same days during the initial variable assignment. This was not only to limit the scope of the inputs and constraints, but also to honor the preferences of the professors, who likely selected those days for instruction. The linear program was split into MWF classes and TR classes and run independently of each other in order to simplify the program and address conflicts on an hourly basis. Classes in the MWF program were assigned either $x$ or $y$ values, whereas all classes on TR were assigned either $z$ or $a$ values.

### Room Availability

It is assumed that a total of four rooms are made available for CEE classes per time period, as per the University classroom availability policy. Lab space does not count towards this count, as the lab space is considered to always be available.

### Morning versus Afternoon Class Session

For this assumption, the hours of the day are broken into two sessions—morning and afternoon. Classes that end before 12:00 p.m. are considered to be in the morning session. Classes that end at or after 12:00 p.m. are considered to be in the afternoon session (Truong 2011). It was the intent of the program to keep classes within their original sessions to respect the professor's preferences and schedules. Professors are expected to teach any time during the morning session if they select that session; similarly so for the afternoon session. This assumption was addressed in the objective function, as classes outside of the preferred session were multiplied by 1,000, in order to avoid be selected by the minimizing objective function. The 1,000 value is only included in the objective function, and does not carry over into the constraints. In the end, the University has the administrative authority to enforce teaching during reasonable hours of instruction in the interests of education (Truong 2011).





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## Flexibility

In all equations, assumptions, and constraint formulations, there is flexibility, in that the assumption and constraints can be amended to suit any situation or circumstance. The methods proposed in this research are a standardized system that can be applied to any academic department and its respective concerns.

## Linear Program Development

Linear programming has been used in several engineering and management applications, in order to measure relative efficiencies and develop optimization strategies for complex systems. All linear programming for this research was computed through *LINGO* software, an optimization modeling software for linear, nonlinear, and integer programs.

A linear program requires an objective function and input values based upon the system's requirements and components. Constraints are required because they are the situational limitations specific to the given scenario. An understanding of the output values is necessary in order to successfully apply the results in a way that will be beneficial to the system. Each of these linear program components and their relation to the scheduling problem at UH Manoa will be explained in detail in the following sections. This will be followed by the example to which the equations apply.

### Objective Function

The objective function indicates exactly what is trying to be optimized. In the case of the scheduling problem at UH Manoa, the intent is to minimize the number of conflicts and overlaps within the schedule. The purpose for this objective function is to only select the number of time slots necessary for each respective class, and to organize them in such a way that it would eliminate the conflicts from the original schedule. The objective function for this program is a minimization function. The objective function and resulting outputs are ultimately informed by the constraints applied to the problem. Otherwise, a minimization problem with no constraints would assign an output value of zero for all variables.

### Inputs

The selection of inputs is a critical yet difficult process. To select the applicable inputs, it must first be determined what data are available, and then how to apply specific parameters to the data that would be productive and useful to this research. The input variables chosen for this study were created directly from the class schedules drafted by the department chair. The schedule used for the example in this article is provided in Table 1.

An example of the input compilation is given in Table 2. Each class is assigned a variable, $x_{ij}$ for undergraduate classes and $y_{ij}$ for graduate classes, for each time slot throughout the day within reasonable hours of instruction. All courses offered within the department for the given semester are listed in the first column, $A$. The courses offered within the department for the given semester and the 10 time slots available for instruction are listed in the table. The variable $i$ represents the course, and the variable $j$ stands for the time slot in the day. For example, in the seventh course on the list, CEE 370, offered in the fourth time slot at 10:30–11:20 of the MWF schedule, $x_{ij}$ would equal $x_{74}$ (or simply $x74$).

The time slots that were considered less desirable by either the professor or the students were multiplied by the value 1,000 in order to not be considered for the optimal solution. An example of the input variables and objective function used for Fall 2015 MWF, and illustrated as an example in this article, is given in Table 2. This objective function has 23 undergraduate courses and labs sections and four graduate courses. The objective function spans 10 time slots from 7:30 a.m. to 5:20 p.m.

### Outputs

Outputs are considered the resulting values, which in this case are the time-slot assignments for classes entered into the model. This is important when analyzing the results of the linear program, because these help identify possible solutions to class conflicts, or perhaps uncover a broader scope of the conflict than was originally recognized. All variables will be assigned either a 0 or 1 value by the *LINGO* program. Those time-slot variables given an output value of 1 are considered to be optimal and should be utilized. Those with the value of 0 are considered to be not optimal and should not be used for scheduling.

## Constraints

Constraints are recognized as the conditions unique to the situation or problem at hand, which limit and define the calculations in a way that is relevant. For example, if a manager is trying to minimize the number of workers needed on staff at a given time, the first constraint must identify the minimum number of workers needed in order to remain operational—otherwise, the optimal solution could be reduced to zero. If constraints are not applied correctly to a linear programming model, it is likely that either an optimal solution would not be found, or that the solution found would not be applicable to the given problem. It is for this reason that the constraints for this class-scheduling analysis were made after considering the particular preferences and limitations of each class and professor or the semester in question.

### Constraint 1: Availability of 300-Level Classes

This constraint prevents 300-level classes from overlapping, so that junior students are able to maximize the number of classes that they can take in a semester. Ensuring that these classes are taught in different time slots provides students with ample opportunity to fulfill their requirements in a timely manner. This constraint also applies to lab classes associated with 300-level classes, as the labs are required and therefore must not overlap other 300-level lectures or labs. In addition, CEE 271 can be taken concurrently with CEE 330, CEE 335, and CEE 370 (and accompanied lab sections). For this reason, CEE 271 was included into the 300-level overlapping constraints.

To form Constraint 1, all 300-series classes for the same time slot were added together and must be less than or equal to 1 to ensure that only one of the possible classes is selected (in this study, each time slot has a value of 1). The same was repeated for all 10 time slots during the day. An example of the values for this constraint is given in Table 3. Only the values for the first three time slots were included for brevity.

### Constraint 2: Availability of 400-Level Classes

This constraint ensures that all 400-level classes occur in different time periods in order to prevent overlaps, so that the junior and senior students are able to maximize the number that they can take in a semester. This constraint was constructed similarly to Constraint 1, but comprised of variables specific only to 400-level classes. By adding all of the 400-level variables of similar time slots together, they must be less than or equal to 1 in order to ensure only

**Table 1.** CEE Department Fall 2015 Written Schedule

| Course | Section | Hours | Course title | Days | Begins | Ends | Instructor |
|---|---|---|---|---|---|---|---|
| 270 | 1 | 3 | Applied Mechanics I | MWF | 8:30 a.m. | 9:20 a.m. | Prof. A |
| 270 | 2 | 3 | Applied Mechanics I | TR | 2:30 p.m. | 4:15 p.m. | Prof. B |
| 270 | 3 | 3 | Applied Mechanics I | TR | 9:00 a.m. | 10:15 a.m. | Prof. C |
| 271 | 1 | 3 | Applied Mechanics II | TR | 3:00 p.m. | 4:15 p.m. | Prof. D |
| 305 | 1 | 3 | Applied Probability and Statistics | TR | 7:30 a.m. | 8:45 a.m. | Prof. E |
| 320 | 1 | 4 | Fluid Mechanics Fundamentals | TR | 10:30 a.m. | 11:45 a.m. | Prof. F |
| 320L | 1 | — | Lab | T | 12:00 p.m. | 1:50 p.m. | Prof. F |
| 320L | 2 | — | Lab | R | 12:00 p.m. | 1:50 p.m. | Prof. F |
| 320L | 3 | — | Lab | T | 3:00 p.m. | 4:50 p.m. | Prof. F |
| 330 | 1 | 4 | W/Environmental Engineering | MWF | 10:30 a.m. | 11:20 a.m. | Prof. G |
| 330L | 1 | — | Lab | M | 12:30 p.m. | 2:20 p.m. | Prof. G |
| 330L | 2 | — | Lab | W | 12:30 p.m. | 2:20 p.m. | Prof. G |
| 330L | 3 | — | Lab | F | 12:30 p.m. | 2:20 p.m. | Prof. G |
| 355 | 1 | 4 | Geotechnical Engineering I | TR | 9:00 a.m. | 10:15 a.m. | Prof. H |
| 355L | 1 | — | Lab | T | 12:00 p.m. | 1:50 p.m. | Prof. H |
| 355L | 2 | — | Lab | R | 12:00 p.m. | 1:50 p.m. | Prof. H |
| 360 | 1 | 3 | Fundamentals of Transportation | MWF | 9:30 a.m. | 10:20 a.m. | Profs. I and J |
| 370 | 1 | 3 | Mechanics of Materials | MWF | 1:30 p.m. | 2:20 p.m. | Prof. B |
| 370L | 1 | — | Lab | M | 2:30 p.m. | 3:50 p.m. | Prof. B |
| 370L | 2 | — | Lab | W | 2:30 p.m. | 3:50 p.m. | Prof. B |
| 370L | 3 | — | Lab | F | 2:30 p.m. | 3:50 p.m. | Prof. B |
| 375 | 1 | 2 | Construction Materials | MWF | 8:30 a.m. | 9:20 a.m. | Prof. K |
| 375L | 1 | 1 | Lab | M | 2:30 p.m. | 4:20 p.m. | Prof. K |
| 375L | 2 | 1 | Lab | W | 2:30 p.m. | 4:20 p.m. | Prof. K |
| 375L | 3 | 1 | Lab | W | 4:30 p.m. | 6:20 p.m. | Prof. K |
| 381 | 1 | 3 | Structural Analysis | MWF | 11:30 a.m. | 12:20 p.m. | Prof. M |
| 431 | 1 | 3 | Water and Wastewater Engineering | TR | 3:00 p.m. | 4:15 p.m. | Prof. N |
| 444 | 1 | 3 | Sustainable Infrastructure | MW | 3:30 p.m. | 4:45 p.m. | Prof. O |
| 455 | 1 | 3 | Geotechnical Engineering II | MW | 8:30 a.m. | 9:45 a.m. | Prof. P |
| 461 | 1 | 3 | Pavement Engineering | TR | 12:00 p.m. | 1:15 p.m. | Prof. Q |
| 472 | 1 | 3 | Construction Project Management | TR | 12:00 p.m. | 1:15 p.m. | Prof. R |
| 473 | 1 | 3 | Construction Equipments and Methods | MWF | 10:30 a.m. | 11:20 a.m. | Prof. R |
| 474 | 1 | 3 | Construction Bidding and Estimating | MWF | 12:30 p.m. | 1:20 p.m. | Prof. R |
| 485 | 1 | 4 | Reinforced Concrete | TR | 10:30 a.m. | 11:45 a.m. | Prof. S |
| 485L | 1 |  | Lab | M | 1:30 p.m. | 3:20 p.m. | Prof. S |
| 489B | 1 | 2 | Senior Topic: Survey and Planning | W | 1:30 p.m. | 3:20 p.m. | Prof. N |
| 489C | 1 | 1 | Professional Ethics | F | 2:30 p.m. | 3:20 p.m. | Prof. N |
| 491 | 1 | 3 | Loads on Structures | MWF | 12:30 p.m. | 1:20 p.m. | Prof. A |
| 491 | 1 | 3 | Climate Impact and Adapt for Control | TR | 9:00 a.m. | 10:15 a.m. | Prof. T |
| 601 | 1 | 3 | Linear Programming Applications | TR | 12:00 p.m. | 1:15 p.m. | Prof. E |
| 633 | 1 | 3 | Physical and Chemical Treatment | TR | 1:30 p.m. | 2:45 p.m. | Prof. D |
| 653 | 1 | 3 | Advanced Soil Mechanics | MW | 10:30 a.m. | 11:45 a.m. | Prof. P |
| 664 | 1 | 3 | Advanced Transportation Modeling | TR | 3:00 p.m. | 4:15 p.m. | Prof. U |
| 677 | 1 | 3 | Smart Structures Technology | MW | 2:30 p.m. | 3:45 p.m. | Prof. M |
| 681 | 1 | 3 | Theory Modern Structure Analysis | MW | 10:30 a.m. | 11:45 a.m. | Prof. V |
| 687 | 1 | 3 | Prestressed Concrete | WF | 3:00 p.m. | 4:15 p.m. | Profs. R and W |
| 691 | 1 | 1 | Seminar | Th | 4:30 p.m. | 5:20 p.m. | Prof. C |

Note: MW = Monday–Wednesday; MWF = Monday–Wednesday–Friday; Prof. = Professor; TR = Tuesday–Thursday.

one class is selected per time period. An example of the first three time slots for this constraint is given in Table 4.

### Constraint 3: Availability of 600-Level Classes

This constraint addresses the availability of 600-level classes, which are specific to graduate students within the Department of Civil and Environmental Engineering. Considering that graduate classes are more specialized based upon their areas of focus, it is very important for graduate students to be able to take the classes required for their degrees. It is also important because there are very limited numbers of classes offered to graduate students within a given semester, so an overlap could be very costly to an entire graduate contingency of students. A similar approach is taken for the 600-level classes as the previous two constraints, the only difference being that all graduate level classes were assigned a $y$ variable, rather than an $x$ as a way to better differentiate between the two. The variables assigned to the same time slot were added together and must be less than or equal to 1. An example of the first three time slots for this constraint is provided in Table 5.

### Constraint 4: Professors Cannot Teach Two Classes in the Same Time Slot

The reasoning behind this constraint would appear obvious and is included so that the linear program does not allow for the optimal solution to include professors teaching separate classes during the same time period. To form this constraint, professors who teach more than one class (both undergraduate and graduate level) must be identified, as well as the input variables associated with those

**Table 2.** Input Values for Objective Function (Minimization) (Fall 2015, MWF)

| | | | Time slots available | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 7:30–8:20 a.m. | 8:30–9:20 a.m. | 9:30–10:20 a.m. | 10:30–11:20 a.m. | 11:30 a.m.–12:20 p.m. | 12:30–1:20 p.m. | 1:30–2:20 p.m. | 2:30–3:20 p.m. | 3:30–4:20 p.m. | 4:30–5:20 p.m. |
| Courses | Instructor | $x_{ij}/y_{ij}$ | $x_{i1}/y_{i1}$ | $x_{i2}/y_{i2}$ | $x_{i3}/y_{i3}$ | $x_{i4}/y_{i4}$ | $x_{i5}/y_{i5}$ | $x_{i6}/y_{i6}$ | $x_{i7}/y_{i7}$ | $x_{i8}/y_{i8}$ | $x_{i9}/y_{i9}$ | $x_{i10}/y_{i10}$ |
| 270 | Prof. A | $x_{1j}$ | x11+ | x12+ | x13+ | x14+ | x15+ | 1,000x16+ | 1,000x17+ | 1,000x18+ | 1,000x19+ | 1,000x110+ |
| 330 | Prof. G | $x_{2j}$ | x21+ | x22+ | x23+ | x24+ | x25+ | 1,000x26+ | 1,000x27+ | 1,000x28+ | 1,000x29+ | 1,000x210+ |
| 330L1 | Prof. G | $x_{3j}$ | 1,000x31+ | 1,000x32+ | 1,000x33+ | 1,000x34+ | 1,000x35+ | x36+ | x37+ | x38+ | x39+ | x310+ |
| 330L2 | Prof. G | $x_{4j}$ | 1,000x41+ | 1,000x42+ | 1,000x43+ | 1,000x44+ | 1,000x45+ | x46+ | x47+ | x48+ | x49+ | x410+ |
| 330L3 | Prof. G | $x_{5j}$ | 1,000x51+ | 1,000x52+ | 1,000x53+ | 1,000x54+ | 1,000x55+ | x56+ | x57+ | x58+ | x59+ | x510+ |
| 360 | Profs. I and J | $x_{6j}$ | x61+ | x62+ | x63+ | x64+ | x65+ | 1,000x66+ | 1,000x67+ | 1,000x68+ | 1,000x69+ | 1,000x610+ |
| 370 | Prof. B | $x_{7j}$ | 1,000x71+ | 1,000x72+ | 1,000x73+ | 1,000x74+ | 1,000x75+ | x76+ | x77+ | x78+ | x79+ | x710+ |
| 370L | Prof. B | $x_{8j}$ | 1,000x81+ | 1,000x82+ | 1,000x83+ | 1,000x84+ | 1,000x85+ | x86+ | x87+ | x88+ | x89+ | x810+ |
| 370L | Prof. B | $x_{9j}$ | 1,000x91+ | 1,000x92+ | 1,000x93+ | 1,000x94+ | 1,000x95+ | x96+ | x97+ | x98+ | x99+ | x910+ |
| 370L | Prof. B | $x_{10j}$ | 1,000x101+ | 1,000x102+ | 1,000x103+ | 1,000x104+ | 1,000x105+ | x106+ | x107+ | x108+ | x109+ | x1010+ |
| 375 | Prof. K | $x_{11j}$ | x111+ | x112+ | x113+ | x114+ | x115+ | 1,000x116+ | 1,000x117+ | 1,000x118+ | 1,000x119+ | 1,000x1110+ |
| 375L | Prof. K | $x_{12j}$ | 1,000x121+ | 1,000x122+ | 1,000x123+ | 1,000x124+ | 1,000x125+ | 1,000x126+ | 1,000x127+ | x128+ | x129+ | 1,000 × 1210+ |
| 375L | Prof. K | $x_{13j}$ | 1,000x131+ | 1,000x132+ | 1,000x133+ | 1,000x134+ | 1,000x135+ | x136+ | x137+ | x138+ | x139+ | x1310+ |
| 375L | Prof. K | $x_{14j}$ | 1,000x141+ | 1,000x142+ | 1,000x143+ | 1,000x144+ | 1,000x145+ | x146+ | x147+ | x148+ | x149+ | x1410+ |
| 381 | Prof. M | $x_{15j}$ | x151+ | x152+ | x153+ | x154+ | x155+ | 1,000x156+ | 1,000x157+ | 1,000x158+ | 1,000x159+ | 1,000x1510+ |
| 444 | Prof. O | $x_{16j}$ | 1,000x161+ | 1,000x162+ | 1,000x163+ | 1,000x164+ | 1,000x165+ | x166+ | x167+ | x168+ | x169+ | x1610+ |
| 455 | Prof. P | $x_{17j}$ | x171+ | x172+ | x173+ | x174+ | x175+ | 1,000x176+ | 1,000x177+ | 1,000x178+ | 1,000x179+ | 1,000x1710+ |
| 473 | Prof. R | $x_{18j}$ | x181+ | x182+ | x183+ | x184+ | x185+ | 1,000x186+ | 1,000x187+ | 1,000x188+ | 1,000x189+ | 1,000x1810+ |
| 474 | Prof. R | $x_{19j}$ | 1,000x191+ | 1,000x192+ | 1,000x193+ | 1,000x194+ | 1,000x195+ | x196+ | x197+ | x198+ | x199+ | x1910+ |
| 485L | Prof. S | $x_{20j}$ | 1,000x201+ | 1,000x202+ | 1,000x203+ | 1,000x204+ | 1,000x205+ | x206+ | x207+ | x208+ | x209+ | x2010+ |
| 489B | Prof. N | $x_{21j}$ | 1,000x211+ | 1,000x212+ | 1,000x213+ | 1,000x214+ | 1,000x215+ | x216+ | x217+ | x218+ | x219+ | x2110+ |
| 489C | Prof. N | $x_{22j}$ | 1,000x221+ | 1,000x222+ | 1,000x223+ | 1,000x224+ | 1,000x225+ | x226+ | x227+ | x228+ | x229+ | x2210+ |
| 491 | Prof. A | $x_{23j}$ | 1,000x231+ | 1,000x232+ | 1,000x233+ | 1,000x234+ | 1,000x235+ | x236+ | x237+ | x238+ | x239+ | x2310+ |
| 653 | Prof. P | $y_{1j}$ | y11+ | y12+ | y13+ | y14+ | y15+ | 1,000y16+ | 1,000y17+ | 1,000y18+ | 1,000y19+ | 1,000y110+ |
| 677 | Prof. M | $y_{2j}$ | 1,000y21+ | 1,000y22+ | 1,000y23+ | 1,000y24+ | 1,000y25+ | y26+ | y27+ | y28+ | y29+ | y210+ |
| 681 | Prof. V | $y_{3j}$ | y31+ | y32+ | y33+ | y34+ | y35+ | 1,000y36+ | 1,000y37+ | 1,000y38+ | 1,000y39+ | 1,000y310+ |
| 687 | Profs. R and W | $y_{4j}$ | 1,000y41+ | 1,000y42+ | 1,000y43+ | 1,000y44+ | 1,000y45+ | y46+ | y47+ | y48+ | y49+ | y410 |

**Table 3.** Example of 300-Level Overlapping Constraint (from Fall 2015, MWF)

| Time slot | CEE 330 | CEE 360 | CEE 370 | CEE 375 | CEE 381 | < = | Constraint |
|---|---|---|---|---|---|---|---|
| 7:30–8:20 a.m. | $x21+$ | $x61+$ | $x71+$ | $x111+$ | $x151$ | < = | 1 |
| 8:30–9:20 a.m. | $x22+$ | $x62+$ | $x72+$ | $x112+$ | $x152$ | < = | 1 |
| 9:30–10:20 a.m. | $x23+$ | $x63+$ | $x73+$ | $x113+$ | $x153$ | < = | 1 |

**Table 4.** Example of 400-Level Overlapping Constraint (from Fall 2015, MWF)

| Time slot | CEE 444 | CEE 455 | CEE 473 | CEE 474 | CEE 485 | CEE 489B | CEE 489C | CEE 491 | < = | Constraint |
|---|---|---|---|---|---|---|---|---|---|---|
| 7:30–8:20 a.m. | $x161+$ | $x171+$ | $x181+$ | $x191+$ | $x201+$ | $x211+$ | $x221+$ | $x231$ | < = | 1 |
| 8:30–9:20 a.m. | $x162+$ | $x172+$ | $x182+$ | $x192+$ | $x202+$ | $x212+$ | $x222+$ | $x232$ | < = | 1 |
| 9:30–10:20 a.m. | $x163+$ | $x173+$ | $x183+$ | $x193+$ | $x203+$ | $x213+$ | $x223+$ | $x233$ | < = | 1 |

**Table 5.** Example of 600-Level Overlapping Constraint (from Fall 2015, MWF)

| Time slot | CEE 653 | CEE 677 | CEE 681 | CEE 687 | < = | Constraint |
|---|---|---|---|---|---|---|
| 7:30–8:20 a.m. | $y11+$ | $y21+$ | $y31+$ | $y41$ | < = | 1 |
| 8:30–9:20 a.m. | $y12+$ | $y22+$ | $y32+$ | $y42$ | < = | 1 |
| 9:30–10:20 a.m. | $y13+$ | $y23+$ | $y33+$ | $y43$ | < = | 1 |

**Table 6.** Example of Professor Teaching in Same Slot Constraint (from Fall 2015, MWF)

| Time slot | CEE 270 | CEE 491 | < = | Constraint |
|---|---|---|---|---|
| 7:30–8:20 a.m. | $x11+$ | $x231$ | < = | 1 |
| 8:30–9:20 a.m. | $x12+$ | $x232$ | < = | 1 |
| 9:30–10:20 a.m. | $x13+$ | $x233$ | < = | 1 |

Note: Professor A, CEE 270 and CEE 491.

**Table 7.** Example of Professor Needs a Break Constraint (from Fall 2015, MWF)

| Time slot | CEE 270 | Break | CEE 491 | Break | < = | Constraint |
|---|---|---|---|---|---|---|
| 7:30–8:20 a.m. | $x11+$ | $x12+$ | $x231+$ | $x232$ | < = | 1 |
| 8:30–.9:20 a.m. | $x12+$ | $x13+$ | $x232+$ | $x233$ | < = | 1 |
| 9:30–10:20 a.m. | $x13+$ | $x14+$ | $x233+$ | $x234$ | < = | 1 |

Note: Professor A, CEE 270 and CEE 491.

classes. The variables within the same time period must be added together and be less than or equal to 1, so the linear program will only be able to select one of the options per any given time slot. An example of this constraint is given in Table 6, where the variables for CEE 270 and CEE 491, which are both taught by Professor A, are added together within their respective time slots.

### Constraint 5: Professors Need a Break between Classes

This constraint supports the professors of CEE by not forcing them to teach lectures back-to-back. Professors need time to gather materials, speak with students, prepare lectures, and change classrooms if necessary—and cannot always do so in the 10-min break between class time periods. Certain professors do, however, choose to teach their classes back to back and are accommodated for in the final schedules for these linear programs. This information is given by the department chair.

To form this constraint, the variables for those classes taught by the same professor are taken, adding those in the same time period and the periods immediately following, and must be equal to or less than 1 in order to ensure that only one is selected per time slot. An example of this constraint is offered in Table 7, where the variables from CEE 270 and CEE 491, both taught by Professor A, are added together in the method described herein to guarantee a break between both.

### Constraint 6: Lecture and Accompanied Labs Must Be Staggered

This constraint ensures that the lecture and associated lab sections are not scheduled during overlapping time slots. Although the professor does not need to be present during the lab sections, because they are taught by graduate students, the students would not be able to be present in both the lecture and lab during the same time slot. To form this constraint, the values of the lecture and lab sections during the same time slot are added and must be less than or equal to 1 to ensure that only one may be selected per any given time slot. An example of this constraint is offered in Table 8, where the variables for CEE 330 and its three accompanying lab sections (CEE 330L1, CEE 330L2, and CEE 330L3) are all added together within their respective time slots to allow for only one at a time.

### Constraint 7: Longer Classes Must Occur in Consecutive Time Slots

Several classes in the UH schedule extend beyond one of the 50-min time slots in order to meet their weekly credit-hour requirement. This constraint is crucial to the scheduling of those classes. To ensure that those classes receive consecutive class periods so the class goes uninterrupted. To construct this constraint, two equations are required. The first equation adds all time-slot values for one specific class together, and their sum must equal the number of class periods it requires. For example, a lab section lasts for 2 h, so therefore adding all of the time-slot variables together must be equal to two. The second equation (or rather set of equations) ensures that if the program schedules the first hour of the class in Time Slot $x51$, for instance, then the second hour of the class will be scheduled in $x52$. Succeeding equations perform the same function for other time slots (Truong 2011), ensuring that only one class is scheduled in any 2-h slot selected by the linear program. Examples of both parts of this constraint are given in Tables 9 and 10, using the variables for CEE 330 L1, taught by Professor G, which must have a 2-h consecutive duration because it is a lab section.

## Methodology

This section will explain the existing scheduling methodology performed by the Department of Civil Engineering at UH, as well as explain the process used for this study. The proposed methodology was performed using *LINGO* linear programming software, which is easily available and is well-supported for education and research.

**Table 8.** Example of Staggered Lecture and Accompanied Lab Constraint (Fall 2015, MWF)

| Time slot | CEE 330 | CEE 330L1 | CEE 330L2 | CEE 330L3 | < = | Constraint |
|---|---|---|---|---|---|---|
| 7:30–8:20 a.m. | $x21+$ | $x31+$ | $x41+$ | $x51$ | < = | 1 |
| 8:30–9:20 a.m. | $x22+$ | $x32+$ | $x42+$ | $x52$ | < = | 1 |
| 9:30–10:20 a.m. | $x23+$ | $x33+$ | $x43+$ | $x53$ | < = | 1 |

Note: Professor G, CEE 330, CEE 330L1, CEE 330L2, and CEE 330L3.

### *Existing Methodology*

Class scheduling for CEE at UH Manoa is tasked to the department chair. Before every semester, the department chair asks each professor in the department for their preference and input on the classes they are responsible for in the upcoming semester. The department chair considers these preferences while compiling the schedule using a personal, undisclosed method. A draft schedule is released the professors to ask for feedback and any necessary

**Table 9.** Example of Longer Classes Scheduled in Consecutive Time-Slots Constraint, Time Requirement of Two Consecutive Hours (Fall 2015, MWF)

| | Time slot | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Course | 7:30–8:20 a.m. | 8:30–9:20 a.m. | 9:30–10:20 a.m. | 10:30–11:20 a.m. | 11:30 a.m.–12:20 p.m. | 12:30–1:20 p.m. | 1:30–2:20 p.m. | 2:30–3:20 p.m. | 3:30–4:20 p.m. | 4:30–5:20 p.m. | Hours required |
| CEE 330L1 | $x31+$ | $x32+$ | $x33+$ | $x34+$ | $x35+$ | $x36+$ | $x37+$ | $x38+$ | $x39+$ | $x310$ | = 2 |
| CEE 330L2 | $x41+$ | $x42+$ | $x43+$ | $x44+$ | $x45+$ | $x46+$ | $x47+$ | $x48+$ | $x49+$ | $x410$ | = 2 |
| CEE 330L3 | $x51+$ | $x52+$ | $x53+$ | $x54+$ | $x55+$ | $x56+$ | $x57+$ | $x58+$ | $x59+$ | $x510$ | = 2 |

Note: CEE 330 L1 (Professor G) must have a 2-h consecutive duration.

**Table 10.** Example of Longer Classes Scheduled in Consecutive Time Slots Constraint, Consecutive Scheduling (Fall 2015, MWF)

| Time slot | 7:30–8:20 a.m. | 8:30–9:20 a.m. | 9:30–10:20 a.m. | 10:30–11:20 a.m. | 11:30 a.m.–12:20 p.m. | 12:30–1:20 p.m. | 1:30–2:20 p.m. | 2:30–3:20 p.m. | 3:30–4:20 p.m. | 4:30–5:20 p.m. | < = | Constraint |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 7:30–8:20 a.m. | $x51+$ | — | $x53$ | — | — | — | — | — | — | — | < = | 1 |
| 7:30–8:20 a.m. | $x51+$ | — | — | $x54$ | — | — | — | — | — | — | < = | 1 |
| 7:30–8:20 a.m. | $x51+$ | — | — | — | $x55$ | — | — | — | — | — | < = | 1 |
| 7:30–8:20 a.m. | $x51+$ | — | — | — | — | $x56$ | — | — | — | — | < = | 1 |
| 7:30–8:20 a.m. | $x51+$ | — | — | — | — | — | $x57$ | — | — | — | < = | 1 |
| 7:30–8:20 a.m. | $x51+$ | — | — | — | — | — | — | $x58$ | — | — | < = | 1 |
| 7:30–8:20 a.m. | $x51+$ | — | — | — | — | — | — | — | $x59$ | — | < = | 1 |
| 7:30–8:20 a.m. | $x51+$ | — | — | — | — | — | — | — | — | $x510$ | < = | 1 |
| 8:30–9:20 a.m. | — | $x52+$ | — | $x54$ | — | — | — | — | — | — | < = | 1 |
| 8:30–9:20 a.m. | — | $x52+$ | — | — | $x55$ | — | — | — | — | — | < = | 1 |
| 8:30–9:20 a.m. | — | $x52+$ | — | — | — | $x56$ | — | — | — | — | < = | 1 |
| 8:30–9:20 a.m. | — | $x52+$ | — | — | — | — | $x57$ | — | — | — | < = | 1 |
| 8:30–9:20 a.m. | — | $x52+$ | — | — | — | — | — | $x58$ | — | — | < = | 1 |
| 8:30–9:20 a.m. | — | $x52+$ | — | — | — | — | — | — | $x59$ | — | < = | 1 |
| 8:30–9:20 a.m. | — | $x52+$ | — | — | — | — | — | — | — | $x510$ | < = | 1 |
| 9:30–10:20 a.m. | — | — | $x53+$ | — | — | — | — | — | — | — | < = | 1 |
| 9:30–10:20 a.m. | — | — | $x53+$ | — | $x55$ | — | — | — | — | — | < = | 1 |
| 9:30–10:20 a.m. | — | — | $x53+$ | — | — | $x56$ | — | — | — | — | < = | 1 |
| 9:30–10:20 a.m. | — | — | $x53+$ | — | — | — | $x57$ | — | — | — | < = | 1 |
| 9:30–10:20 a.m. | — | — | $x53+$ | — | — | — | — | $x58$ | — | — | < = | 1 |
| 9:30–10:20 a.m. | — | — | $x53+$ | — | — | — | — | — | $x59$ | — | < = | 1 |
| 9:30–10:20 a.m. | — | — | $x53+$ | — | — | — | — | — | — | $x510$ | < = | 1 |
| 10:30–11:20 a.m. | — | — | — | $x54+$ | — | $x56$ | — | — | — | — | < = | 1 |
| 10:30–11:20 a.m. | — | — | — | $x54+$ | — | — | $x57$ | — | — | — | < = | 1 |
| 10:30–11:20 a.m. | — | — | — | $x54+$ | — | — | — | $x58$ | — | — | < = | 1 |
| 10:30–11:20 a.m. | — | — | — | $x54+$ | — | — | — | — | $x59$ | — | < = | 1 |
| 10:30–11:20 a.m. | — | — | — | $x54+$ | — | — | — | — | — | $x510$ | < = | 1 |
| 11:30 a.m.–12:20 p.m. | — | — | — | — | $x55+$ | — | $x57$ | — | — | — | < = | 1 |
| 11:30 a.m.–12:20 p.m. | — | — | — | — | $x55+$ | — | — | $x58$ | — | — | < = | 1 |
| 11:30 a.m.–12:20 p.m. | — | — | — | — | $x55+$ | — | — | — | $x59$ | — | < = | 1 |
| 11:30 a.m.–12:20 p.m. | — | — | — | — | $x55+$ | — | — | — | — | $x510$ | < = | 1 |
| 12:30–1:20 p.m. | — | — | — | — | — | $x56+$ | — | $x58$ | — | — | < = | 1 |
| 12:30–1:20 p.m. | — | — | — | — | — | $x56+$ | — | — | $x59$ | — | < = | 1 |
| 12:30–1:20 p.m. | — | — | — | — | — | $x56+$ | — | — | — | $x510$ | < = | 1 |
| 1:30–2:20 p.m. | — | — | — | — | — | — | $x57+$ | — | $x59$ | — | < = | 1 |
| 1:30–2:20 p.m. | — | — | — | — | — | — | $x57+$ | — | — | $x510$ | < = | 1 |
| 2:30–3:20 p.m. | — | — | — | — | — | — | — | $x58+$ | — | $x510$ | < = | 1 |



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changes. A final schedule is released after all complaints are addressed by the department chair (Truong 2011).

### Proposed Methodology

The proposed methodology is applied through the use of linear programming combined with manual adjustments. This method is recommended for all class-scheduling applications, because it provides the most objective, logical, and optimal schedule for students and faculty alike. In this section, the proposed method is explained step by step, as well as illustrated in the flowchart of Fig. 1. This method was applied to the draft schedules used for the research in this study.

- Step 1. Obtain draft schedule: Obtain the draft schedule for CEE for a given semester. All input values will be taken from the draft schedule;
- Step 2. Create a visual model: Make a visual model of the schedule to identify the times of proposed class deliveries. An example of this is seen in Fig. 2;
- Step 3. Define and separate categories: Separate classes into respective categories; Monday–Wednesday (MW), MWF, TR, or classes held one day a week. The categories are differentiated by patterns on the schedule for clarity, as seen in Fig. 2;
- Step 4. Identify conflicts: Mark, number, and list all conflicts that are identified on that original visual schedule. In Fig. 2, conflicts numbered from 1 through 11 are illustrated. For instance, Conflict 5 shows that CEE 330L3 overlaps with CEE 361. As another example, Conflict 10 shows that CEE 653 and CEE 681 occur in exactly the same time slot;
- Step 5. Generate input variables: Assign input variables for all time slots using the visual schedule as a template. Identify which classes are scheduled for the morning session and afternoon sessions, because these are likely reflections of the professors' indicated preference. For time slots outside of the preferred session, multiply the variable by 1,000 in order to avoid being selected for the optimal solution;
- Step 6. Create objective function: Create an objective function using the input variables created in Step 5. The *LINGO* function MIN is placed before all of the variables, because the intention is to minimize conflict and select those variables that present the lowest level of conflict;
- Step 7. Form constraints: Create the constraints based upon the newly assigned variables and the restrictions under the "Assumptions" and "Constraints" sections previously. All constraints must be run in the linear program model at the same time in order to find one optimal solution that adheres to all limitations and requirements. However, MWF schedules are run separately from the TR schedules, because they would not conflict with each other because of their day assignments;
- Step 8. Run *LINGO* trial: Run a trial using the *LINGO* software. If an optimal solution is possible, the program will respond with "global optimum solution found," meaning there is no conflict. It will list all variables that were included in the function, as well as an output value of 0–1. The code GIN must is entered as the last constraint in *LINGO* before running the program to ensure that all values are integers. Using GIN will ensure that only whole integers are used as output values, which will make the schedule formulation process much easier. If there is infeasibility or no optimum solution can be found, proceed to Step 8A;
- Step 8A. Use DEBUG to modify: For identified infeasible equations, use the DEBUG feature in *LINGO*. The program will only identify those equations that are contributing to the infeasible solution and will offer suggestions to solve the problem. The programmer must manually address the suggestions offered

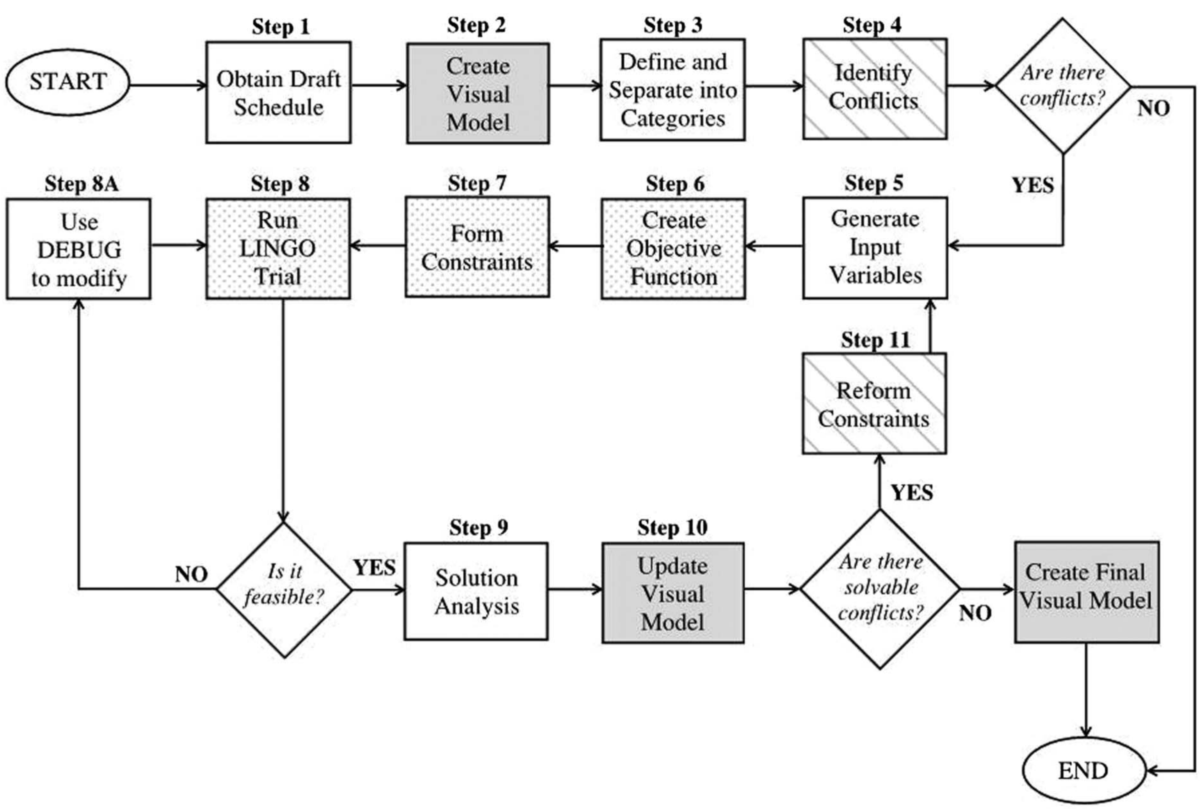


**Fig. 1.** Proposed methodology flowchart

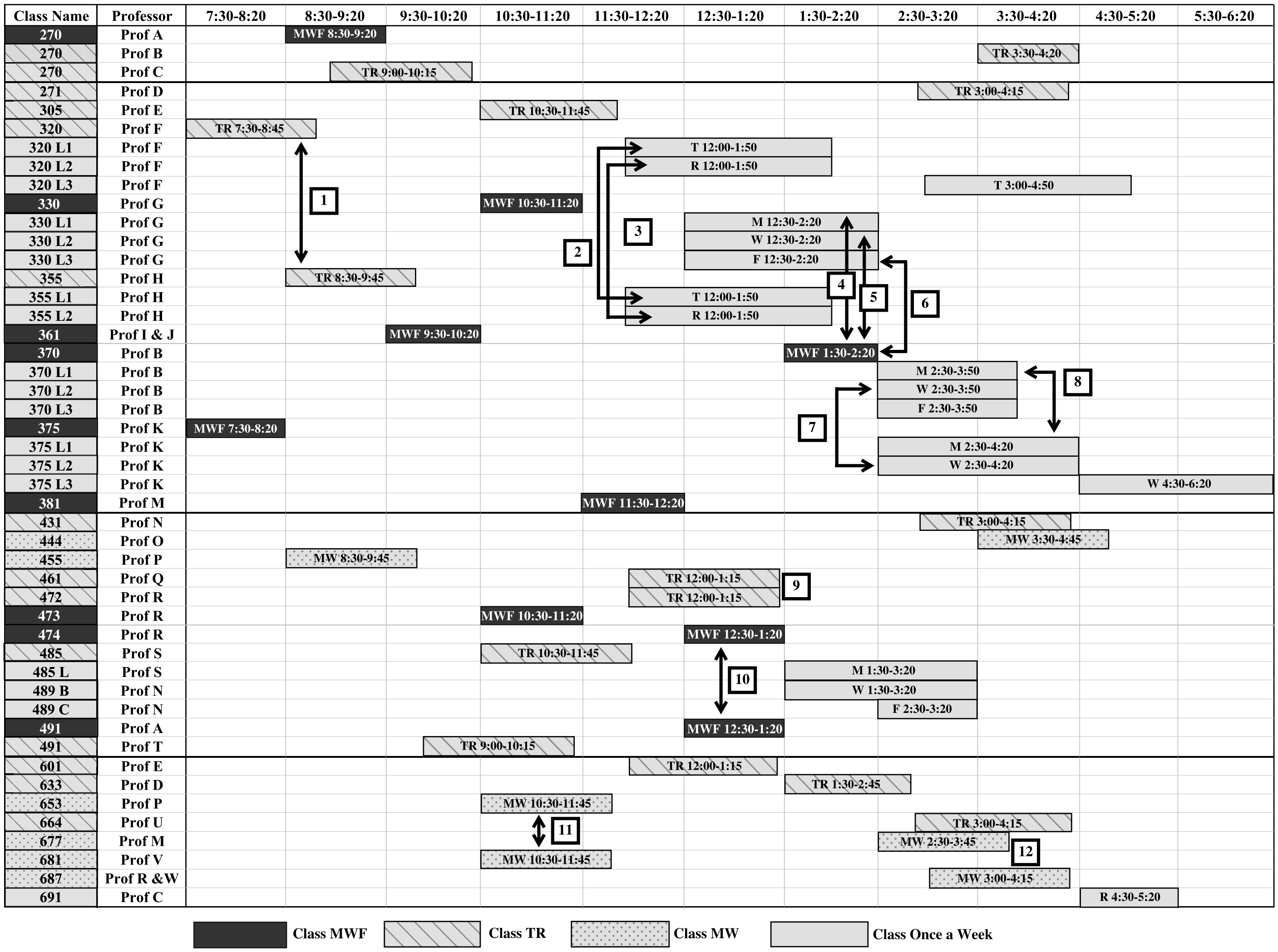


**Fig. 2.** Fall 2015 Visual model: Original schedule

by *LINGO* until the program may generate an optimum solution. If conflicts persist and cannot be resolved within the existing limitations, eliminate the constraints from the *LINGO* equation in order to obtain the optimal solution;

- Step 9. Solution analysis: Analyze the output values generated by *LINGO*. Variables with an output value of 1 should be selected as the optimal time slot for that class. Similarly, variables with an output value of 0 should not be selected for scheduling purposes, because they likely either create a conflict or do not satisfy the limitations indicated by the constraints;
- Step 10. Update visual model: Import the output values into the visual schedule. Check for existing and/or new conflicts. Classes may be adjusted manually by moving left or right or changing the date if necessary. These changes may only be done in a logical and thoughtful way that does not create new conflicts. This requires the modeler's discretion and judgement; and
- Step 11. Reform constraints: If conflicts still exist, repeat Steps 5–10 by manually moving time slots to the left or right to eliminate as many potential conflicts as possible. If conflicts cannot be eliminated, reform release constraints to see if an optimal solution can be achieved. Do this until either all conflicts are resolved or the infeasible equations are identified.

## Example Application: Fall 2015

The original schedule for Fall 2015 (Fig. 2) had 12 schedule conflicts—10 regarding undergraduate classes and 2 regarding graduate classes. The improvement for Fall 2015 required two *LINGO* trials in order to obtain the optimal solution. The improved final schedule for Fall 2015 resulted with four total conflicts, all regarding undergraduate classes. The whole linear program—objective function and constraints included—were presented earlier in this article. The exact steps taken in this example were as follows:

1. Obtain original schedule;
2. Create visual model (original);
3. Discover conflicts in the visual model (original);
4. Run *LINGO* Trial I;
5. DEBUG *LINGO* Trial I;
6. Adjust constraints;
7. Make Visual Model I;
8. Discover conflicts in Visual Model I;
9. Rewrite equations;
10. Run *LINGO* Trial II;
11. Make Visual Model II;
12. Discover conflicts in Visual Model II;
13. Manually adjust classes to reduce conflicts; and



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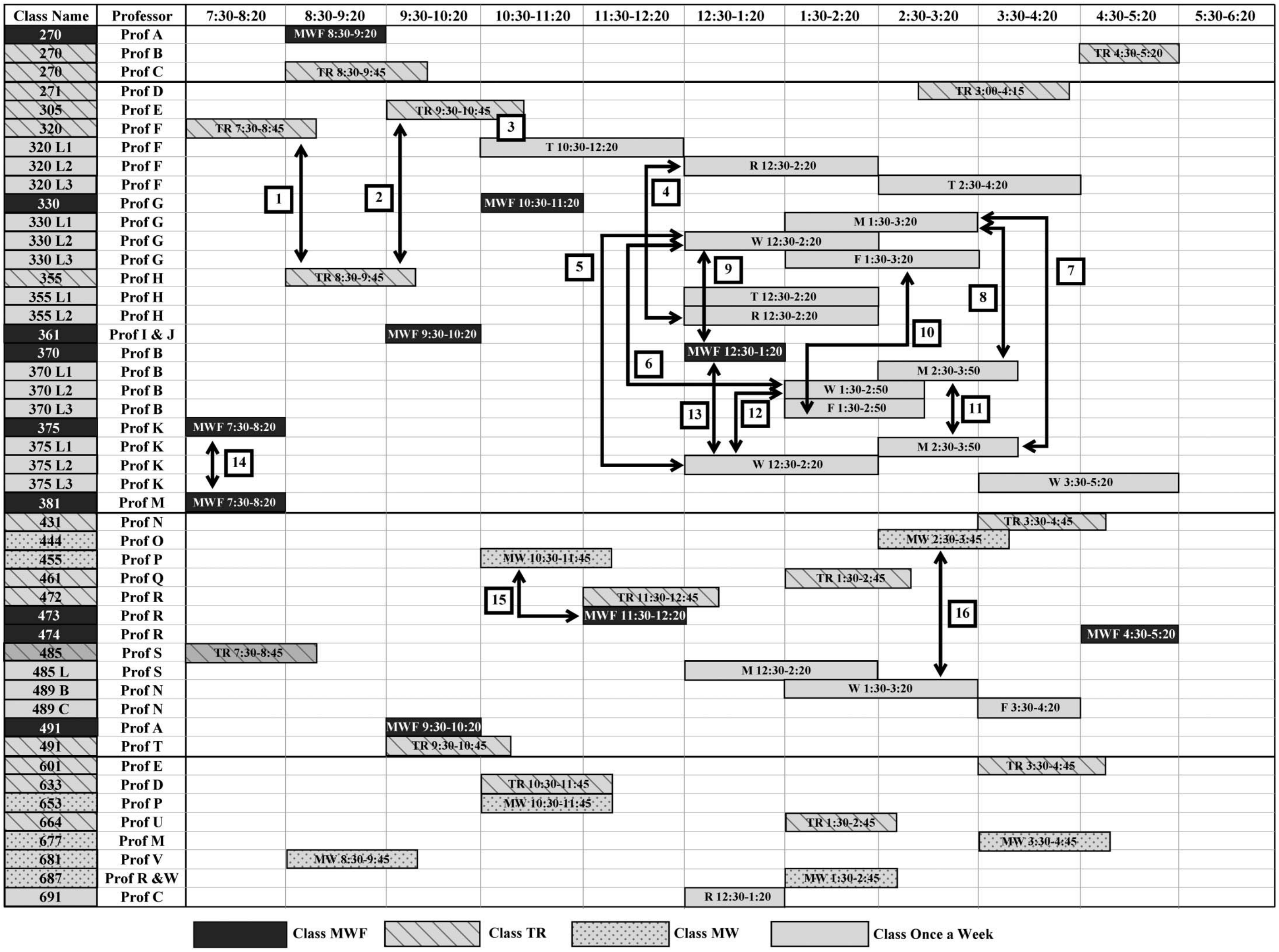


**Fig. 3.** Fall 2015 Visual model: Trial I

14. Obtain Visual Model (Final).

The above steps are discussed in the following sections.

### *LINGO* Trial I and Visual Model I

During Trial I in *LINGO*, coming from the equations and constraints of the original schedule, the MWF category was initially infeasible. After using the DEBUG feature, the constraints required separating the 300-level lectures and labs into independent constraints, as opposed to having all variables in one equation. Some overlap had to be allowed, because there was no way to satisfy the overlapping constraint within the 10 time slots of the day. Hence, the some labs were allowed to overlap with the lectures (not of the same subject). After allowing for this change, a global optimal solution at this stage was achieved through *LINGO*, but created 12 conflicts for the MWF schedule. These are illustrated in the visual model of Fig. 3 and documented as follows:

- Conflict 5;
- Conflict 6;
- Conflict 7;
- Conflict 8;
- Conflict 9;
- Conflict 10;
- Conflict 11;
- Conflict 12;
- Conflict 13;
- Conflict 14;
- Conflict 15; and
- Conflict 16.

The TR Trial I in *LINGO* was also initially infeasible because of the high volume of 2-h lectures and labs. Again, after DEBUG feature was used, it was discovered that the same problem as mentioned earlier occurred for the lectures and labs for the 300-level courses. Hence, some overlap of classes had to be allowed at the modeler's discretion. The ensuing solution, once applied to the visual model, still had four conflicts remaining in the TR schedule. They are illustrated in Fig. 3 and documented as follows:

- Conflict 1;
- Conflict 2;
- Conflict 3; and
- Conflict 4.

All of the conflicts in Trial I were for undergraduate classes only in this example. In total, the number of class conflicts at this iteration has increased from 11 to 13. Graduate class conflicts were resolved after running *LINGO* Trial I. Thus, the *LINGO* equations for graduate classes were subsequently excluded from *LINGO* Trial II.

## LINGO Trial II and Visual Model II

It was observed that the most common conflict was overlapping lab sections for the 300-level courses, particularly in MWF sessions. For this reason, the objective function and applied constraints needed modifications. Labs are only held once a week but were given their own variable, similar to lectures held three times a week, with the initial intention of avoiding overlaps between any and all 300-level classes. However, there was no feasible way to not have overlaps occur with such a high volume of 300-level classes and a limited number of time slots. It was up to the discretion of the modeler to decide which overlaps would be allowable and which constraints needed to be adjusted.

In this example application, there were four 300-level courses that had three lab sections each. Three of those courses had each lab section occurring on a different day of the week, per the original schedule. For Trial II, those labs that occurred on different days of the week were grouped under one variable, rather than three individual ones, in order to simplify the program. This way, the labs grouped under the same variable would be scheduled for the same time slot, but occurring on a different day from each other. An example of the new objective function illustrating the grouped lab sections can be seen in Table 11.

Considering the problems that were encountered in Trial I, the 300-level lectures and labs were left in individual constraints. However, as a result of change in lab input variables, the constraint preventing 300-level lab overlaps needed to be modified. By making this change, the labs for the same class are offered in the same slot but on a different day. An example of the updated constraint used in Trial II is presented in Table 12.

Once these changes to the linear programming model were made, a global optimal solution was achieved through *LINGO*. The simplified model used in Trial II produced fewer conflicts than Trial I, but still had 10 conflicts remaining. These conflicts are illustrated in Fig. 4. Once the output values were modeled in Fig. 4, it appeared that several conflicts could be eliminated if adjusted manually via the visual scheduling method. The primary objective was to make sure that no lab section overlapped another, because two lab sections at the same time would exceed the lab capacity. The lab sections were moved laterally in order to ensure that no lab sections on the same day overlapped with each other. This process was repeated until no lab sections overlapped with each other.

A similar logic was applied to overlapping lectures. One of the conflicting classes was moved either earlier or later as long as the movement did not generate new conflicts. This manual adjustment process eliminated four conflicts.

## Manual Adjustments

There are two types of manual adjustments: (1) during the DEBUG process, and (2) during the visual modeling.

The manual adjustments during visual modeling require logical input and decisions from the modeler, but in no way require expertise in the field of linear programming or scheduling. Manual adjustments during the visual modeling require simple adjustments to classes on the schedule to eliminate overlaps—which would likely be done during any other kind of scheduling analysis.

The manual adjustments made during the linear programming portion of the process (i.e., reforming the constraints, choosing which to allow or relax during the DEBUG process, etc.) require a logical understanding of the relationships between the constraints and knowledge of linear programming. The linear programming for the overall process only provides a more logical starting point for adjustments to be made, rather than arbitrarily creating a schedule together and adjusting from there.

**Table 11.** Input Values for Objective Function (Minimizaton), Trial II (Fall 2015, MWF)

| | | | Time slots available | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 7:30–8:20 a.m. | 8:30–9:20 a.m. | 9:30–10:20 a.m. | 10:30–11:20 a.m. | 11:30 a.m.–12:20 p.m. | 12:30–1:20 p.m. | 1:30–2:20 p.m. | 2:30–3:20 p.m. | 3:30–4:20 p.m. | 4:30–5:20 p.m. |
| Courses | Instructor | $x_{ij}$ | $x_{i1}$ | $x_{i2}$ | $x_{i3}$ | $x_{i4}$ | $x_{i5}$ | $x_{i6}$ | $x_{i7}$ | $x_{i8}$ | $x_{i9}$ | $x_{i10}$ |
| 330 | Prof. G | $x_{2j}$ | x21+ | x22+ | x23+ | x24+ | x25+ | 1,000x26+ | 1,000x27+ | 1,000x28+ | 1,000x29+ | 1,000x210+ |
| 330L (1, 2, 3) | Prof. G | $x_{3j}$ | 1,000x31+ | 1,000x32+ | 1,000x33+ | 1,000x34+ | 1,000x35+ | x36+ | x37+ | x38+ | x39+ | x310+ |
| 361 | Profs. I and J | $x_{6j}$ | x61+ | x62+ | x63+ | x64+ | x65+ | 1,000x66+ | 1,000x67+ | 1,000x68+ | 1,000x69+ | 1,000x610+ |
| 370 | Prof. B | $x_{7j}$ | 1,000x71+ | 1,000x72+ | 1,000x73+ | 1,000x74+ | 1,000x75+ | x76+ | x77+ | x78+ | x79+ | x710+ |
| 370L (1, 2, 3) | Prof. B | $x_{8j}$ | 1,000x81+ | 1,000x82+ | 1,000x83+ | 1,000x84+ | 1,000x85+ | x86+ | x87+ | x88+ | x89+ | x810+ |
| 375 | Prof. K | $x_{11j}$ | x111+ | x112+ | x113+ | x114+ | x115+ | 1,000x116+ | 1,000x117+ | 1,000x118+ | 1,000x119+ | 1,000x1,110+ |
| 375L (1, 2) | Prof. K | $x_{12j}$ | 1,000x121+ | 1,000x122+ | 1,000x123+ | 1,000x124+ | 1,000x125+ | 1,000x126+ | 1,000x127+ | x128+ | x129+ | 1,000x1,210+ |
| 375L | Prof. K | $x_{14j}$ | 1,000x141+ | 1,000x142+ | 1,000x143+ | 1,000x144+ | 1,000x145+ | x146+ | x147+ | x148+ | x149+ | x1,000+ |
| 381 | Prof. M | $x_{15j}$ | x151+ | x152+ | x153+ | x154+ | x155+ | 1,000x156+ | 1,000x157+ | 1,000x158+ | 1,000x159+ | 1,000x1,510+ |
| 444 | Prof. O | $x_{16j}$ | 1,000x161+ | 1,000x162+ | 1,000x163+ | 1,000x164+ | 1,000x165+ | x166+ | x167+ | x168+ | x169+ | x1,610+ |
| 455 | Prof. P | $x_{17j}$ | x171+ | x172+ | x173+ | x174+ | x175+ | 1,000x176+ | 1,000x177+ | 1,000x178+ | 1,000x179+ | 1,000x1,710+ |
| 473 | Prof. R | $x_{18j}$ | x181+ | x182+ | x183+ | x184+ | x185+ | 1,000x186+ | 1,000x187+ | 1,000x188+ | 1,000x189+ | 1,000x1,810+ |
| 474 | Prof. R | $x_{19j}$ | 1,000x191+ | 1,000x192+ | 1,000x193+ | 1,000x194+ | 1,000x195+ | x196+ | x197+ | x198+ | x199+ | x1,910+ |
| 485L | Prof. S | $x_{20j}$ | 1,000x201+ | 1,000x202+ | 1,000x203+ | 1,000x204+ | 1,000x205+ | x206+ | x207+ | x208+ | x209+ | x2,010+ |
| 489B | Prof. N | $x_{21j}$ | 1,000x211+ | 1,000x212+ | 1,000x213+ | 1,000x214+ | 1,000x215+ | x216+ | x217+ | x218+ | x219+ | x2,110+ |
| 489C | Prof. N | $x_{22j}$ | 1,000x221+ | 1,000x222+ | 1,000x223+ | 1,000x224+ | 1,000x225+ | x226+ | x227+ | x228+ | x229+ | x2,210+ |
| 491 | Prof. A | $x_{23j}$ | 1,000x231+ | 1,000x232+ | 1,000x233+ | 1,000x234+ | 1,000x235+ | x236+ | x237+ | x238+ | x239+ | x2,310 |

**Table 12.** Example of Revised 300 Overlapping Lab Constraint (from Trial II, Fall 2015, MWF)

| Time slot | CEE 330L1-3 | CEE 370L1-3 | CEE 375L1-2 | CEE 375L3 | <= | Constraint |
|---|---|---|---|---|---|---|
| 7:30–8:30 a.m. | $x31+$ | $x81+$ | $x121+$ | $x141$ | <= | 1 |
| 8:30–9:30 a.m. | $x32+$ | $x82+$ | $x122+$ | $x142$ | <= | 1 |
| 9:30–10:30 a.m. | $x33+$ | $x83+$ | $x123+$ | $x143$ | <= | 1 |

Those with more experience would likely generate more productive results with fewer conflicts, but the linear programming analysis provides improvements given a basic understanding of the process outlined in this article.

These manual adjustments did not take the authors more than 15–30 min for each visual model. Revising the linear programming equations subsequent to adjustments on the visual model took another 1 h per simulation run, largely because care needs to be exercised to get the equations correct.

### *Final Analysis*

Four conflicts were impossible to eliminate and were left on the final schedule, as seen in Fig. 5, which is the final visual model for this example. The issues and recommended changes to the original schedule are listed in Tables 13–15. The primary scheduling problem derived from the undergraduate lab sections and trying to avoid overlaps with other lectures or lab sections. It is recommended to minimize the number of lab sections per lecture in order to avoid these types of scheduling conflicts in the future.

## Statistical Analysis

Comparing the number of original conflicts to the improved schedule results provides a statistical comparison proving this research is beneficial in terms of course scheduling conflict remediation. The original and improved numbers, along with their averages, are shown in Table 16 for undergraduate classes, Table 17 for graduate classes, and Table 18 for all classes within the Department of Civil Engineering. The three tables also show the percent improvement over the original methodology across eight semesters of data, and also provide a percentage of how much worse the original schedules are compared to the results from the proposed methodology. For all classes within the Department of Civil Engineering, the average improvement over the original was 83.46%.

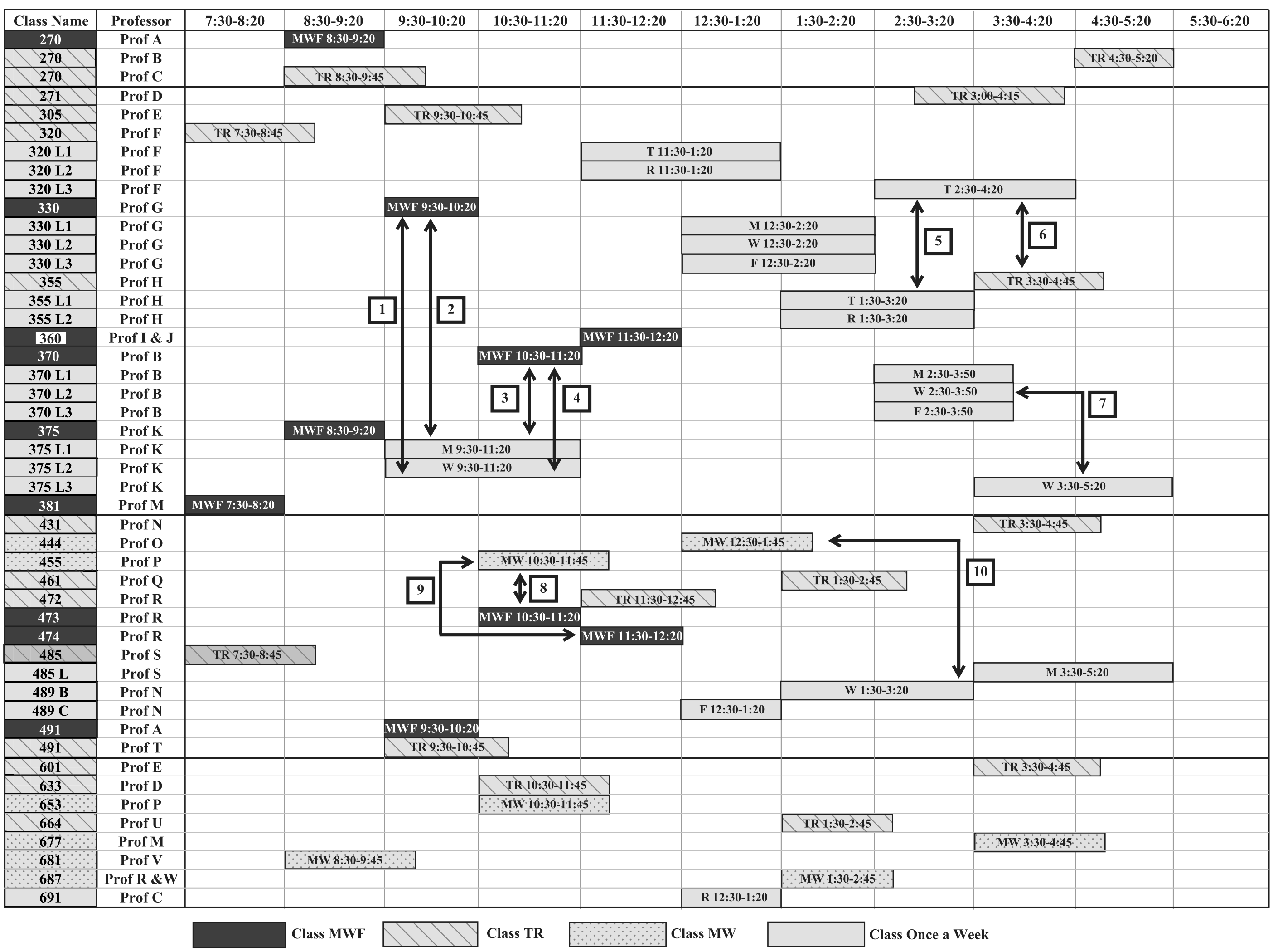


**Fig. 4.** Fall 2015 Visual model: Trial II

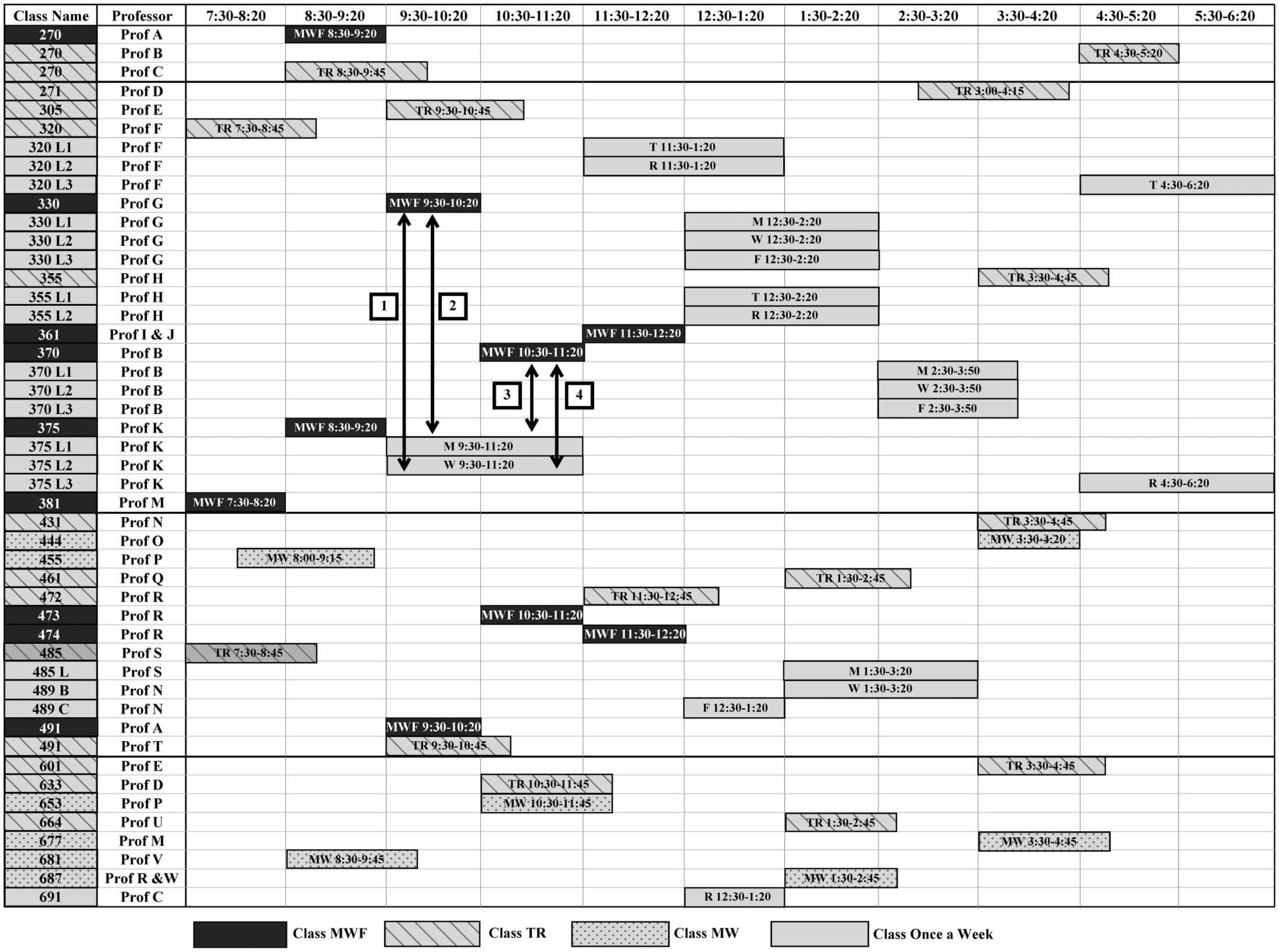


**Fig. 5.** Fall 2015 Visual model: Final schedule

**Table 13.** Fall 2015 Conflicts before Improvement

| Conflict | Reason | Classes affected |
|---|---|---|
| 1 | Classes can be taken concurrent | 320, 355 |
| 2 | Classes can be taken concurrent | 320L1, 355 L1 |
| 3 | Classes can be taken concurrent | 320L2, 355L2 |
| 4 | Classes can be taken concurrent | 370, 330L1 |
| 5 | Classes can be taken concurrent | 370, 330L2 |
| 6 | Classes can be taken concurrent | 370, 330L3 |
| 7 | Classes can be taken concurrent | 370L2, 375L2 |
| 8 | Classes can be taken concurrent | 370L1, 375L1 |
| 9 | Classes can be taken concurrent | 461, 472 |
| 10 | Classes can be taken concurrent | 474, 491 |
| 11 | Classes can be taken concurrent | 653, 681 |
| 12 | Classes can be taken concurrent | 677, 687 |

Note: Total conflicts = 12.

**Table 14.** Fall 2015 Conflicts after Improvement (Final)

| Conflict | Reason | Classes affected |
|---|---|---|
| 1 | Classes can be taken concurrent | 330, 375L2 |
| 2 | Classes can be taken concurrent | 330, 375L1 |
| 3 | Classes can be taken concurrent | 370, 375L1 |
| 4 | Classes can be taken concurrent | 370, 375L2 |

Note: Total conflicts after improvement = 4.

### Student-*t* Distribution

Student-*t* distribution was utilized to determine the significance of the results. The student-*t* test has been applied because it is very robust even when there are deviations from normality. As such, it is the most robust of many common distributions and most easily applicable when a single test must be selected for adoption (Skovlund and Fenstad 2001).

The terms $n_1$ and $n_2$ represent the sample size for the original group and improved group, respectively. For this research, data on eight semesters were used, so therefore $n_1$ and $n_2$ both equal 8. The degree of freedom is equal to $n_1 + n_2 - 2$, which in this case is 14 for comparing each semester. The terms $\bar{x}_1$ and $\bar{x}_2$ represent the mean value of conflicts for both of the original and improved sample populations respectively. The terms $s_1$ and $s_2$ equal the variances of the original and improved sample groups respectively. An example calculation of $t_{\text{stat}}$ is given in Table 19. The $t_{\text{stat}}$ for other semesters is calculated likewise, and results are reported in Table 19.

### Hypothesis and Determination of Significance

The hypothesis tested in this study is whether the number of conflicts in the improved schedule ($\bar{x}_1$) are statistically and significantly better than the original schedule ($\bar{x}_2$) or not. The hypothesis in equation form is

**Table 15.** Fall 2015 Movement of Classes from Fig. 2 (Original) to Fig. 5 (Final)

| Classes | Movement | Δ hour | Date change |
|---|---|---|---|
| | Monday–Wednesday–Friday movement of classes | | |
| 320L1 | Earlier | 0.5 | No |
| 320L2 | Earlier | 0.5 | No |
| 320L3 | Later | 1.5 | No |
| 330 | Earlier | 1 | No |
| 361 | Later | 2 | No |
| 370 | Earlier | 3 | No |
| 375 | Later | 1 | No |
| 375L1 | Earlier | 5 | No |
| 375L2 | Earlier | 5 | No |
| 381 | Earlier | 4 | No |
| 444 | Later | 3 | No |
| 455 | Earlier | 0.5 | No |
| 474 | Earlier | 1 | No |
| 485 | Earlier | 3 | No |
| 485L | Later | 2 | No |
| 489C | Earlier | 2 | No |
| 491 | Earlier | 3 | No |
| 677 | Later | 1 | No |
| 681 | Earlier | 2 | No |
| 687 | Earlier | 1.5 | No |
| | Tuesday–Thursday movement of classes | | |
| 270 | Later | 1 | No |
| 270 | Earlier | 0.5 | No |
| 305 | Earlier | 1.5 | No |
| 355 | Later | 6 | No |
| 355L1 | Later | 1.5 | No |
| 355L2 | Later | 1.5 | No |
| 431 | Later | 0.5 | No |
| 461 | Later | 1.5 | No |
| 472 | Earlier | 0.5 | No |
| 491 | Later | 0.5 | No |
| 601 | Later | 3.5 | No |
| 633 | Earlier | 3 | No |
| 664 | Earlier | 1.5 | No |
| 691 | Earlier | 4 | No |

$$H_0: \bar{x}_1 = \bar{x}_2 \tag{1}$$

$$A: \bar{x}_1 > \bar{x}_2 \tag{2}$$

From the calculated $t_{stat}$ values given in Table 20, a significance value was determined for each semester in order to establish a confidence limit. Table 20 provides the confidence limits of the MWF, TR, and total categories for all undergraduate classes, all graduate classes, and all classes within the Department of Civil Engineering. The total undergraduate class-schedule improvements remained significant up to a minimum confidence of 95.14%, being more than 99% confident in all but one case. The total graduate class schedule improvements remained significant for a confidence of 99.80%.

## Summary

The purpose of this study was to maximize the availability of classes within the Department of Civil Engineering to provide students with the most course selections possible within a semester with an aim of helping them graduate sooner. The study was conducted to present a course-scheduling model that provides the particular department with the optimal class schedule for a given semester.

Data from eight semesters were analyzed using the proposed method. The original class schedules for each semester were obtained from either the CEE website or the department chair. The input values and objective functions were created from the original schedule, because it accounted for the professors' preferences in terms of morning or afternoon sessions. Seven constraints were applied to the input values in order to schedule classes optimally. Visual modeling was applied to the linear programming output, as it was the best indicator for identifying conflicts and overlaps for classes in each schedule. The linear modeling was reapplied to the visual model until such time that no further improvements could be made.

The results of the study showed that the existing method generated an average of 13.63 conflicts per semester. The proposed method was able to reduce this number to an average of 2.38 conflicts. The improved schedules showed to be an average of 83.46% better than the original schedules. This was significant for a minimum confidence of 95.14%, but mostly significant above 99%. Hence, it is seen that the procedure outlined in this article produces efficient results. Thus, the procedure stands validated.

## Discussion

This study shows the number of conflicts within a given semester schedule are often unnecessary and can be solved. It could be argued that the similar result can be achieved if done purely through a manual process, but this would take a considerable amount of time, which is not always available to the department chair. The proposed system would provide the optimal solution in a way that would not require as much time, be scientifically validated, assures the

**Table 16.** Analysis of Undergraduate Class-Scheduling Improvements

| | Number of conflicts: Undergraduate | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Original | | | Improved | | | Improvement over original (%) | | |
| Semester | MW-MWF | TR | Total | MW-MWF | TR | Total | MW-MWF | TR | Total |
| Fall 2009 | 6 | 5 | 11 | 0 | 0 | 0 | 100.00 | 100.00 | 100.00 |
| Spring 2010 | 2 | 6 | 8 | 0 | 3 | 3 | 100.00 | 50.00 | 62.50 |
| Fall 2010 | 2 | 0 | 2 | 0 | 0 | 0 | 100.00 | 100.00 | 100.00 |
| Spring 2011 | 3 | 8 | 11 | 0 | 4 | 4 | 100.00 | 50.00 | 63.64 |
| Fall 2011 | 1 | 1 | 2 | 0 | 0 | 0 | 100.00 | 100.00 | 100.00 |
| Spring 2012 | 2 | 5 | 7 | 0 | 2 | 2 | 100.00 | 60.00 | 71.43 |
| Fall 2015 | 6 | 4 | 10 | 4 | 0 | 4 | 33.33 | 100.00 | 60.00 |
| Spring 2016 | 6 | 1 | 7 | 0 | 0 | 0 | 100.00 | 100.00 | 100.00 |
| Average | 3.50 | 3.75 | 7.25 | 0.50 | 1.13 | 1.63 | 85.71 | 68.87 | 82.20 |

**Table 17.** Analysis of Graduate Class-Scheduling Improvements

| | Number of conflicts: Graduate | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Original | | | Improved | | | Improvement over original (%) | | |
| Semester | MW-MWF | TR | Total | MW-MWF | TR | Total | MW-MWF | TR | Total |
| Fall 2009 | 3 | 8 | 11 | 0 | 1 | 1 | 100.00 | 92.31 | 95.45 |
| Spring 2010 | 9 | 9 | 18 | 2 | 3 | 5 | 77.78 | 66.67 | 72.22 |
| Fall 2010 | 5 | 9 | 14 | 0 | 2 | 2 | 100.00 | 77.78 | 85.71 |
| Spring 2011 | 6 | 8 | 14 | 1 | 4 | 5 | 83.33 | 50.00 | 64.29 |
| Fall 2011 | 2 | 6 | 8 | 0 | 0 | 0 | 100.00 | 100.00 | 100.00 |
| Spring 2012 | 4 | 8 | 12 | 0 | 2 | 2 | 100.00 | 75.00 | 83.33 |
| Fall 2015 | 2 | 0 | 2 | 0 | 0 | 0 | 100.00 | 100.00 | 100.00 |
| Spring 2016 | 1 | 1 | 2 | 0 | 0 | 0 | 100.00 | 100.00 | 100.00 |
| Average | 4.00 | 6.13 | 10.13 | 0.38 | 1.50 | 1.88 | 90.50 | 75.53 | 81.44 |

**Table 18.** Analysis of Total Class-Scheduling Improvements

| | Number of conflicts: All classes | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Original | | | Improved | | | Improvement over original (%) | | |
| Semester | MW-MWF | TR | Total | MW-MWF | TR | Total | MW-MWF | TR | Total |
| Fall 2009 | 9 | 13 | 22 | 0 | 1 | 1 | 100.00 | 92.31 | 95.45 |
| Spring 2010 | 9 | 9 | 18 | 2 | 3 | 5 | 77.78 | 66.67 | 72.22 |
| Fall 2010 | 5 | 9 | 14 | 0 | 2 | 2 | 100.00 | 77.78 | 85.71 |
| Spring 2011 | 6 | 8 | 14 | 1 | 4 | 5 | 83.33 | 50.00 | 64.29 |
| Fall 2011 | 2 | 6 | 8 | 0 | 0 | 0 | 100.00 | 100.00 | 100.00 |
| Spring 2012 | 4 | 8 | 12 | 0 | 2 | 2 | 100.00 | 75.00 | 83.33 |
| Fall 2015 | 9 | 3 | 12 | 4 | 0 | 4 | 55.56 | 100.00 | 66.67 |
| Spring 2016 | 7 | 2 | 9 | 0 | 0 | 0 | 100.00 | 100.00 | 100.00 |
| Average | 6 | 7.25 | 13.63 | 0.88 | 1.50 | 2.38 | 89.58 | 79.31 | 83.46 |

**Table 19.** Student-*t* Distribution for Undergraduate Classes (MW-MWF)

| Variable | Value |
|---|---|
| $n_1$ | 8 |
| $n_2$ | 8 |
| Degrees of freedom | 14 |
| $\bar{x}_1$ | 3.50 |
| $\bar{x}_2$ | 0.50 |
| $s_1^2$ | 4.57 |
| $s_2^2$ | 2 |
| $t_{\text{stat}}$ | 3.30 |

**Table 20.** Confidence Limits

| Category | $t$ value | Confidence limit (%) |
|---|---|---|
| Undergraduate classes (MWF) | 3.30 | 99.47 |
| Undergraduate classes (TR) | 2.16 | 95.14 |
| Undergraduate classes (total) | 3.90 | 99.84 |
| Graduate classes (MWF) | 3.77 | 99.79 |
| Graduate classes (TR) | 3.56 | 99.69 |
| Graduate classes (total) | 3.80 | 99.80 |
| All engineering classes (MWF) | 5.26 | 99.99 |
| All engineering classes (TR) | 4.23 | 99.92 |
| All engineering classes (total) | 6.18 | 100 |

department chair that the solution is correct, and benefits both the University and the students within CEE.

After analyzing the conflicts within each semester, it was found that the primary source of the conflicts was the lab sections either overlapping each other or with other lectures. It is recommended that the lab sections are either combined under one variable or reduced within a semester, so as to reduce the possibility of conflicts. In the case of Spring 2016, almost all of the conflicts were solved by changing the day on which the classes or labs occurred. Ensuring there is a balance between the MWF and TR sessions would likely reduce the possibility for conflicts as well.

## Conclusion

Upon analyzing eight different semester schedules for the Department of Civil Engineering, conflicts from the original schedules were reduced by anywhere from 62.5 to 100%. This indicates that the existing methodology practiced in the department is in need of improvement because the schedules it produces are far from optimal. From the student-*t* distribution test, the improvements made through the proposed methodology are significant and large with a confidence of more than 95.14%.

Although this proposed system is not perfect, it is certain that it is far better than the existing scheduling methodology. Reducing the conflicts within any given semester benefits the student body by facilitating timely graduations by creating an environment that has fewer class-scheduling conflicts and allows students more flexibility in their schedule.

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