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Multi-Semester Course Staffing Optimization

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ABSTRACT

Course scheduling and staffing is a problem that academic institutions need to solve every semester or quarter. The problem can be formulated as a combinatorial optimization problem to produce optimal course schedules and/or staffing assignments by assigning classes to faculty members while meeting multiple constraints. These constraints include faculty availability, qualification, and teaching preferences. Conflict in days and hours when faculty are available is the intrinsic nature of the underlying problem. Teaching load is also an essential constraint. During an academic year, each faculty member must meet a minimum and a maximum number of classes to teach.

Typically, the scope of the scheduling and staffing problem is a single semester or a quarter. However, some universities with accelerated programs offer courses in a unique Accelerated Term (AT) format that spans over multiple weeks (e.g., four, six, or eight weeks). Under a traditional university setting, this is equivalent to staffing instructors across multiple semesters or quarters. Therefore, in addition to the multi-criteria combinatorial complexity, the problem is further complicated by attempting to optimize course assignments across multiple accelerated terms within an academic year.

In this paper, we model the multi-semester course staffing problem and optimize the assignment of faculty to classes across multiple accelerated terms in the scope of an academic year. The goal is to efficiently and effectively allocate instructors to courses that meet all the constraints and favor allocating courses to instructors who are highly qualified and interested in teaching the subject. The optimality of the solutions is determined by an objective function that is formulated into the problem statement along with the constraints. Based on the literature survey, the constraints considered represent staffing requirements at most universities.

Two different approaches are used to solve the problem. First, the problem is modeled and solved using 0/1 *integer programming. In the next step, a Genetic Algorithm is used to find an optimal course staffing by modeling the problem as an optimal path search problem. The proposed algorithms have been back tested and the result are presented and analyzed.*

Keywords*: Course Scheduling, Faculty Staffing, Schedule Optimization, Integer Programming, Genetic Algorithms.*

1. INTRODUCTION

The number of US public and private colleges and universities stands at 6,063 in 2020-2021. There are 14.66 million students in public and 5.15 million in private universities. Most of these universities consider teaching as their primary goal and therefore regularly work on efficiently scheduling and staffing their classes [1]. Academic institutions spend hours and days on issues that arise from dealing with scheduling processes, avoiding time conflicts for faculty availability, and even space availability for classrooms.

The scheduling is not only a complex problem for academic departments, but also an unavoidable exhaustive and tedious task of matching limited resources to available time slots in many other industries. For example, the automation of the time-consuming process of manually scheduling nurses in a hospital can increase the efficient use of resources to a great extent. Such an automated scheduling system once integrated with existing clinical information systems saves time, and money, and helps with serving more people with limited resources, resulting in added affordability of the service [2].

Scheduling and staffing of university classes can be expressed as the allocation of resources, such as faculty and classrooms, considering all constraints, which will avoid issues like double assignment of lectures, classrooms, and wrong faculty staffing. Each college and/or department sets a standard regarding scheduling and staffing of classes, considering institutional effectiveness and students' timely graduation from programs. This can help ensure there is no bias of any kind in course offering and/or staffing [3]. Due to changes in the education landscape over the past years, faculty strength in many academic institutions largely comprises of adjunct or part-time faculty [4] thus making staffing of courses even more challenging because of additional availability limitations of adjunct faculty due to their full-time industry employment or teaching at multiple institutes.

The university course scheduling problem constraints can be divided into hard constraints and soft constraints [5]. Hard constraints are those that must be satisfied under all circumstances, such as when a faculty cannot teach onsite classes, whereas soft constraints are those that can be considered as preferences, such as a faculty who prefers to teach online but can teach onsite as well. In most cases, it will not be possible to generate a class staffing schedule that will satisfy every hard and soft constraint for all the faculty and courses [6]. An optimal class schedule will be a solution that meets all the hard constraints and violates a minimal number of soft constraints, maximizing a defined efficiency and effectiveness criterion.

Scheduling and staffing in different industries are studied in various papers. Authors in [5] proposed a Particle Swarm Optimization (PSO) based approach for class scheduling. The constraints include allowing instructors with flexible preferences (day of the week, consecutive lecture periods, etc.). A Genetic Algorithm is proposed in [7] for the Optimum Broadcast Scheduling (OBS) problem. Paper [8] used the Simulated Annealing for solving course scheduling problems. Greedy Algorithms are used in [9, 10] to execute a sequence of processes like the selection of available time for a class, classroom, and faculty based on the limitation of available resources.

Some of the solutions proposed for the course scheduling problem generate a report with class schedules that also includes room allocation for each class, a list of offering departments, and the academic year in which each class is offered. However, many of the proposed solutions lack considerations for faculty availability for various classes based on their respective background, interest in topics, or availability for online, onsite, or both types of classes. Availability of faculty to teach online and onsite has become an increasingly important aspect of staffing as many universities moved to online and hybrid classes due to the pandemic.

In this paper, we model and solve multi-semester staffing problem considering conditions including faculty qualification and interest in topics they teach, the months they are available to teach, their availability to teach onsite and/or online classes, as well as teaching load limits. Based on the literature survey, these constraints represent staffing considerations at most universities. Two different approaches are utilized to solve the problem. First, the problem is modeled and solved using 0/1 integer programming. Then a genetic algorithm is proposed and used to find the optimal sequence of instructors to staff courses. The algorithms have been back tested using the data from the M.Sc. Computer Science (MSCS) program at National University and produced schedules allocating instructors to courses that meet the constraints while favoring allocating courses to instructors who are highly qualified to teach the subject.

2. COURSE STAFFING OPTIMIZATION USING 0/1 INTEGER PROGRAMMING

In this section, a multi-semester hybrid course staffing problem is modeled as an integer programming problem. The model is defined based on a practical real case example and used to optimally staff all classes in the MSCS program at National University. The program is offered in the accelerated format where each course is completed within four weeks. The objective is to assign instructors to courses for which they have the highest level of interest and expertise in the topic while meeting all the constraints for the instructors and courses. Following are two of the instructor constraints considered in the course scheduling problem studied in this paper.

1. Each instructor can teach one course in each term (Month).
2. Some online instructors cannot teach onsite classes.

The graduate MSCS program studied in this paper consists of 13 courses. The program is offered three times a year, twice a year in onsite format, and once a year in the online format. There are 12 instructors who teach these 13 courses offered in the program.

Table 1 shows the offering of courses for each month from January to December in a given year, the same pattern is repeated each year. Each of the 13 courses is abbreviated with lowercase letters a, b, c, …, m. The 12 instructors are denoted using uppercase letters *A*, *B*, *C*, *D*, …, *L*. The courses that are listed with "OL" are offered in the online format. For example, in the month of February four courses are offered. Course *a*, *f*, and *m* are offered in the onsite format while course *h* is offered in the online format. Table 1 also shows that for some months, the number of onsite and online classes is different. However, during July for example, the number of onsite and online classes to be staffed is the same.

Problem Statement (0/1 Integer Programming)

We denote the decision variables by x_{ikmt} which take on the values of 0 or 1. The indices *i*, *k*, *m*, and *t* describe the attributes of the staffed course as follows:

1. *i:* A unique lowercase letter identifying the course name, number, and title.
2. *K:* An integer with a value either 1 or 2, where *k* = 1 designates an onsite class and the value *k* = 2 represents an online course offering.
3. *m:* An integer with a value ranging between 1 and 12 indicating the month in which a particular course is being offered
4. *t:* A unique uppercase letter identifying the individual instructors.

For example, the decision variable $x_{b13F} = 1$, states that the onsite offering of course *b* in month ***3*** (March) is assigned to instructor *F*. An assignment of 0 to this decision variable would indicate that instructor *F* is not assigned to this class.

Table 2 shows the availability of different instructors to teach in a particular month as well as their willingness to teach an onsite class. The second column in this table shows the months for which the instructor is not available to teach. The values 1 and 0 in column three represent the availability and non-availability of instructors to teach onsite, respectively.

Each instructor is given a weight score w_{it}, which quantifies the instructor *t*'s overall qualifications and preference to teach course *i*. The score w_{it} has an integer value between 0 and 3 and is a measure of interest, qualification, and preference of instructor *t* in teaching course *i*. A score of zero indicates the non-existence of qualification and preference for the instructor while a score of 3 reflects the instructor's high interest and high level of qualification to teach the class. Table 3 provides the description of the scores. The preference is to staff classes with the most interested and qualified instructors. Table 4 shows instructors teaching in the example program and their respective weighted scores for each course in the program.

Table 1: Course offering monthly schedule for the graduate program.

Month	**Courses**			
January		*g (OL)*	*e*	*l*
February	*a*	*h (OL)*	*f*	*m*
March	*b*	*i (OL)*	*g*	
April	*c*	*j (OL)*	*h*	
May	*d*	*k (OL)*	*i*	
June	*e*	*l (OL)*	*j*	
July	*f*	*m (OL)*	*k*	*a (OL)*
August	*g*		*l*	*b (OL)*
September	*h*	*a*	*m*	*c (OL)*
October	*i*	*b*		*d (OL)*
November	*j*	*c*		*e (OL)*
December	*k*	*d*		*f (OL)*

Table 2: The availability of instructors in different months and their availability to teach onsite classes.

Instructor	Months Not Available	Available to Teach Onsite
A	1, 6,8,11,12	1
B	2	0
C	1, 7, 8	1
D	6	1
E	8	1
F	6, 7, 9	1
G	10	1
H	7, 8, 11, 12	0
I	4	1
J	3, 4, 5, 6, 7	1
K	1, 3, 4, 8, 9	1
L	1, 6,8,11,12	0

Table 3: Description of the instructor's weight scores w_{it}

w_{it}	Description
0	Lacks qualifications and has no interest in teaching the course
1	Lacks qualifications but has an interest in teaching the course
2	Qualified but has low interest in teaching the course
3	Qualified and interested in teaching the course

Table 4: Instructor's weight scores for the graduate program

Course / Instructor	*a*	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*i*	*j*	*k*	*l*	*m*
A	3	2	2	1	1	0	3	3	1	0	3	3	3
B	0	3	2	0	0	0	1	0	0	3	0	0	0
C	0	3	3	0	0	0	0	0	0	0	2	2	2
D	0	0	0	3	0	3	1	0	0	3	0	0	0
E	0	0	0	0	3	0	0	0	0	0	0	0	0
F	2	0	0	0	0	3	1	0	3	0	0	0	0
G	0	0	0	0	0	0	3	3	2	0	3	3	3
H	0	0	0	0	0	0	0	0	2	0	0	0	0
I	0	3	3	0	0	0	0	0	0	0	3	3	3
J	3	0	0	0	0	0	0	0	0	0	0	0	0
K	0	0	0	3	3	0	0	0	0	0	0	0	0
L	0	0	0	0	0	0	3	2	0	0	0	0	0

The goal is to staff classes across multiple accelerated terms with available instructors. A solution to the course staffing problem must satisfy the following conditions:

1. Each class must be staffed by one instructor.
2. Instructors must not be staffed in two classes in a single accelerated term.
3. Full-time faculty must meet their required annual teaching load L.
4. Part-time instructors should meet their maximum yearly teaching load L_M.
5. Instructors must only be staffed to teach in the months they are available.
6. Some instructors are designated as online instructors and must not be staffed in onsite classes.

The objective is to optimally staff classes in such a way that satisfies the above constraints and maximizes the total sum of the staffing weight scores by assigning the course to highly qualified and interested instructors.

Problem Formulation

Starting with the 0/1 decision variables x_{ikmt}, the following constraint is imposed on the solution to ensure each class is staffed by a single instructor.

$$\sum_{t} x_{ikmt} = 1 \quad \forall\, i, k, m$$

For any fixed triplet combination of class *i*, modality *k*, and month *m*, the sum of decision variables over all instructors *t* must equal one. So, only one instructor gets to teach each class. Furthermore, an instructor cannot be assigned to more than one class in a month. This is formulated as follows.

$$\sum_{i} \sum_{k} x_{ikmt} \leq 1 \quad \forall\, m, t$$

For any fixed month *m* and instructor *t*, the sum of classes, regardless of their modality, staffed by instructor *t* in that month *m* must be either 1 or 0. Full-time faculty must teach their assigned teaching load *L* during a set number of months or a full year. Part-time instructors, on the other hand, can teach up to their maximum load L_M over a given period.

$$\sum_{i} \sum_{k} \sum_{m} x_{ikmt} = L \qquad \forall\; t \text{ (where } t \text{ is a fulltime faculty)}$$

$$\sum_{i} \sum_{k} \sum_{m} x_{ikmt} \leq L_M \quad \forall\; t \text{ (where } t \text{ is a parttime instrcutor)}$$

The values of L and L_M are known and can vary from instructor to instructor. The objective of the staffing assignment is to maximize the sum of the weight scores w_{it} to ensure classes are staffed with instructors who have high levels of expertise and interest in teaching the topics. This can be formulated as the following objective function $f(x)$ that considers the sum of the weights of the instructors staffed in the classes for any valid solution $\overline{\boldsymbol{x}} \in W$.

$$f(\overline{\boldsymbol{x}}) = \sum_i \sum_t x_{ikmt} . w_{it} \quad \forall\;\; i, t, \text{ where } \overline{\boldsymbol{x}} \in W$$

The goal is to find an optimal staffing assignment solution $\overline{\boldsymbol{x}}^*$ that maximizes this objective function

$$\overline{\boldsymbol{x}}^* = \underset{\overline{x} \in \boldsymbol{W}}{\arg max}\, f(\overline{\boldsymbol{x}}).$$

Implementation and Results

In this section, the integer programming model defined in the previous section is applied and used to solve a real case course staffing problem. Several trial runs were performed with given instructor weight scores, teaching availability, and teaching load to evaluate the optimal staffing solutions.

For the sample run result presented in this section, we set the period to five months and defined the problem as optimal staffing of sixteen classes in the months of January, February, March, April, and May to twelve instructors. We first set the teaching load for all instructors to be less than or equal to 5. The optimal staffing solution found assigned all classes to instructors with a score of 3 and reached a total score of 48. We then applied another set of conditions that modeled the staffing problem with different full-time and part-time instructors and their teaching load constraints. Table 5 shows the teaching load constraints for instructors labeled with letters *A* through *L* in a given period, e.g., an academic year. The data in Table 5 along with the instructor availability and interest/qualification scores partially shown in Table 6 for the month of January, define the staffing optimization problem described and modeled in the previous section. A "1" in the "Teaching Assignment" row of Table 6 indicates that instructor *E* is assigned to the class "*e*" in the month of January.

Table 7 shows the staffing result for all sixteen classes in the test run. The classes highlighted in grey, in the column "course", are offered in the online format, while the rest of the classes are offered onsite. The letter "*A*" in the first column heading in Table 7 represents the faculty teaching in the program, and the number "5" next to it indicates the teaching load constraint. The three digits in the row below the instructor indicate the instructor's *score*, *availability*, and *teaching modality* for each course in the given month. In the example shown, the staffing assignment solution has reached a total score of 46. The optimal staffing has assigned 14 out of 16 classes to instructors with a score of 3 for interest and qualification, and 2 of the courses are staffed with instructors with a score of 2. The staffed instructor and their scores for the scheduled courses are highlighted in Table 7.

Table 5: Faculty teaching load constraints.

Faculty	*A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*	*K*	*L*
Load Limit	<= 5	<= 4	<= 5	= 1	= 1	= 1	= 2	= 1	= 1	<= 4	<= 5	<= 5

Table 6: Availability and qualification scores of different instructors for a sample January month. Instructor *E* is assigned to class *e* in this month.

January	Xe11A	Xe11B	Xe11C	Xe11D	Xe11E	Xe11F	Xe11G	Xe11H	Xe11I	Xe11J	Xe11K	Xe11L
Teaching Assignment	0	0	0	0	1	0	0	0	0	0	0	0
Interest and Background	1	0	0	0	3	0	0	0	0	0	3	0
Availability Month (1 = Not Available)	1	0	1	0	0	0	0	0	0	0	1	0
Onsite (1 = Not Available)	0	1	0	0	0	0	0	1	0	0	0	1

Table 7: The optimal course staffing schedule found for all the courses in the months from January through May.

Course																																				
	January																																			
	A		**5**	***B***		**4**	***C***		**5**	***D***		**1**	***E***		**1**	***F***		**1**	***G***		**2**	***H***		**1**	***I***		**1**	***J***		**4**	***K***		**5**	***L***		**5**
e	1	1	0	0	0	1	0	1	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	3	1	0	0	0	1
l	3	1	0	0	0	1	2	1	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	1	3	0	0	0	0	0	0	1	0	0	0	1
g	3	1	0	1	0	0	0	1	0	1	0	0	0	0	0	1	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	1	0	3	0	0
	February																																			
a	3	1	0	0	1	1	0	0	0	0	0	0	0	0	0	2	0	0	0	1	0	0	0	1	0	0	0	3	0	0	0	0	0	0	0	1
f	0	1	0	0	1	1	0	0	0	3	0	0	0	0	0	3	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1
m	3	1	0	0	1	1	2	0	0	0	0	0	0	0	0	0	0	0	3	1	0	0	0	1	3	0	0	0	0	0	0	0	0	0	0	1
h	3	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
	March																																			
b	2	1	0	3	0	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	0	0	1	0	0	1	0	0	0	1
g	3	1	0	1	0	1	0	0	0	1	0	0	0	0	0	1	0	0	3	0	0	0	0	1	0	0	0	0	1	0	0	1	0	3	0	1
i	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	2	0	0	2	0	0	0	0	0	0	1	0	0	1	0	0	0	0
	April																																			
c	2	1	0	2	0	1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	1	0	0	1	0	0	1	0	0	0	1
h	3	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	1	0	1	0	0	1	0	0	1	0	2	0	1
j	0	0	0	3	0	1	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	1	0	0	1	0	0	0	0
	May																																			
d	1	0	0	0	0	1	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	3	0	0	0	0	1
i	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	3	0	0	2	0	0	2	0	1	0	0	0	0	1	0	0	0	0	0	0	1
k	3	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	3	0	0	0	1	0	0	0	0	0	0	0

3. COURSE STAFFING OPTIMIZATION USING GENETIC ALGORITHMS

In the previous section, the course staffing optimization was solved by modeling it as an integer programming problem. One limitation of this approach is that the complexity of the problem dramatically increases by applying this approach to a larger scheduling problem with more courses, more faculty members, and more program offerings throughout the year. The complexity will be exacerbated if this approach is used in department or university levels for multi-program course staffing with many instructors and several hundred course sections, each with different constraints.

In this section, a solution based on Genetic Algorithms is proposed to find optimal course staffing schedules for larger staffing problems. We model the staffing problem as an optimal path search problem. Each path is a sequence of instructors that is used to schedule the courses giving the priority to the instructors at the beginning of the path. Figure 1 shows two sample paths for a sample staffing problem with 6 instructors. For the ***path*** = [F, B, E, D, A, C] in Figure 1(b), the scheduling will first staff instructor F, then B, and will continue until the last instructor C is staffed.

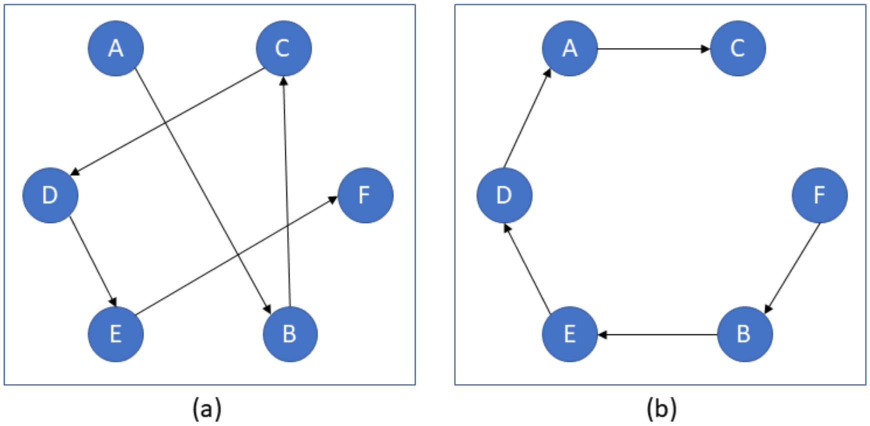

Figure 1: Two different paths of instructors. (a) *path* = [A, B, C, D, E, F], and (b) *path* = [F, B, E, D, A, C]

The goal is to find the optimal ***path****** that maximizes the objective function and assigns the maximum number of courses to instructors who have high levels of experience, qualification, and interest in teaching the subject while minimizing the number of courses that are left unstaffed.

The proposed approach is used to schedule all 39 course sections given in Table 1, using instructor availability in Table 2, and instructor score in Table 3. Figure 2 shows the result using a genetic algorithm with a population size of 20. Using 100 generations, the algorithm has found a schedule with a total score of 73.

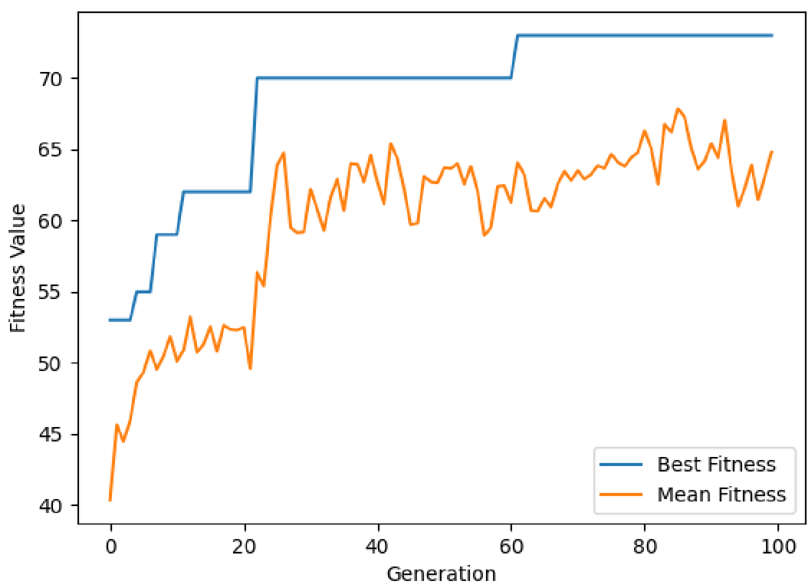

Figure 2: Best Fitness and Mean Fitness vs. Generation; Population Size = 20, and Generations = 100

CONCLUSION

In this paper, two approaches for multi-semester course staffing were proposed. The methods were then applied to optimally staff classes for a real case graduate program. The proposed approaches provide the functionality of considering all soft and hard constraints including the availability of faculty, their preference for online and onsite classes, the use of the instructor's qualification for each of the courses in the program, and the maximum teaching load. Further, the proposed algorithms work across multiple terms such as semesters or quarters and model the teaching load constraints over multiple terms.

The optimality of the solutions is determined by an objective function that is formulated into the problem statement along with the constraints. The staffing schedule generated allocates instructors to courses that meet the constraints with the objective that prioritizes staffing courses to instructors who are highly qualified and interested in teaching the subject. Both methods were applied to the MSCS program at National University and produced schedules meeting the constraints and favoring highly qualified instructors by maximizing the total weight scores.

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