Integer Goal Programming Approach to Optimized Office Assignment in Research and Academic Facilities

Anjiya Sharif and Eveline Thevasagayam
Department of Chemical Engineering
University of Waterloo
Waterloo, ON, Canada
ethevasa@uwaterloo.ca, anjiya.sharif@uwaterloo.ca

Hedia Fgaier
Full Sail University, 3300 University Blvd, Winter Park, FL 32792, United States
& Valencia College, 1800 S Kirkman Rd, Orlando, FL 32811, United States

Ali Elkamel
Department of Chemical Engineering
University of Waterloo, Waterloo, ON, Canada & Khalifa University, Abu Dhabi, UAE
aelkamel@uwaterloo.ca

Abstract

This paper addresses the problem of allocating office space to personnel in an academic institution. The objectives of accommodating everyone, meeting Council of Ontario Universities (COU) guidelines, and proximity of personnel in the same research area are identified. A binary integer goal programming model is created to optimize allocation. To further improve the quality of the allocation, goals are weighted independently, and deviations are disallowed for some goals. The model is illustrated on a case study consisting of 6 research groups, 3 personnel categories, and 108 office spaces. Depending on the personnel category, square footage is assigned which roughly translates to a room capacity of 1 for professors, 2 for post-doctoral fellows and 4 for graduate students. The accommodation goal is met completely (i.e., all individuals are allotted space), there is minimal deviation with the group floor assignment goal (i.e., some individuals are not on the same floor as the rest of the research group) and moderate deviation in meeting the COU space goal (i.e., the room capacity constraints are not completely met).

Keywords
Optimization, Space Utilization, Operations Management, Facilities Planning, Integer Programming.

1. Introduction
Office space allocation is the task of assigning offices to personnel subject to specified constraints. This task has been optimized to cater to the specific needs of a university. Local university councils publish recommendations for space utilization that help inform and direct optimization model creation (Committee on Space Standards and Reporting 2018). Optimized allocation allows for better utilization of space and can help organizations improve employee experience and better plan for future personnel changes (Ulker 2013). This paper aims to optimize office space allocation process for the Department of Chemical Engineering at the University of Waterloo to be better aligned with Council of Ontario Universities (COU) guidelines and to improve collaboration. The COU categorizes space allocation requirements based on the space's occupant and its intended use: for faculty, for research supporting personnel (e.g., post-doctoral fellows), for graduate students (i.e., full-time masters and PhDs), for technical and administrative staff and, unit supporting spaces (e.g., meeting rooms and lounges) (Committee on Space Standards and Reporting 2018). Each of these categories is entitled a specified square footage of space according to the COU which the department is currently only partially implementing. More specifically, there is no differentiation between Post-Doctoral Fellows (PDFs) and graduate students in the current space allocation process. The scope of this project is limited to only the first three categories (faculty, PDFs, and graduate students). Since each office available to the department has similar dimensions, the optimization model can be created using

occupancy-based constraints. Occupancy-based constraints are set such that COU-specified square footage requirements are met and problem definition is simplified. Problem formulation in this way allows for the use of binary integer variables. Based on COU guidelines and space availability, the following occupancy-based constraints are set: (1) faculty offices to have an occupancy of 1, (2) PDF offices to have an occupancy of 2 and, (3) graduate student offices to have an occupancy of 4. Incidentally, this imposes a limitation on problem definition in that the total number of PDFs in any research group must be rounded to a multiple of 2 and graduate student personnel totals must be rounded to a multiple of 4. It also minimizes heterogeneity as it ensures all people in the same COU categorization are placed in the same room. The model imposes a penalty if any person is receiving less space than is outlined in the COU. This is a soft constraint.

It is also theorized that collaboration is promoted when personnel working in the same area of research are placed in proximity. The department has 6 distinguishing areas of research which are termed research groups in this paper. The model assigns a research group to a specific floor and imposes a penalty if the model assignment does not match. This is another soft constraint. A hard constraint preventing re-allocation of an allocated room is applied (i.e., no redundant assignments). Moreover, since it is known that there is excess space, there is a hard constraint that all employees should be accommodated.

1.1 Objectives

The primary aim of this report is to design an office assignment model that caters to the specific needs of the Department of Chemical Engineering at the University of Waterloo. To do so, several iterations of problem definition and variable identification are tested and a hypothetical, yet representative case study scenario is solved. In creating this model, the relevant personnel data was collected and cleaned to make larger scale model implementation more accessible. The overall objective is to recommend next steps for program improvement and mass implementation at the University of Waterloo's Faculty of Engineering.

2. Literature Review

The space allocation problem is structured like a multidimensional knapsack problem (Ulker 2013). It employs linear binary integer goal programming. All objective and constraint mathematical functions are linear. Each decision variable is binary and represents the assignment of personnel to a specific office room. To accommodate multiple objectives, a goal programming approach is employed; it allows for multiple targets to be specified and attempts to find a solution that best meets targets (i.e., soft constraints). In other words, the advantage of goal programming is that it allows for relaxation of constraints which allows the program to arrive at a feasible solution. Similar problems have been solved by Özgür Ülker (2013), Giannikos et. Al. (1995), and Ritzman et Al. (1979).

The integer goal programming model can be visualized as a matrix where each column is an office, and each row is a personnel group (e.g. faculty in research group 1). As this matrix gets larger (e.g., > 200 variables), many proprietary software programs cannot compute a feasible solution as they are not designed to consume this heavy amount of processing power. Consequently, algorithms tailored to increase processing efficiency of combinatorial optimization problems have been developed; the most prominent algorithms are hill-climbing and genetic (Burke, 2001). The hill-climbing algorithm consists of three functions that allocate resources to rooms: allocate resource, move resource, swap room. The allocate resource function uses a random fit to allocate all unallocated resources to rooms. The move resource function reapplies a fit method to move an allocated resource to another room. The swap room function swaps resources from one area of space with another. For each iteration in the hill climbing algorithm, one of these functions is chosen to produce an allocation, the allocation is evaluated (based on minimization of the objective equation). If the second iteration is better than the first it is made the" current allocation" and used as a basis to compare all further allocation function iterations (Burke 1999). Genetic algorithms employ a similar iterative technique but are significantly better at handling discontinuous functions (Kramer 2017). To solve the case study described in this paper, an iterative approach based on selecting the lowest basic feasible solution calculated using pivot operations is employed. This method is highly effective for condensed case studies but the number of iterations grows exponentially as the number of variables increases (Tano 2019).

3. Methods

There are 1944 decision variables that were solved using the model and program. The binary integer decision variables are defined as follows. Table 1 indicates the model index j and its corresponding group name. Table 2 indicates the member index k and its corresponding member type.

$$x_{ijk} = \begin{cases} 1, & if\ office\ i\ is\ assigned\ to\ member(s)\ k\ in\ group\ j \\ 0, & if\ office\ i\ is\ not\ assigned\ to\ member(s)\ k\ in\ group\ j \end{cases}$$

$$i = 1 \dots 108$$
$$j = 1 \dots 6$$
$$k = 1 \dots 3$$

Table 1. Group Index and Corresponding Name

Index j	Group Name
1	Biotechnology and Biomedical Engineering
2	Interfacial Phenomena, Colloids, and Porous Media
3	Nanotechnology
4	Polymer Science and Engineering
5	Process Systems Engineering
6	Lecturers

Table 2. Member Index and Corresponding Name

Index k	Member Type
1	Professors
2	PDF's (Post- Doctoral Fellows)
3	Graduate Students (Masters and PhD)

3.1 Exclusivity Constraint

One of the constraints in this model is defined as a non-goal constraint that is non-negotiable and must be met for the program to arrive at a feasible solution. This is the exclusive room assignment constraint that prohibits an office from being assigned to more than one group and member type:

$$\sum_{j=1}^{6}\sum_{k=1}^{3} x_{ijk} \leq 1, \qquad for\ i = 1 \dots 108$$

3.2 Accommodation Goal

The first goal constraint is the accommodation constraint wherein every person should be assigned to an office. In the specific study using current data of the chemical engineering department within the University of Waterloo, it is already known that there are enough office spaces to accommodate all faculty and postgraduate students. However, this model was formulated for a broader case so that in the instance where there are presently not enough office spaces to accommodate, the number of persons assigned will be the most important goal constraint to be met. The deviation variables in this constraint, d_{1jk}, identifies the number of people in each group and member type that have not been assigned an office space if the value is positive and excess spots within the assigned offices if negative. This deviation value can be used to then make strategic planning decisions on acquiring more offices spaces to accommodate all people.

$$\sum_{i=1}^{108} C_{ik} x_{ijk} + d_{1jk}^{+} = N_{jk}, \qquad for\ j = 1 \dots 6\ and\ k = 1 \dots 3$$

As for the parameters in this constraint, N_{jk} is the total headcount of people in group j of member category k rounded up to the nearest multiple designated for each category. That is, for members of k=2, N_{jk} is rounded up to multiples of 2 and for k=3, N_{jk} is rounded up to the next multiple of 4. This is done because rooms are assigned based on group and member type. C_{ik} is the designated capacity of the room that is set based upon space standards, furniture, and overall office utility availability such as electrical outlets and computer stations.

3.3 Group Floor Assignment Goal

The second highest priority goal constraint for this model is the assigned floor constraint which seeks to assign persons of all members categories k and the same group j to the same floor or building section which have been pre-assigned. This is done to promote higher levels of productivity and efficiency among members of the same research groups.

$$\sum_{i=1}^{108} x_{ijk} a_{ij} C_{ik} + d_{2jk}^{+} = N_{jk}, \quad for\ j = 1 \dots 6\ and\ k = 1 \dots 3$$

The parameter a_{ij} is a binary value that indicates whether an office i is assigned to research group j. If the value is 1 then the statement is true, and office is pre-assigned to research group j. The positive deviation variable d_{3jk} in this constraint specifies the number of persons of member category k in group j who are not assigned to an office on their group designated floor.

3.4 COU Space Goal

The third highest priority goal constraint is the COU space goal which is to ensure that the number of persons assigned to an office have as close to the allotted space as per guidelines from the Council of Ontario Universities. r_i is the floor area of office i rounded to the nearest integer and s_k is the minimum space required by member category k rounded to the nearest integer. The value of s_k is the space for member k determined by the Council of Ontario Universities (Committee on Space Standards and Reporting, 2018). The deviation variable in this constraint d_{2jk} specifies the area by which the space for members the k in group j deviates from the designated space guidelines. A positive deviation indicates that minimum space requirements are not met, and a negative deviation indicates excess space.

$$\sum_{i=1}^{108} r_i x_{ijk} + d_{3jk} = s_k N_{jk}, \quad for\ j = 1 \dots 6\ and\ k = 1 \dots 3$$

3.5 Model Features for Physical Realizability

To warrant a physically realizable optimal solution, the following features must be included in the model. To further cement the hierarchy of goals, a weight is placed on each goal in the objective function (i.e., goal summation function). Weights also function to normalize goals with higher individual totals. Since the objective function is being minimized, placing a higher weight on a goal connotes less slack. The accommodation goal is given top-most priority since all personnel must have an allocated space, a weight of three is chosen for this. All subsequent weights are chosen relative to three. Weights for the floor grouping goal are divided into personnel groups; it was determined most important that all faculty in a research area be placed on the same floor (weight = 3), followed by PDFs (weight = 1) and then graduate students (weight = 0.125). The COU space goal has weights less than 1 assigned to normalize the higher totals. An additional constraint to only allow positive deviations for the accommodation and floor grouping goals is needed. For the accommodation goal, a negative deviation indicates that a room is filled above capacity, whereas a positive deviation means that a room is not completely full. This constraint prevents overcrowded rooms. For the floor grouping goal, a negative deviation indicates (similar to the exclusivity constraint) that personnel have not been assigned a room whereas a positive deviation indicates that one has been assigned, just in a different location to other members of the research group. In this case, the positive deviation constraint ensures personnel accommodation is prioritized above the location of allocation.

3.6 Objective Function

The objective function for this model seeks to minimize the sum of the positive deviation variables for each goal constraint. Since not every goal constraint is of equal importance and priority, weights have been assigned to each.

$$f = \sum_{j=1}^{6} \sum_{k=1}^{3} w_{1k} d_{1jk}^{+} + w_{2k} d_{2jk}^{+} + w_{3k} d_{3k}$$

The weights w_{1k}, w_{2k} and w_{3k} correspond to goals 1, 2 and 3 accordingly and are listed in Table 3. The weights are specific to member type in each group as the ranking of the group members are significant when finding the optimal solution. In other words, if group floor goal constraint is to be compromised, it is more important that professors are assigned to their designated research floor. That is if the program reaches a decision point where either a grad student is unassigned or a professor is unassigned, the program prioritizes assigning the professor.

Table 3. Weights used for each goal and member type

	Goal Constraint Index		
Member Index (k)	1	2	3
1	3	3	0.2
2	3	1	0.2
3	3	0.125	0.025

4. Data Collection

Two sources of data are consulted in the generation of the optimization model: (1) a 2017 account of student information (i.e., name of supervisor(s), full-time/part-time status, and room allocation) and (2) a 2023 account of space information (i.e., NASM and capacity). Publicly available information on the University of Waterloo web domain is also referenced to categorize personnel into research groups.

5. Results and Discussion

5.1 Numerical Results

As for the model's optimized assignment solution for the department of Chemical Engineering at the University of Waterloo, a smaller re[presentative case study of 189 variables was used to check for the performance and validity of the model. In this case study, 3 research groups and 21 office spaces were considered with numbers for the headcounts in each member categories. Table 4 details the properties on each of the 21 offices spaces that are relevant to the creation of the model parameters and constraints. Table 5 indicates the headcount of each member type in each research group.

Table 4. Office Categorization and Attributes

Office Indices (i)	Building Code	Floor Codes	Room Area Range	Designated Floor Grouping
i= 1..5	DWE	1&3	12-16 m^2	Unassigned Overflow Offices
i= 6..10	E6	2	13 m^2	Interfacial Phenomena, Colloids, and Porous Media
i= 11..15	E6	4	13 m^2	Biotechnology and Biomedical Engineering
i= 16..21	QNC	5	12-13 m^2	Nanotechnology

Table 5. Number of Individuals for Each Member Type and Research Group

Member (k)	Biotechnology and Biomedical Engineering (j=1)	Interfacial Phenomena, Colloids, and Porous Media (j=2)	Nanotechnology (j=3)
Professors (k=1)	3	2	4
PDF (k=2)	3	4	8
Grad Students (k=3)	2	2	12

For all rooms, the capacity if assigned to professors was 1, to post-doctoral fellows was 2 and to graduate students was 4. Using this data, the solution to the model was implemented in the Excel solver with an integer optimality setting of 0.5%. Table 6 shows the results of the optimized model results.

Table 6. Case Study Optimization Model Results

Office Index	Assigned Group	Assigned Member(s)
1	Interfacial Phenomena, Colloids and Porous Media	Graduate Student
2	Unassigned	
3	Interfacial Phenomena, Colloids and Porous Media	Graduate Student

4	Unassigned	
5	Unassigned	
6	Interfacial Phenomena, Colloids and Porous Media	PDF
7	Interfacial Phenomena, Colloids and Porous Media	Professor
8	Interfacial Phenomena, Colloids and Porous Media	Professor
9	Interfacial Phenomena, Colloids and Porous Media	Professor
10	Interfacial Phenomena, Colloids and Porous Media	PDF
11	Biotechnology and Biomedical Engineering	Professor
12	Biotechnology and Biomedical Engineering	Graduate Student
13	Biotechnology and Biomedical Engineering	Professor
14	Biotechnology and Biomedical Engineering	Professor
15	Biotechnology and Biomedical Engineering	PDF
16	Nanotechnology	Graduate Student
17	Nanotechnology	Graduate Student
18	Nanotechnology	Professor
19	Nanotechnology	Graduate Student
20	Nanotechnology	Professor
21	Nanotechnology	PDF

Table 7. Goal deviation values, and final objective function values

Goal 1 Deviation	0
Goal 2 Deviation	2
Goal 3 Deviation	-22
Minimized Objective Function Value	-1

From Table 7 it is clear that goal 1 was completely met. That is all people were assigned to an office. As for goal 2, 2 offices were assigned to groups whose research group members could not be placed in one of their designated research group offices. In this case study, it was namely graduate students from research group 2. The model assigned them to offices in another building (DWE) that is not attributed to any research group. Goal 3 deviation was not strictly to be positive as described in the decision model section of this paper. The deviation from this case study solution was -22 which means 22 square meters of extra space have been assigned across all members and groups. This is not a major concern since the goal is to meet minimum space requirements for each member.

5.2 Proposed Improvements

Due to the scale of the problem, it may be necessary to investigate alternative algorithms such as hill-climbing that reduce the computation time required by the integer programming optimizer. A graphical interface can also be developed to enable decision-makers without knowledge of integer programming to use the office allocation package effectively.

To develop a similar model that optimally allocates personnel to labs, occupancy data is required. Strides are being made in the development of occupancy sensors that enhance space use management to achieve operational efficiency. Sensor resolution can be quantified in four levels: level 1 is identifying occupancy (whether someone is present in the space), level 2 is the frequency (how many occupants are present), level 3 is identity (who the occupant is) and level 4 is activity (what the occupant is engaged within the space (Azizi et al. 2020). The higher the sensor resolution, the better the optimization model can be developed. Ideally, a level 3 or 4 sensor is required to distinguish which research groups are accessing the space and which instruments are being frequently used. From this, decisions can be made about the amount of lab space that should be allocated (e.g., the biotechnology research group may need a lot more bench space than the process systems engineering group) and where instruments with a lot of interdisciplinary use should be placed.

6. Conclusion

The space allocation model programming approach and results from the simplified model implementation can be used as a starting point for development of a more robust model for the chemical engineering department at the University of Waterloo. The data currently shows that COU guidelines are being followed for faculty and graduate students but not for PDFs. It also shows that each member in a research group is placed in relative proximity but there is room for improvement. The developed model addresses both concerns. The ultimate objective of this paper is to study space allocation and design a decision support system that can be used to easily evaluate the current situation and explore possible alternatives.

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Biographies

Eveline Thevasagayam is a recent graduate from the University of Waterloo holding a BASc in Chemical Engineering with an Option in Management Sciences and a Dean’s List Distinction. She is currently a Quality Control Engineer at Toyota Motor Manufacturing Canada. While she was a student at the University of Waterloo, her team was awarded the Final Year Design Award for their capstone project on an Optimized Hydroponics for Sustainable Agriculture on the UW Campus. Her industry-specific interest is the transition to clean energy in the automotive industry and vehicle design for optimized energy consumption.

Anjiya Sharif is a fourth-year undergraduate student in the Chemical Engineering program at the University of Waterloo. During her undergraduate career, she has used neural networks to optimize sensor readings for a medical device, researched novel catalysts for electrochemical cells, used data-driven continuous improvement to increase yields in food production, and built pilot plants spanning industries as a project engineering assistant. She has also established and led an undergraduate design team at the university to build a functional CO_2 capture device over two years and competed as a finalist in an international design competition. Her research interests include technology commercialization, axiomatic design, and sustainability.

Hedia Fgaier is currently a Professor of Mathematics at Full Sail University. Prior to this she was a Lecturer at the University of Waterloo and an Assistant Professor of Applied Mathematics at Al-Ain University of Science & Technology. Dr. Fgaier holds a PhD and a Master's degree in Applied Mathematics from the University of Guelph, ON, Canada. Her research interests lie in the areas of dynamical systems, computer simulation, machine learning, parameter estimation, and optimal control with applications to biology and medicine. Dr. Fgaier envisions her research to be a blend of theoretical investigations, development of computational methods, and the building and analysis of mathematical models of nonlinear systems. She has published in peer review journals such as Journal of Theoretical Biology and Computers & Chemical Engineering. She has participated in national and international conferences and workshops.

Ali Elkamel is a Full Professor of Chemical Engineering. He is also cross appointed in Systems Design Engineering. He holds a BSc in Chemical Engineering and BSc in Mathematics from Colorado School of Mines, MSc in Chemical Engineering from the University of Colorado, and PhD in Chemical Engineering from Purdue University. His specific research interests are in computer-aided modeling, optimization, and simulation with applications to energy planning, sustainable operations, and product design. His activities include teaching graduate and undergraduate courses, supervising post doctorate and research associates, and participation in both university and professional societal activities. He is also engaged in initiating and leading academic and industrial teams, establishing international and regional research collaboration programs with industrial partners, national laboratories, and international research institutes. He supervised over 120 graduate students (of which 47 are PhDs) and more than 45 post-doctoral fellows/research associates. He has been funded for several research projects from government and industry. Among his accomplishments are the Research Excellence Award, the Excellence in Graduate Supervision Award, the Outstanding Faculty Award, and IEOM Awards. He has more than 425 journal articles, 175 proceedings, 50 book chapters, and has been an invited speaker on numerous occasions at academic institutions throughout the world. He is also a co-author of six books.