

**ANESTHESIOLOGIST AND NURSE ANESTHETIST (CRNA)
ASSIGNMENT ON THE DAY OF SURGERY**

A Thesis Presented

by

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ABSTRACT

Surgery department is one of the most expensive and most profitable resources in a hospital. The demand for surgeries has been increasing due to aging population and advances in medical technology. However, the number of nurses and anesthesia providers is not increasing at the same rate. The efficient management of operating rooms is of great importance to hospitals due to increasing demand and high staffing costs. Every day providers and managers face the task of assigning healthcare professionals to various patients seeking medical assistance in their hospitals. The assignment process is time-consuming and provides only suboptimal solutions due to difficulty of simultaneous consideration of staff requirements and patient needs. The overall goal of this study is to develop a fast, user-friendly, optimization-based decision support tool to solve anesthesia provider assignment problem.

We proposed two mixed integer programming (MIP) models to assign anesthesiologists and nurse anesthetists (CRNA) to operating rooms on the day of the surgery. The proposed models are developed based on the data that was gathered from carefully monitoring the physicians who were put in charge of daily assignment of anesthesiologists and CRNAs. The MIP models consider working hours, skill levels, surgery durations, difficulty of surgeries, and patient preferences while assigning anesthesia providers to operating rooms. The objective is providing a fair workload assignment among providers while satisfying the demand.

The proposed models are first tested using CPLEX. However, most people in healthcare settings do not know how to use CPLEX. Therefore, an Excel VBA based tool is developed where OpenSolver is used to solve the mixed integer programming models. The tool has a user-friendly interface, where required information related to providers and scheduled cases are entered. The assignments are displayed after the MIP models are solved in less than a minute. A numerical example is provided to show the difference between the manual assignment and the optimal assignments with respect to the number of operating rooms assigned per provider.

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CHAPTER 1: INTRODUCTION

1.1 Surgery departments

The number of surgeries has been increasing due to aging population and advances in medical technology (Cullen et al., 2009). The medical advances, which include improvements in anesthesia where patients become conscious more quickly and better analgesics used for pain relief, made surgery less complex and less risky (Cullen et al., 2009). The total number of outpatient surgeries has increased from 20.8 million in 1996 to 34.7 million in 2006 (Cullen et al., 2009). Outpatient surgeries accounted for nearly two thirds of all surgery visits in 2006.

Surgery departments are the most profitable (60% of the total revenue) and most expensive resources (40% of the total cost) in hospitals (Guerriero and Guido, 2011). The resources required to perform a surgery include personnel (surgeons, anesthesiologists, nurse anesthetists, nurses, etc.) and facilities (equipment, pre-operative care units, operating rooms, post anesthesia care units, and intensive care units) (Guerriero and Guido, 2011). There is need for effective management of surgery departments to ensure optimal utilization of medical resources, and improved patient flow without incurring additional costs or excessive patient waiting (Guerriero and Guido, 2011).

1.1.1 Surgery scheduling

Surgery scheduling is amongst the most important tasks that usually takes place on a daily basis. It can be defined as detailed planning of various patients and cases in a surgery department. Various decisions should be made during a surgery scheduling process; these decisions can vary from how to assign different cases to different operating rooms, the order of surgeries considering the start time, end time and duration of each case, and the reservation of specialized equipment (Guerriero and Guido, 2011). Such schedules should be flexible enough to adapt to situations such as uncertainties in surgery durations, cancellations and arrival of emergent surgeries.

1.1.2 Staffing and staff scheduling

Staffing is the process of deciding on the appropriate number of full-time employees to be hired in each skill level at each location, department, position, and shift to meet care needs of patients (Ozcan, 2009). Staff scheduling is to establish when each staff will be on or off duty and

on which shifts they will work while considering work regulations, ensuring night and weekend shifts are distributed fairly, and satisfying staff preferences (Ernst et. al., 2004 and Ozcan, 2009). In healthcare systems, optimized and effective staffing and staff scheduling plays a greater role in managing the costs and satisfying the demand of the patients. The reason behind that is the increasing number of surgeries due to aging population combined with the current shortage in various staff types that US healthcare is facing with, such as the shortage for registered nurses (Mobasher et. al., 2011) or anesthesia providers (Daugherty et. al., 2010). According to a RAND study, 54% of states are experiencing shortages of anesthesiologists and 60% of states a shortage of nurse anesthetists (CRNAs) (Daugherty et. al., 2010).

1.1.3 Staff assignment

Staff assignment problem can be defined as assigning different staff members to various tasks in their scheduled units, while considering their skill levels, availability, system's regulations along with their physical and psychological characteristics. In every surgery department, different types of personnel such as OR nurses or anesthesia providers are assigned every day. The nurse or physician in charge has to assign every staff member to different operating rooms based on the demand in those operating rooms while considering each staff specialty and working hours. The main focus of this thesis is anesthesia provider assignment. The task of assignment, if being done manually, can lead to suboptimal solutions as well as being very time consuming.

1.2 Anesthesia care team

The main focus of this thesis is the assignment of anesthesia providers to surgeries in operating rooms. The anesthesia care team includes physician anesthesiologists, anesthesiology resident physicians and nurse anesthetists. Each member of this team plays an essential role by working together to provide the best possible care for the patients. The physician anesthesiologist acts as the leader of the team, evaluating a patient's medical condition, recommending a plan for anesthesia, diagnosing and treating whatever problems that may occur during various procedures and following through with the patients' post-procedures (ASA, 2006). The physician anesthesiologist may at times entrust patient monitoring and appropriate tasks to anesthesiologist assistants and nurse anesthetists but still maintains the overall responsibility for the patient.

1.2.1 Anesthesiologists

The job of anesthesiologists requires many tasks. They are responsible for administering anesthetic or sedation during medical procedures. Also they have to communicate with other medical professionals to determine the best possible type and method of anesthetic or sedation to make their patients numb to pain. Their other tasks include coordinating the administration of anesthetics with surgeons during operations, determining whether or not patients have recovered enough to be moved to another location or to go home following outpatient surgery, examining patients, obtaining their medical history and using diagnostic test to determine the risks during medical procedures, and monitoring patients before, during, and after anesthesia (ASA, 2006).

1.2.2 Nurse anesthetists (CRNAs)

CRNAs are nurses who, through advanced practice, are qualified to safely provide anesthetics for surgical, obstetrical, and trauma care. CRNAs have responsibilities associated with their work which include conducting pre-anesthetic evaluations, administering anesthesia locally, generally or regionally, as well as intravenous sedation, monitoring their patients while they are under or recovering from anesthesia, and providing post-anesthesia care such as giving medicine or fluids and providing ventilator support when needed (AANA, 2010). CRNAs usually work under the supervision of physician anesthesiologists. But, in some U.S. states, CRNAs can work without physician supervision (AANA, 2010).

1.2.3 Anesthesiologist and CRNA workflow

Physician-nurse collaboration is well-known to improve job satisfaction and retention. Nurse anesthetists and anesthesiologists work together in many different settings and employment situations. Some settings involve individual, self-employed providers working together, while other settings have a more employer/employee nature. In an operating room, anesthesiologists typically present at the start and end of surgery. As stated above, their responsibilities include coordinating the administration of anesthetics with surgeons at the beginning of the surgery and determining whether or not patients have recovered enough to be moved to another location, or to go home at the end. They also check-in with the CRNA at least once every hour for checking the patient's conditions.

On the other hand, nurse anesthetists continuously monitor the patients while surgery is taking place to monitor patients' conditions. Figure 1 shows the workflow of anesthesiologist

and nurse anesthetist during a surgery. It should be noted that if the anesthesiologist works alone without nurse anesthetist support, then he/she will be present in the operating room throughout the surgery.

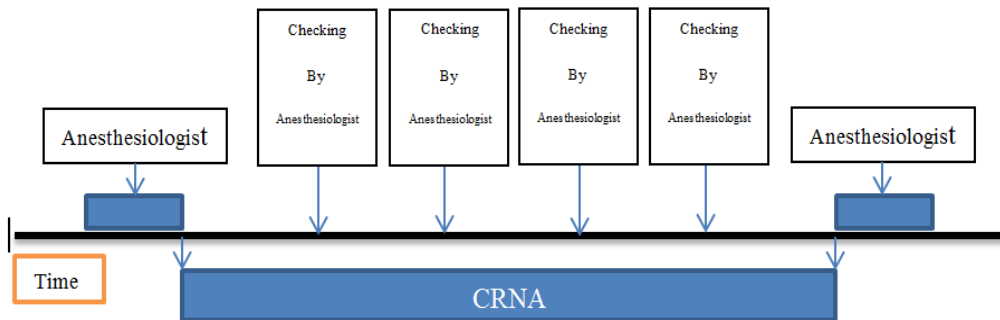


Figure 1: Anesthesiologist and nurse anesthetist workflow

1.2.4 Anesthesiologist and CRNA assignment

Anesthesiologists can be assigned to multiple operating rooms that have CRNA support in each, or to a single operating room to work alone without CRNA support. The aim of this study is to create a method to optimally assign anesthesiologists and nurse anesthetists to different operating rooms. These assignments must be done while considering different constraints related to skill levels, availability and other regulations. In order to do that, two mixed integer programming (MIP) models are proposed for both anesthesiologist and nurse anesthetist assignment problems.

1.3 Literature review

In this section, the relevant studies will be reviewed in three parts: i) studies on anesthesiologist staffing and assignment, ii) studies on nurse staffing and assignment, and iii) other relevant studies performed in the surgical settings. Tables 1 and 2 show the details of the studies on anesthesiologist staffing and assignment, and nurse staffing and assignment, respectively.

1.3.1 Studies on anesthesiologist staffing and assignment

Anesthesiologist staffing is one of the important component of operating room management. McIntosh et al. (2006) provided a tutorial to review the techniques of calculating the effect of

operating room management on anesthesiologists and generally the whole operating room labor productivity and efficiency. Dexter and Epstein (2006) proposed a method for operating room staffing (including anesthesiologists, surgeons and nurses). In order to do that, they statistically analyzed weekend and holiday data from a university hospital. The studies by Dexter and Epstein (1999) or Dexter and Rodney (2006) used statistical forecasting methods to estimate the number of anesthesiologists needed in a surgery room. Dexter et al. (2001) analyzed different anesthesia group staffing problems solved with statistical staffing methods. Based on their analysis such methods can propose proper solutions that cover all the cases.

There are a few studies that consider anesthesiologist assignment problem. Sugimoto and Kohno (2011) used a genetic algorithm to assign anesthesia providers efficiently. In their study they have monitored the work of anesthesia providers using electronic devices. Using such devices has enabled them to understand different stages of busyness and urgencies of an anesthetic's workflow. They have divided anesthesiologist's workflow to different parts. In their results, they have shown that their method has been useful in order to increase the anesthesiologists' efficiency by reducing the operation period time. Dexter et al. (1999) tried to assign anesthetics to late running operating rooms. They used a relief system, which relies on a statistical analysis of historical case durations. O'Sullivan and Dexter (2006) provided examples that highlight OR management and staff assignment decisions when regional anesthetic blocks (i.e. epidurals, nerve blocks) affect schedules on the day of surgery.

1.3.2 Studies on nurse staffing and assignment

The existing studies on anesthesia provider staffing and assignment problems do not use any optimization methods. However, there are several studies that use integer programming, constraint programming, stochastic programming, and simulation to solve nurse assignment and staffing problems in hospital settings. Mobasher et al. (2011) proposed a multi-objective integer programming model for the daily task of assigning nurses to different operating rooms. They have used two different methodologies for solving their models. One is based on the idea of a solution pool and the other one is a form of modified goal programming. 50% less overtime and idle time are observed after implementation of their model. Ozkarahan (1991) has used an analytical model for assignment of nurses, in which an integration procedure has been developed to deal with the case of unlimited staff size. Also a heuristic procedure was developed to assign

the start time of optimum work patterns for each day. An IT-prototype was developed to minimize the excess workload on nurses, which consequently resulted in an increase in the quality of patient care. Barnoon and Wolfe (1968) developed a computer simulation model to find the best way to assign anesthetists, nurses and operation rooms to each case. They showed that using such a method enhances the utilization of operation rooms by reducing the overall time being spent on each case.

Similarly in an attempt to efficiently assign nurses to patients in inpatient units, Punnakitikashem (2008) developed an optimization-based prototype to efficiently assign nurses to patients based on the patient's condition and the nurse's skill level. Another study by Punnakitikashem et.al. (2007) developed a two-stage stochastic integer programming model for the nurse assignment problem. They used a greedy algorithm to solve the recourse sub problems, which has a penalty function to minimize excess workload for nurses. They have solved the problem using a Benders' decomposition approach. Similar to Mobasher et al. (2011), Ferland et al. (2001) formulated the nurse assignment problem as generalized assignment type goal programming problem. They proposed several methods that include a short-term tabu search algorithm and diversification strategies. Schaus et al. (2009) investigated the assignment of nurses to the newborn babies with the objective is of developing an optimal schedule in which the workload of nurses is balanced. In their study, they presented a constraint programming (CP) model that can solve two-zone instances. They first assign nurses to each zone and then the babies to each nurse. The noticeable feature of their work is designing a system, which enable the user to assign a large number of nurses to different zones with huge amount of patients in few seconds. Gutjahr and Rauner (2007) tried to schedule nurses and assign them to different public hospitals by using ant colony approach. Their main objective was to minimize the cost of assigning nurses.

1.3.3 Other relevant studies in surgical settings

In this section, we are focusing on other studies related to operating rooms, post anesthesia units and other healthcare units staff scheduling, patient scheduling and staffing. Okada (1988) implemented a system for nurse scheduling on a personal computer, which uses Prolog. He conducted an experiment in which he has assigned eight skilled and eight unskilled nurses to patients in a certain nursing unit using the Prolog-based system. He then used the results of his

experiment, which shows an evenly distributed workload for all the nurses during the 7-month period as a proof of well functioning of this system. Jebalia et al. (2006) tried to assign surgical operations to operating rooms by the use of a mixed integer program model. Rosenbloom and Goertzen (1987) used integer linear programming to schedule nurses in different health care units more efficiently. Siferd and Benton (1994) used a simulation model to study the interaction between number of nurses needed, number of patients and also the mean rate and change of patient acuities in healthcare units. Cardoen et al. (2010) reviewed the literature for recent operational research on operating room planning and scheduling. Also Van den Bergh et al. (2013) reviewed the literature on personnel scheduling.

There are also some studies related to staffing. Dexter and Rittenmeyer (1997) presented a statistical method with a high level of reliability and accuracy in forecasting future patient numbers and related PACU staffing requirements. Lucas et al. (2001) used mathematical modeling methods to define optimum operating room staffing needs for a trauma center. Anderson and Talsma (2011) used network analysis methods to determine how the operating room staffing of two surgical specialties compares in terms of social network variables.

Table 1: Studies on anesthesiologist staffing and assignment

Study	Title	Aim of the study	Study setting	Modeling and solution method	Objectives	Constraints
O’Sullivan and Dexter (2006)	Assigning surgical cases with regional anesthetic blocks to anesthesiologists and operating rooms based on operating room efficiency	Show the impact of day-of-surgery decisions (i.e. rearranging OR schedules to place regional anesthetic blocks, meet surgeon requests, or move up incision times) on OR efficiency	USA		<ul style="list-style-type: none"> - Improve patient safety - Maximize OR efficiency - Reduce waiting times 	
Sugimoto and Kohno (2011)	Operation scheduling method by efficient anesthesiologist assignment using genetic algorithm	Schedule and assign operations to anesthesiologists according to three main phases of anesthesia (pretreatment, maintenance /observation, recovery)	Japan	<p>Wearable sensors are used to learn the behavioral patterns during anesthetic work.</p> <p>A genetic algorithm is proposed to schedule and assign operations to anesthesiologists.</p>	<ul style="list-style-type: none"> - Minimize the cost of work assignment, which is a combination of degree of overlapping urgency and busyness - Maximize work efficiency - Minimize the risk from parallel anesthesia 	<ul style="list-style-type: none"> - Pretreatment, maintenance and observation of anesthesia, and recovering procedure should not overlap

Dexter et. al. (1999)	A strategy for deciding operating room assignments for second-shift anesthetists	Develop a relief strategy to decide which late-running ORs should get a second-shift anesthetist	USA	A statistical method analyzing historical case durations is used to predict the expected remaining time of surgeries and to assign second-shift anesthetists to ORs with longer expected remaining time.	- Minimize anesthetist staffing costs	
Dexter and Epstein (2006)	Holiday and weekend operating room on-call staffing requirements	Determine operating room staffing (surgeons, nurses and anesthetists) requirements at weekends and holidays	University of Iowa Hospital and Clinics, USA	A statistical method analyzing weekend and holiday data is used.	- Start all cases without a delay on at least 95% of days	
Dexter and Traub (2000)	The lack of systematic month-to-month variation over one-year periods in ambulatory surgery caseload – application to anesthesia staffing	Estimate the number of anesthesia providers needed	USA	A statistical method analyzing month-to-month variation is used.	- Minimize labor costs during regularly scheduled hours, second-shifts, and weekends	

Dexter et al. (2006)	Staffing and case scheduling for anesthesia in geographically dispersed locations outside of operating rooms	Forecast the anesthesia staffing outside of operating rooms	University of Iowa Hospital and Clinics, USA	A statistical method analyzing billing data is used.	- Maximize the efficiency of use of anesthesia time	- Provide a service guarantee (i.e. care within 2 weeks) - Do not schedule a case in overutilized anesthesia time
Dexter et al. (2001)	A statistical analysis of weekday operating room anesthesia group staffing costs at nine independently managed surgical suites	Determine anesthesia staffing requirements during weekdays	University of Iowa Hospital and Clinics, USA	A statistical method analyzing case duration and staffing data on weekdays is used.	- Minimize staffing costs	
McIntosh et al. (2006)	The impact of service-specific staffing, case scheduling, turnovers, and first-case starts on anesthesia group and operating room productivity: A tutorial using data from an Australian hospital	Determine the impact of staffing, case scheduling, turnovers, and first case starts on anesthesia group and OR productivity	USA	A tutorial showing how to calculate the impact of OR management on anesthesia group and OR labor productivity is provided.	- Maximize OR efficiency	

Table 2: Studies on nurse staffing and assignment

Study	Title	Aim of the study	Study setting	Modeling and solution method	Objectives	Constraints
Mobasher et. al. (2011)	Daily scheduling of nurses in operating suites	Assign nurses to surgery cases based on their specialties and competency levels	Texas MD Anderson Cancer Center, USA	<p>A multi-objective integer programming model is proposed.</p> <p>A solution pool approach and a modified goal programming approach are proposed to find solutions.</p>	<ul style="list-style-type: none"> - Minimize demand deviation for any case - Maximize number of nonconsecutive breaks for any nurse - Maximize amount of overtime for any nurse - Maximize the number of room assignments to any nurse - Maximize the number of cases assigned to any nurse - Maximize the number of times an individual assignment to a case is broken due to shortages for any nurse 	<ul style="list-style-type: none"> - Shift restrictions - Nurse skill levels - Number of breaks in a shift - Overtime - Number of different cases assigned to a nurse - Number of job changes - Number of breaks over the day

Punnakitikashem et al. (2007)	An optimization-based prototype for nurse assignment	Develop an IT prototype to assign nurses to patients in a medical surgical unit	Baylor Regional Medical Center, TX, USA.	A mixed-integer programming model is proposed. An IT prototype with three main functions (shift and nurse information entry, data transfer, optimal assignment display) is developed.	- Minimize the excess workload on nurses	- Nurse assignment - Total workload (direct and indirect care) - Indirect care
Punnakitikashem et al. (2008)	Stochastic programming for nurse assignment	Assign nurses to patients in a medical surgical unit	Baylor Regional Medical Center, TX, USA.	A stochastic integer programming model is proposed. A Benders' decomposition approach is used to solve the main problem. A greedy algorithm is used to solve the recourse problem.	- Minimize the excess workload on nurses	- Nurse assignment - Indirect care
Schaus et al. (2009)	Scalable load balancing in nurse to patient assignment problems	Assign nurses to newborn infants in a hospital	USA	A constraint programming model is proposed.	- Balance the workload of the nurses	- Shift distribution balance among nurses - Fair allocation of individual schedules

Gutjahr and Rauner (2007)	An ACO algorithm for a dynamic regional nurse-scheduling problem in Austria	Schedule nurses and assign them to different public hospitals	Vienna Hospital, Austria	An ant colony optimization (ACO) approach is proposed.	<ul style="list-style-type: none"> - Minimize the cost of assigning nurses 	<ul style="list-style-type: none"> - Working patterns - Nurse qualifications - Nurse and hospital preferences - Costs
Ferland et al. (2001)	Generalized assignment type goal-programming problem: Application to nurse scheduling	Generate a schedule of working days and days-off for each nurse of a hospital unit	USA	<p>A generalized assignment type goal programming model is proposed.</p> <p>Tabu search heuristic is proposed.</p>	<ul style="list-style-type: none"> - Minimize the number of cases assigned to any nurse - Minimize the cost of assigning nurse 	<ul style="list-style-type: none"> - Assignment (every patient is assigned to a nurse) - Upper and lower bounds on the marginal workload variables
Barnoon and Wolfe (1968)	Scheduling a multiple operating room system: a simulation approach	Assign anesthetists, nurses and ORs to each case	USA	Simulation is used.	<ul style="list-style-type: none"> - Minimize idle time of anesthetists, nurses and ORs - Minimize surgeon waiting 	
Ozkarahan (1991)	Disaggregation model of a flexible nurse scheduling support system	Assign nurses	USA	A linear goal programming model is proposed.	<ul style="list-style-type: none"> - Minimize the cost of assigning nurses 	<ul style="list-style-type: none"> - Assignment (each nurse should be assigned to exactly one case, each case should get exactly one nurse)

1.4 Contributions of this study

Based on the existing studies, most of the studies that consider anesthesia providers rely on statistical methods to determine the staffing levels. No optimization model is proposed to solve anesthesiologist and nurse anesthetist assignment problems. Optimization models are proposed to solve nurse staffing, scheduling and assignment problems in several settings. However, none of these studies can be applied to anesthesia provider assignment problem due to specific characteristics of the problem where the workflow of anesthesia providers is different compared to classical nurse assignment models. This thesis study aims to develop optimization methods to solve the anesthesia provider assignment problem, and create a user-friendly spreadsheet-based tool.

In this study, we proposed mixed integer programming (MIP) models to assign anesthesiologists and CRNAs to operating rooms on the day of the surgery. To the best of our knowledge, this is the first study that uses optimization methods to solve the anesthesia provider assignment problem. The proposed models are developed based on the data that was gathered from carefully monitoring the physicians who were put in charge of daily assignment of anesthesiologists and CRNAs. The MIP models consider working hours, skill levels, surgery durations, difficulty of surgeries, and patient preferences while assigning anesthesia providers to operating rooms. The objective is providing a fair workload assignment among providers while satisfying the demand.

The proposed models are first tested using CPLEX. However, most people in healthcare settings do not know how to use CPLEX. Therefore, an Excel VBA based tool is developed where OpenSolver is used to solve the mixed integer programming models. The tool has a user-friendly interface, where required information related to providers and scheduled cases are entered. The assignments are displayed after the MIP models are solved in less than a minute. A numerical example is provided to show the difference between the manual assignment and the optimal assignments with respect to the number of operating rooms assigned per provider.

The rest of the thesis is structured as follows: The problem is defined and the proposed MIP models are presented in Chapter 2. The Excel VBA-based tool developed to solve the proposed MIP models using OpenSolver is explained in detail in Chapter 3. In Chapter 4, a numerical example is provided and computations are performed to show the impact of different parameters

on performance measures. In Chapter 5, the overall conclusion of this thesis along with some future research directions is provided.

CHAPTER 2: PROBLEM DEFINITION AND PROPOSED MODELS

2.1 Problem definition

In order to define the anesthesiologist and nurse anesthetist assignment problem, we observed the current practice at the Anesthesia Department of the Lahey Hospital and Medical Center (LHMC). In this section, we will explain the current process to define the constraints taken into account while assigning anesthesiologists and nurse anesthetists to operating rooms.

An anesthesiologist, who will be the floor runner for next day, performs the anesthesia provider assignment task the day before. The floor runner receives the floor runner’s worksheet that includes the names of all anesthesiologists and nurse anesthetists working in the department. A list of physicians, who are assigned to certain tasks or locations, have meetings on that day, away for the day, and requested by patients, is written on the floor runner’s worksheet (see Table 3).

Table 3: The list of anesthesiologists that should be written to the floor runner's worksheet

In-house (IH)	Unavailable
Next day floor runner (FR)	
1 st call	
2 nd call	
3 rd call	
Consult	Do not assign unless necessary
Pre-op (pre-operative testing center)	Do not assign unless necessary
Post IH	Unavailable
Post 1 st call	Assign to the ORs that finish early
Post 2 nd call	Assign to the ORs that finish early
Post 3 rd call	Assign to the ORs that finish early
Post weekend (WE) IH	Unavailable
Away	Unavailable
Lahey North	Unavailable
Requests	
Meeting	

The physicians who are “in-house”, “post IH”, “post WE IH”, “away”, and “Lahey North” are unavailable for the next day, and should not be assigned to any operating room. The physicians, who are assigned for consult and pre-op, work at other locations of the hospital, and should not be assigned unless it is absolutely necessary. The physicians who are post on-call

(post 1st call, post 2nd call, post 3rd call) might come to the hospital for emergency cases at night, and therefore, should be assigned to the operating rooms that finish early.

The floor runner marks the unavailable physicians, the physicians who will be at other locations of the hospital, and post on-call physicians on the floor runner’s worksheet. The floor runner also looks at the CRNA schedules in the computer and marks unavailable CRNAs on the worksheet. He/she writes the shift end times of available nurse anesthetists. The CRNAs work for 8-hour, 10-hour, or 12-hour shifts with shift end times of 3:30pm, 5:50pm and 7:30pm, respectively.

The floor runner receives another document that includes a list of anesthesiologists sorted according to the times they are scheduled to leave the hospital today. This list is used to generate an assignment where the physicians who work longer hours today are assigned to the operating rooms with shorter completion times the next day. The physicians who are at the end of the list are scheduled to leave early today and should be assigned to the operating rooms finishing late for a fair assignment among the physicians.

The anesthesiologist also receives the surgery schedule to determine the number of cases scheduled, the start time and completion time of the surgeries, and the specific skill sets required for the surgeries scheduled in each operating room. He prepares a list of operating rooms with scheduled completion times and number of cases scheduled. Table 4 shows the operating rooms’ worksheet prepared by the anesthesiologist. The operating rooms finishing late are candidates for physicians who will be going home late that day and nurses who work 10-12 hour shifts. Sometimes an anesthesiologist, scheduled to stay late today, may be scheduled to a late room or rooms tomorrow, if that anesthesiologist is on-call tomorrow.

Table 4: Operating rooms' worksheet

OR / other areas no.	Completion time	Number of cases scheduled
1	15:40	4
2	17:30	4
4	16:35	3
5	15:20	2
6	14:45	1
7	15:10	3
8	17:10	3
9	13:35	1

10	15:45	1
11	11:35	1
12	14:20	2
15	16:45	2
16	14:50	2
17	17:05	3
18	14:25	1
19	14:35	4
20	18:10	4
21	16:40	3
22	16:10	3
23	17:15	2
26 (LI - Lithotripsy)	S:12:00 14:30	2
27 (PULM - Pulmonary)	10:00	1
28 (MRI/CATLAB/INR/IR – Magnetic resonance imaging, catheterization lab, interventional neuroradiology, interventional radiology)	12:00	1
29 (GI - Gastrointestinal endoscopy) - 2 rooms		
30 (EP lab – Electrophysiology)		

After all the necessary information is collected and analyzed, the manual assignment is performed as follows: i) residents and attending physicians are assigned to the operating rooms that have cases suitable for the residents' education; ii) the physicians who can do cardiac are assigned to the operating rooms with cardiac cases; iii) the physicians who have been requested by specific patients are assigned to the operating rooms in which those patients are scheduled; iv) CRNAs who work for 10- or 12-hour shifts are assigned to the operating rooms with late completion times; and v) the rest of CRNAs and physicians are assigned to the remaining operating rooms while taking into account several criteria. For example, a physician can be assigned to a single OR to work alone or to multiple ORs (2-4) to work with CRNAs. Fast track room should have an anesthesiologist and a CRNA. Two CRNAs should be assigned to the two GI rooms. If a physician is assigned to multiple operating rooms, there should be a resident or a CRNA in each room. Multiple operating rooms with difficult cases (i.e. two operating rooms with nerve blocks) should not be assigned to the same physician in order to have a more

balanced workload among physicians. If a resident or a CRNA cannot be assigned to an operating room, then the physician should work alone and the operating rooms with single case are more suitable for those physicians.

Table 5 shows a sample assignment created by the floor runner during our observation (the names of the providers are changed to protect privacy). The table includes the operating room number, number of cases scheduled, scheduled completion times, and names of anesthesiologists, residents, and nurse anesthetists assigned to each OR. The final assignment depicted in Table 5 is created by putting into consideration various factors and requirements: i) patient requests for specific physicians are satisfied (e.g. Dr. Landrovski is assigned to OR7 because the patient in that room requested him); ii) physicians qualified to handle cardiac cases are assigned to the operating rooms with cardiac cases (e.g. OR23 has cardiac cases and Dr. Sabel can perform cardiac cases); iii) CRNAs who work for 10- or 12-hour shifts are assigned to the operating rooms with latest completion times (e.g. Araujo (12-hour), Rabas (12-hour), Earbyn (10-hour), Haaker (10-hour), and Sainz (10-hour) are assigned to operating rooms with completion times of 18:10, 17:30, 17:10, 17:05, and 16:45, respectively); iv) two CRNAs are assigned to GI rooms; v) CRNAs are not assigned to operating rooms with residents in them (e.g. OR6, OR10, OR18, and OR23 have residents and no CRNAs); vi) 1-2 operating rooms are assigned to each physician; vii) CRNAs are assigned to operating rooms with physicians who cover multiple operating rooms.

Table 5: Final assignment (manual assignment by the anesthesiologist)

OR number	Number of cases scheduled	Scheduled completion time	Anesthesiologist	Resident	CRNA
1	4	15:40	Lian		Bauck
2	4	17:30	Allen		Rabas (12-hr)
4	3	16:35	Lian		Salem
5	2	15:20	Louis		Saler
6	1	14:45	Cox	Alhakim	
7 (patient request)	3	15:10	Landrovski (requested)		
8	3	17:10	Louis		Earbyn (10-hr)
9	1	13:35	Cooper		

10	1	15:45	Gray	Maral	
11	1	11:35	Kimber		
12	2	14:20	Bonnet		Baude
15	2	16:45	Racey		Sainz (10-hr)
16	2	14:50	Tabak		Baust
17	3	17:05	Racey		Haaker (10-hr)
18	1	14:25	Oachs	Mccain	
19	4	14:35	Rach		Laff
20	4	18:10	Allen		Abas (12-hr)
21	1	16:40	Waber		Maca
22	3	16:10	Waber		Lading
23 (cardiac)	2	17:15	Sabel	Maftu	
26 (LI)	2	S: 12:00 14:30	Garcia		Lacko
27 (PULM)	1	10:00	Flores		
28 (MRI/CATL AB/ INR/IN)	1	12:00	Garcia		Lacko
29 (GI x 2)			Carpenter		Sagon Saba

2.2 Mixed integer programming models

The manual assignment takes 20-30 minutes every day and might be suboptimal due to sequential nature of the process. In order to reduce the time required to perform the assignment and consider multiple criteria simultaneously, we proposed two mixed integer programming (MIP) models that solve anesthesiologist and nurse anesthetist assignment problems. To prevent any interference between constraints of these models and also to make sure that models are capable of producing efficient assignments, the MIP models have been tested and verified using ILOG CPLEX software. Table 6 shows the notation used in the proposed models.

Table 6: Notation including sets, parameters and decision variables

Sets	
I	Set of available physicians
R	Set of available nurses
I_H	Set of physicians who can do cardiology (heart) cases
O	Set of available operating rooms

O_H	Set of operating rooms with cardiology (heart) cases
O_d	Set of operating rooms with difficult cases
$O_{\text{zero-case}}$	Set of operating rooms with no scheduled case in them
O_{GI}	Set of available GIs
O_{tenhrs}	Set of ORs with operations ending around 17:00
$O_{\text{twelvehrs}}$	Set of ORs with operations ending between 17:00 and 19:00
O_{support}	Set of ORs which need CRNA support ($\sum_i x_{ij}=1$ and there is no resident in them)
O_{resident}	Set of ORs with a resident assigned to them
S_1	Set of unavailable physicians (including in-house, post IH, post WE IH, away, Lahey North)
S_2	Set of physicians who are at other locations of the hospital and are not assigned to ORs unless it is necessary (including consult, pre-op)
S_3	Set of post on-call physicians (including post 1 st call, post 2 nd call, post 3 rd call) who will be assigned last
S_{ten}	Set of nurses who work for 10 hours
S_{twelve}	Set of nurses who work for 12 hours

Parameters

N	Number of available nurses
M	Number of operating rooms that cannot be covered by the available number of CRNAs. The physicians who are assigned to these M operating rooms should not be assigned to more than one OR, because they have to work alone.
T_j^s	Start time of surgeries in OR j
T_j^e	End time of surgeries in OR j
D_j	Total scheduled duration of surgeries in operating room j
K_j	Number of cases scheduled in operating room j
h_i	Total working hour of physician i the day before
b_{ij}	$\begin{cases} 1 & \text{If physician } i \text{ is requested by a patient in OR } j \\ 0 & \text{If physician } i \text{ is not requested by a patient in OR } j \end{cases}$
u_j	Measure of unpopularity of assigning physicians or nurses to OR j , can be equal to number of cases in each OR
a_j	Coefficient of each OR's workload, can be equal to the total duration of surgeries (from the start time to end time).
w_1, w_2, w_3, w_4	Weights of objective functions

Decision Variables

x_{ij}	$\begin{cases} 1 & \text{If physician } i \text{ is assigned to operating room } j \\ 0 & \text{If physician } i \text{ is not assigned to operating room } j \end{cases}$
y_{ij}	$\begin{cases} 1 & \text{If physician } i \text{ (who can be assigned to only one room) is assigned to OR } j \\ 0 & \text{If physician } i \text{ (who can be assigned to only one room) is not assigned to OR } j \end{cases}$
z_{ij}	$\begin{cases} 1 & \text{If nurse } i \text{ is assigned to OR } j \\ 0 & \text{If nurse } i \text{ is not assigned to OR } j \end{cases}$
U_i	$\sum_j a_j \times u_j \times x_{ij}$
U^{max}, U^{min}	U_i with the maximum and minimum value

2.2.1 Anesthesiologist assignment

The first MIP model (MIP1) is proposed to assign anesthesiologists to operating rooms. The model considers anesthesiologists' availability, difficulty of surgeries, patient preferences, surgery types and specialty of anesthesiologists while assigning anesthesia providers to operating rooms with the objective of providing a fair workload assignment among providers while meeting the demand. In this model, an anesthesiologist can be assigned to multiple operating rooms and work with residents or CRNAs. However, the number of available residents and CRNAs might not be enough to cover all the operating rooms. In that case, the anesthesiologist has to work alone. The proposed MIP model uses two decision variables to differentiate the operating rooms with and without resident/CRNA. Since the operating rooms without resident/CRNA are not known in advance, the decision variables x_{ij} and y_{ij} are defined for all operating rooms. x_{ij} is used for the operating rooms that can get a CRNA or resident, and y_{ij} is used for the operating rooms without any CRNA or resident support.

Objective function:

$$\begin{aligned} \text{Min} = & w_1 \sum_i \sum_{j \in S_2} x_{ij} + w_2 \sum_i \sum_{j \in S_3} x_{ij} + \sum_i \sum_j x_{ij} * D_j * h_i \\ & + w_3 \sum_i \sum_{j \in S_2} y_{ij} + w_4 \sum_i \sum_{j \in S_3} y_{ij} + \sum_i \sum_j y_{ij} * D_j * h_i + \sum_i \sum_j y_{ij} * K_j \\ & + U^{max} - U^{min} \end{aligned}$$

The first term of the objective function minimizes the possibility of assigning physicians who are in set S_2 (physicians scheduled to work in other parts of the hospital including consult and pre-op). Similarly, the second term minimizes the possibility of assigning physicians in set S_3 (post on-call physicians). The third term tries to balance the workload between days for each physician. That means, the physicians who are scheduled to work for longer hours the day before

are assigned to operating rooms with earlier completion times. The 4th, 5th, and 6th terms, which are similar to the 1st, 2nd and 3rd terms, are necessary for the operating rooms that cannot get a CRNA or resident. The seventh term of the objective function tries to assign the physicians with no CRNA or resident to the operating rooms with less number of cases in them. The last term minimizes the workload difference between the anesthesiologists with maximum workload and minimum workload, to find a balanced workload among anesthesiologists.

Constraints:

$$\sum_{i \in S_1} x_{ij} = 0, \quad \forall j \quad (1)$$

$$\sum_i x_{ij} = 0, \quad \forall j \in O_{zero-case} \quad (2)$$

$$\sum_i x_{ij} \leq 1, \quad \forall j \in O'_{zero-case} \quad (3)$$

$$\sum_{i \in S_1} y_{ij} = 0, \quad \forall j \quad (4)$$

$$\sum_i y_{ij} = 0, \quad \forall j \in O_{zero-case} \quad (5)$$

$$\sum_i y_{ij} \leq 1, \quad \forall j \in O'_{zero-case} \quad (6)$$

$$\sum_{i \in I'_H} \sum_{j \in O_H} x_{ij} = 0, \quad (7)$$

$$\sum_{i \in I'_H} \sum_{j \in O_H} y_{ij} = 0, \quad (8)$$

$$x_{ij} \geq b_{ij}, \quad \forall i, \forall j \quad (9)$$

$$x_{ig} + x_{ih} \leq 1, \quad \forall g, h \in O_d \quad (10)$$

$$\sum_j x_{ij} \leq 4, \quad \forall i \quad (11)$$

$$\sum_j y_{ij} = 1, \quad \forall i \quad (12)$$

$$\sum_i \sum_{j \in O'_{resident} \& j \in O'_{Gl}} y_{ij} = M, \quad (13)$$

$$x_{ij} + \sum_j y_{ij} \leq 1, \quad \forall i, \forall j \quad (14)$$

$$\sum_i x_{ij} + \sum_i y_{ij} = 1, \quad \forall j \in O'_{zero-case} \quad (15)$$

$$\sum_j a_j \times u_j \times x_{ij} - U^{max} \leq 0, \quad \forall i \quad (16)$$

$$\sum_j a_j \times u_j \times x_{ij} - U^{min} \geq 0, \quad \forall i \quad (17)$$

$$x_{ij}, y_{ij} \text{ binary} \quad \forall i, \forall j \quad (18)$$

According to constraints (1) and (2), the unavailable physicians are not assigned to any operating room, and the operating rooms without cases do not get any physician assigned to them, respectively. At most one physician can be assigned to the operating rooms with at least one case, which is satisfied by constraint (3). Constraints (4), (5), and (6) are similar to the constraints (1), (2), and (3), respectively, but for the decision variable y_{ij} that is required for the operating rooms with no CRNA or resident assigned to them. Constraints (7) and (8) make sure that only the physicians with cardiology skills are assigned to the operating rooms with cardiac cases. Constraint (9) ensures that physicians get assigned to operating rooms with patients who requested them. In constraint (10), the physicians are assigned to at most one operating room with a difficult case. Physicians should not be assigned to more than four operating rooms, which is satisfied by constraint (11). Constraint (12) makes sure that physicians who do not have CRNA or resident support are assigned to only one operating room. The total number of the physicians without CRNA or resident support should be equal to M (M is the number of operating rooms that cannot be covered by CRNAs and residents), which is satisfied by constraint (13). If decision variable y_{ij} is 1 then decision variable x_{ij} should be 0, which is satisfied by constraint (14). Constraint (15) ensures that every operating room with at least one case gets one physician. Constraints (16) and (17) calculate the maximum and minimum workload for the physicians, respectively. Constraint (18) is the integrality constraint for the decision variables.

2.2.2 CRNA assignment

The second MIP model (MIP2) is proposed to assign CRNAs to operating rooms. This model takes into consideration the availabilities of nurses and their working hours. The objective is to minimize the possibility of assigning nurses who have shorter working hours to operating rooms with longer durations. The overall aim is to minimize the number of nurses required in each operating room. For example, if the total scheduled duration in one operating room is 10 hours and a nurse with 8-hour shift is assigned to that operating room, then two nurses are required for that room. However, if a nurse with 10-hour shift is assigned to that room, then only one nurse is required. The proposed model also takes into account other restrictions due to limited number of CRNAs and availability of residents. CRNAs are not assigned to the operating

rooms with residents working in them. CRNAs are assigned to the operating rooms whose physicians cover more than one operating room.

Objective function:

$$\text{Min} = \sum_{i \in S'_{ten}} \sum_{j \in O_{tenhrs}} z_{ij} + \sum_{i \in S'_{twelve}} \sum_{j \in O_{twelvehrs}} z_{ij}$$

The first term of the objective function minimizes the possibility of assigning nurses who are not supposed to work for 10 hours to operating rooms with duration of 10 hours or more. Similarly the second term minimizes the possibility of assigning nurses who are not supposed to work for 12 hours to operating rooms with duration of 12 hours or more.

Constraints:

$$z_{im} + z_{in} \leq 1, \quad \text{if } T_n^s < T_m^s < T_n^e \text{ or } T_m^s < T_n^s < T_m^e \quad (1)$$

$$\sum_{j \in O_{resident}} z_{ij} = 0, \quad \forall i \in R \quad (2)$$

$$\sum_{j \in O_{support} \& j \in O'_{resident}} z_{ij} \geq 1 \quad \forall i \in R \quad (3)$$

$$\sum_{j \in O_{GI}} z_{ij} = 2, \quad \forall i \in R \quad (4)$$

$$\sum_{j \in O_{GI'}} z_{ij} \leq 1, \quad \forall i \in R \quad (5)$$

$$\sum_{j \in K_j=0} z_{ij} = 0, \quad \forall i \in R \quad (6)$$

$$z_{ij} \text{ binary} \quad \forall i, \forall j \quad (7)$$

Constraint (1) makes sure that a nurse is not assigned to two rooms that have overlapping surgery times. If a resident is assigned to a room then there is no need to assign a nurse to that room, which is satisfied by constraint (2). Constraint (3) ensures that a nurse is assigned to operating rooms which need the CRNA support. Constraints (4) and (5) make sure that GI gets two nurses and other ORs get at most one nurse, respectively. According to constraint (6), no nurse is assigned to ORs with zero scheduled case in them. Constraint (7) is the integrality constraint for the decision variable z_{ij} .

2.2.3 Interaction between the two MIP models

The proposed MIP models do not work independently, which means that they use the results of each other as input. For example, if there is a shortage in the number of nurses during their

assignment, some anesthesiologists who will work only in one room will be assigned to the operating rooms that no nurse has been assigned to. In order to satisfy this requirement the decision variable y_{ij} (anesthesiologists who will only work in one room) is created. The total number of anesthesiologists who will be assigned with this decision variable is equal to M (the shortage amount for nurses). In order to solve the anesthesiologist assignment model, one must first calculate the shortage amount for nurses by subtracting the number of operating rooms with at least one case in them from the number of nurses who are currently available. Also, when solving the nurse anesthetist assignment models, CRNAs should first be assigned to rooms in which there are physicians who are working in multiple operating rooms. In order to satisfy this requirement O_{support} (set of ORs that need The CRNA support.) is introduced into the model. This means that when one wants to solve the CRNA assignment model, they must first look at the anesthesiologist assignments and create the set of the operating rooms with the same physician assigned to them. Figure 2 shows the flowchart of the algorithm required to solve both MIP models.

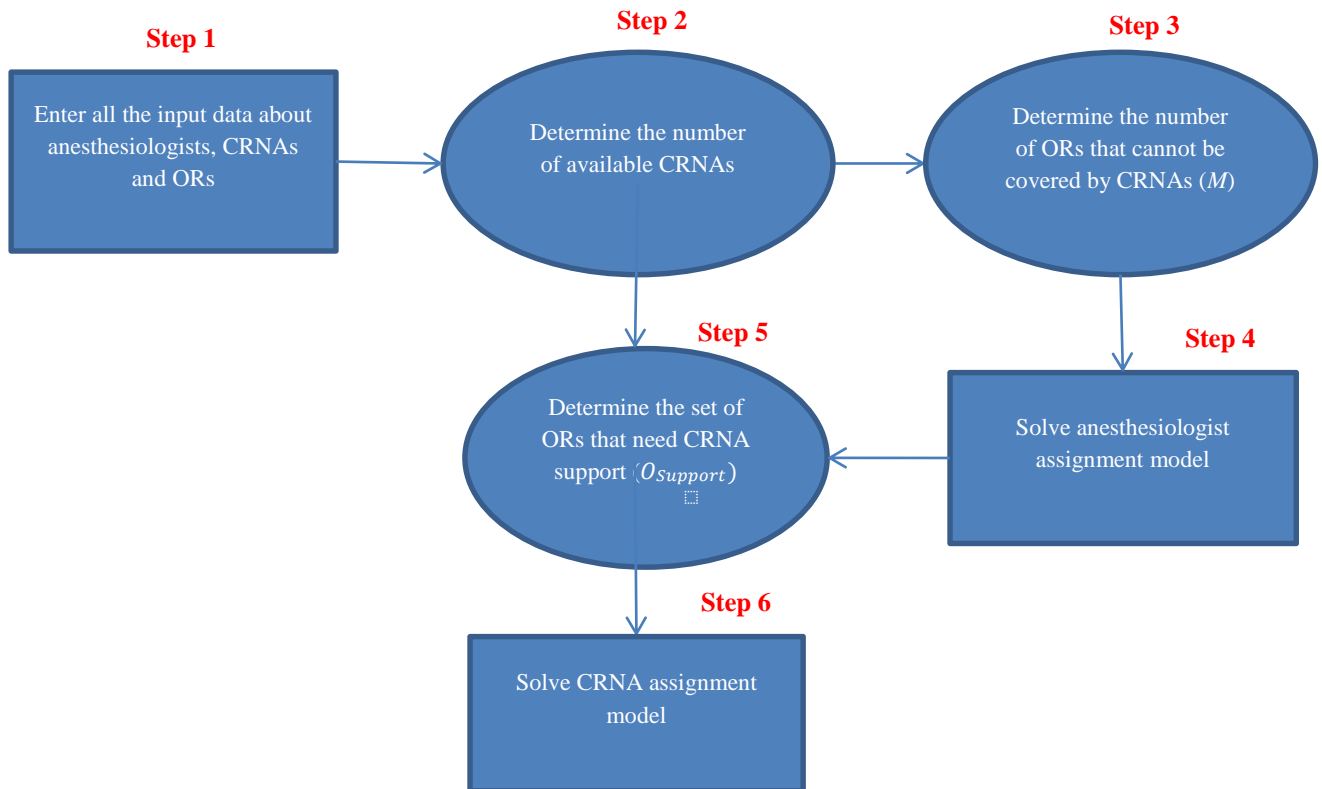


Figure 2: Algorithm to solve anesthesiologist and CRNA assignment models

CHAPTER 3: EXCEL-VBA BASED TOOL TO SOLVE THE PROPOSED MODELS WITH OPENSOLVER

In order to develop a user-friendly tool to solve the proposed MIP models in a real clinic environment, an Excel VBA-based optimization tool is developed where OpenSolver is used to solve the MIP models. The tool has a user-friendly interface, where required information related to anesthesia providers and scheduled cases are entered. Macros are used to read the input data, write the MIP model, and solve the model using OpenSolver. The output with anesthesia provider assignments is displayed after the MIP models are solved.

3.1 Input data

The input data for the models should be entered through three different Excel sheets: i) PhysicianInput, ii) NurseInput, and iii) OperatingRoomsInput.

PhysicianInput Worksheet:

Figures 3-4 show the screenshots of DoctorInput worksheet. This worksheet contains all of the information about physicians (anesthesiologists) including their IDs, names, and specialties (hearts, liver, kidney live donor, neuro, consult, preop). The information in blue area should be entered only when there is a change in the list of available physicians. For example, when a new physician joins the department, he/she can be added to this list. In the same worksheet, the user is also asked to enter the information that changes every day, which includes the task assignments for the physicians (e.g. in-house, post IH, Lahey North, etc.). This information (in orange area) is the same information that should be written in the floor runner's worksheet during the manual assignment. After putting in all this information, the user is supposed to click on the button "Update physician's database" so that the physician database can be updated.

Doctor_ID	Name	Consult (C)? 1:Yes 0:No	Hearts (H)? 1:Yes 0:No	Kidney Live Donor (K)? 1:Yes 0:No	Livers (L)? 1:Yes 0:No	Neuro (N)? 1:Yes 0:No	Pre-op (P)? 1:Yes 0:No	Number of working hours the day before	Notes	Available ? 1: yes, 0: No
1	Allen	0	0	0	0	0	0	10		
2	Baley	0	1	0	0	1	0	10		
3	Bell	0	0	1	0	0	0	10		
4	Barnes	0	1	0	1	0	1	10		
5	Bonnet	0	1	0	1	0	0	10		
6	Carpenter	0	1	0	0	0	1	10		
7	Cooper	0	0	0	0	0	0	10		
8	Cox	0	0	0	0	0	1	10		
9	Cook	0	1	0	1	0	0	10		
10	Delgado	1	0	0	0	1	0	10		
11	Flores	1	0	0	0	1	1	10		
12	Garcia	0	0	0	0	0	0	10		
13	Gray	0	0	0	0	0	0	10		
14	Hernandez	1	1	0	1	0	0	5		
15	Jordan	0	0	0	0	0	0	5		
16	Karim	0	1	0	0	1	0	5		
17	Keith	0	1	0	1	0	0	5		
18	Kimber	0	0	0	0	1	0	5		
19	Landrovski	0	0	1	0	0	0	5		
20	Lee	0	0	0	0	0	0	5		
21	Lian	0	0	0	0	0	0	5		
22	Luis	0	0	0	0	0	0	5		

1. This Excel VBA based tool is developed to solve the anesthesiologist and nurse anesthetist (CRNA) problem on the day of the surgery. The mixed integer programming (MIP) models are solved using OpenSolver, which is an Excel add-in (<http://opensolver.org/>).

2. The user should enter all the information related to the anesthesiologists including their IDs, initials, names, and specialties in the blue area.

For the specialties, the user should enter 0 or 1, where 1 denotes that the anesthesiologist is specialized in those types of surgeries or tasks (hearts, kidney live donor, livers, neuro, consult, preop).

3. The user should enter the number of working hours for the anesthesiologist the day before. This is necessary to provide a fair workload among provider.

Figure 3: Screenshot of PhysicianInput worksheet(1)

In-house	Keith				
Next day FR	Rach				
1 st call	Sabel				
2 nd call	Landeovski				
3 rd call	Cox				
Consult	Oakden				
Preop	Barnes				
Post IH	Wachel				
Post 1 st call	Bonnet				
Post 2 nd call	Waber				
Post 3 rd call	Luis				
Post WE IH	Cook				
Away	Delgado	Hernandez	Jordana	Karim	Saki
Lahey North	Lee	Baley			
Meeting					

4. The user should enter the names of the anesthesiologists assigned for certain tasks for the following day in the orange area. These assignments change every day and they put certain restrictions on the assignment problem.

- Anesthesiologists who are unavailable: In-house, post IH, post WE IH, Away, Lahey North
- Anesthesiologists who work in other parts of the hospital (preop, consult)
- Anesthesiologists who might be called for emergency cases the night before (post 1st call, post 2nd call, post 3rd call)

5. If an anesthesiologist is requested by a patient, then the doctor ID and the OR number of the patient's surgery should be entered in the orange area.

Update doctors' database

6. The user should press this button to update the anesthesiologists' database. The availability of the anesthesiologists will be displayed as the output in the green area (Available? 1: Yes, 0: No)

After that, the user should click on the "NurseInput" worksheet to enter CRNA data.

Requests	Doctor ID	OR ID
	7	21

Figure 4: Screenshot of PhysicianInput worksheet (2)

NurseInput Worksheet:

Figure 5 shows the screenshot of NurseInput worksheet. It includes all the information related to nurses (CRNAs) including nurse IDs, names, initials and their availability on different days of the week. The user should also enter information about the nurses’ working hours. After putting in all these information, the user is supposed to click on the button “Update nurse’s database” to update the nurses’ database.

NurseID	Name	Endoscopy on Mondays? 1:Yes 0:No	Endoscopy on Tuesdays? 1:Yes 0:No	Endoscopy on Wednesdays? 1:Yes 0:No	Endoscopy on Thursdays? 1:Yes 0:No	Endoscopy on Fridays? 1:Yes 0:No	10-hour shift? 1:Yes 0:No	12-hour shift? 1:Yes 0:No	Specialty with Kidney? 1:Yes 0:No	Available today? 1:Yes 0:No
1	Abas	0	0	0	1	0	0	1	1	1
2	Bauck	1	0	0	0	0	0	0	0	1
3	Baude	1	0	0	0	0	0	0	1	0
4	Baust	1	0	0	0	0	0	0	0	1
5	Earby	0	0	0	1	0	1	0	0	1
6	Haaker	0	1	0	0	0	1	0	0	1
7	Hadler	0	0	1	0	0	0	0	0	1
8	Hazy	0	0	0	0	0	0	0	0	1
9	Jacard	0	0	0	0	0	0	0	0	1
10	Labarba	0	0	0	0	1	1	0	0	1
11	Lacko	0	0	0	1	0	0	0	0	1
12	Lading	0	0	0	0	0	0	0	0	1
13	Laff	0	0	0	0	1	0	0	1	1
14	Lagor	0	0	1	0	0	1	0	0	0
15	Mabasa	0	0	0	0	1	0	0	0	1
16	Maca	0	0	0	0	0	0	0	0	1
17	Macatee	0	0	0	0	0	1	0	0	0
18	Noor	0	1	0	1	0	0	0	0	1
19	Oar	0	0	0	1	0	0	0	1	1
20	Ocha	0	0	0	1	0	0	0	1	1

1. The user should enter all the information related to nurse anesthetists (CRNAs) including their IDs, initials, names, and whether they are in endoscopy on a given day (1: Yes, 0: No).

2. The user should enter whether the nurse will work 10-hour or 12-hour shift, and whether she will be available or not.

3. The user should click on this button to update the nurse database. Total number of available nurses for that day are displayed in the green cell.

The user should go to "OperationRoomsInput" worksheet to enter the OR data.

Update nurses' database

Number of available nurses 15

Figure 5: Screenshot of NurseInput worksheet

OperatingRoomInput Worksheet:

Figure 6 shows the third worksheet in which the user is required to enter all the necessary information about scheduled cases in each operating room. This information includes the operating room’s start time, end time, duration of surgeries, and number of cases scheduled in each operating room. The user is also supposed to enter the information for the following questions i) is there a cardiac case in the OR, ii) are the surgeries in this OR complicated, iii) is the physician assigned to this OR also assigned to any other OR, and iv) is there a resident assigned to this room. After the user finishes entering all the information related to each operating room then they should push the button “update the operating rooms' database”. By

pushing this button the database for operating rooms will be updated based on the information entered by the user.

ORID	ORName	Number of cases scheduled	Surgery start time in the OR	Total surgery duration in the OR	Surgery end time in the OR	Is there a cardiac case in this OR? 1:Yes	Are the surgeries in this OR complicated? 1:Yes	Is the doctor assigned to this room, also assigned to any other	Is there a resident assigned to this room?
1	1	4	7:00	8:00:00	15:00	0	0	1	0
2	2	4	7:00	10:30:00	17:30	0	0	0	0
3	3	0	0:00	0:00:00	0:00	0	0	0	0
4	4	3	7:00	9:30:00	16:30	0	0	1	0
5	5	2	7:00	8:20:00	15:20	0	0	1	0
6	6	1	7:00	7:45:00	14:45	0	0	0	1
7	7	3	7:00	8:20:00	15:20	0	0	0	0
8	8	3	7:00	10:20:00	17:20	0	0	1	0
9	9	1	7:00	6:30:24	13:30	0	0	0	0
10	10	1	7:00	8:45:24	15:45	0	0	0	1
11	11	1	7:00	4:30:24	11:30	1	0	0	0
12	12	2	7:00	7:20:00	14:20	0	0	0	0
13	13	0	0:00	0:00:00	0:00	0	0	0	0
14	14	0	0:00	0:00:00	0:00	0	0	0	0
15	15	2	7:00	9:45:00	16:45	0	0	1	0
16	16	2	7:00	7:50:00	14:50	0	0	0	0
17	17	3	7:00	10:10:00	17:10	0	0	1	0
18	18	1	7:00	7:25:00	14:25	0	0	0	1
19	19	4	7:00	7:30:00	14:30	0	0	0	0
20	20	4	7:00	11:20:00	18:20	0	0	0	0

1. The user should enter OR IDs and name in the blue area.

2. The user should enter the OR data based on daily schedule.

OR data: The number of cases scheduled, surgery start time, surgery end time, OR with cardiac cases, OR with complicated cases, OR with anesthesiologists who cover more than one OR, OR with resident.

Figure 6: Screenshot of OperatingRoomInput worksheet

3.2 Macros

The proposed models can be solved using a solver in Excel. OpenSolver is an open source Excel plug-in similar to Excel Solver. Excel Solver cannot be used to solve the proposed models due to the restrictions on the size of the problems. OpenSolver does not have any restriction on number of variables, which makes it suitable to solve the proposed models. The installation of the OpenSolver program is explained on the following website: <http://opensolver.org/installing-opensolver/>.

In order to minimize the work the user does manually, Excel VBA is used to generate macros. The first three macros, which are in the input worksheets, are used to read the input data about anesthesiologists, CRNAs and operating rooms. The last two macros, which are in the OperatingRoomInput worksheet, are used write the optimization models and solve the models using OpenSolver.

3.3 Output

The worksheet OperatingRoomInput is also the place that user will see the assignments for both anesthesiologists and nurse anesthetists after pressing the relevant buttons. The anesthesiologists and CRNAs assigned to each OR are displayed after the optimization models are solved. Figure 7 shows a sample output that shows the assignments.

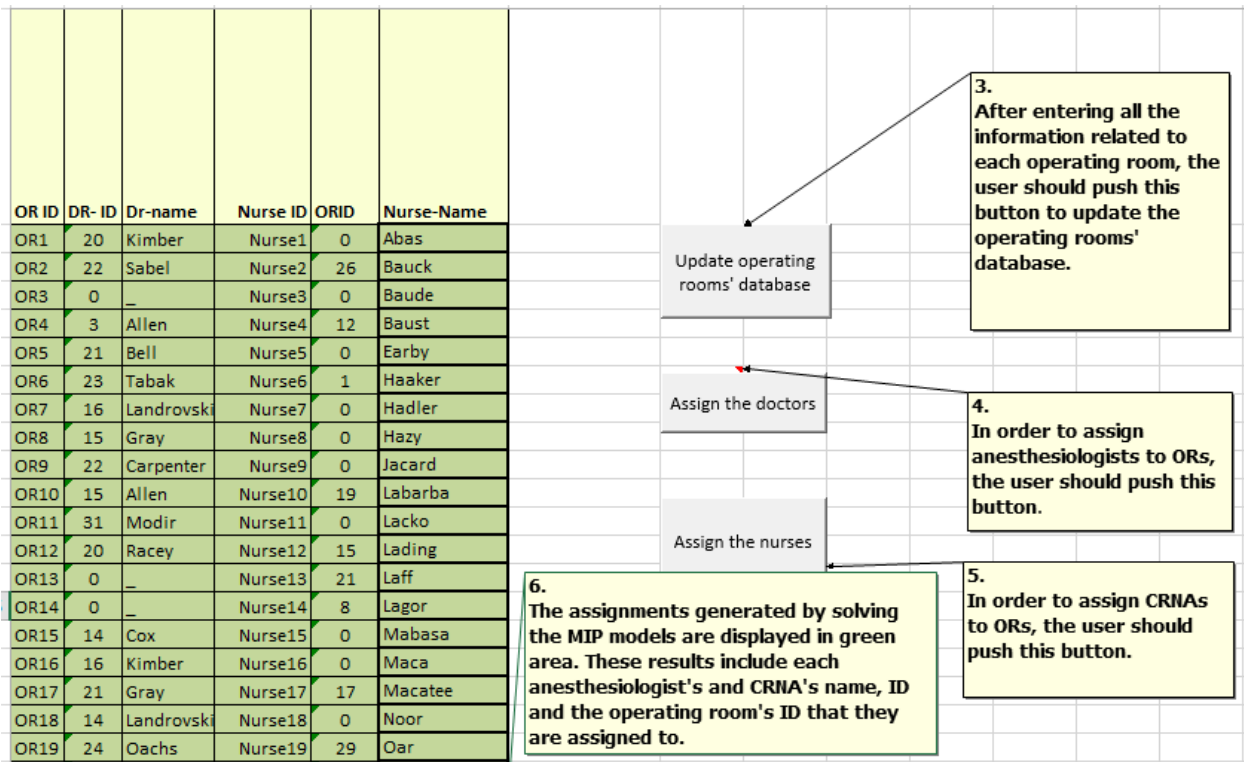


Figure 7: Screenshot of the output in OperatingRoomInput worksheet

CHAPTER 4: CASE STUDY

In this chapter, the proposed MIP models will be used to solve the anesthesia provider assignment problem using sample data from LHMC. The optimal solutions with different objective weight alternatives will be compared with the actual assignment created manually by the anesthesia floor runner.

4.1 Numerical example

The anesthesia department at LHMC has 34 anesthesiologists and 30 CRNAs. The number of ORs and outside areas (including LI, PULM, MRI/CATLAB/INR/IR, GI, and EP) that should be covered by anesthesia providers is equal to 28. The information about anesthesiologists (names, specialties, and availability) can be seen in Table 7.

Table 7: Anesthesiologist information for the numerical example

Anesthesiologist ID	Name	Specialty	Availability (reason for unavailability)
1	Allen		Available
2	Baley	N	Not available (at Lahey North)
3	Bell	H	Available
4	Barnes	L,P	Available (Pre-op)
5	Bonnet	L	Available
6	Carpenter	P	Available
7	Cooper		Available
8	Cox	P	Available
9	Cook	L	Not available (post WE IH)
10	Delgado	C,N	Not available (Away)
11	Flores	C,N,P	Available
12	Garcia		Available
13	Gray		Available
14	Hernandez	C,L	Not available (Away)
15	Jordan	H	Not available (Away)
16	Karim	N	Not available (Away)
17	Keith	L	Not available (in-house)
18	Kimber	N	Available
19	Landrovski	H	Available
20	Lee		Not available (at Lahey North)
21	Lian		Available
22	Louis		Available
23	Modir	H	Available
24	Oachs	N	Available
25	Oakden	C,L,P	Available (Consult)

26	Racey	L	Available
27	Rach		Available
28	Sabbatino		Available
29	Sabel	C,H	Available
30	Saki		Not available (Away)
31	Tabak	H,P	Available
32	Woody	H	Available
33	Waber	H	Available
34	Wachel	L	Not available (Post IH)

The information about CRNAs (names, availability, and shift lengths) can be seen in Table 8.

Table 8: CRNA information for the numerical example

Nurse ID	Nurse name	Availability	Shift length (hours)
1	Abas	Available	12
2	Bauck	Available	8
3	Baude	Available	8
4	Baust	Available	8
5	Earbyn	Available	10
6	Haaker	Available	10
7	Hadler	Not available	8
8	Hazy	Not available	8
9	Jacar	Not available	8
10	Labarba	Not available	10
11	Lacko	Available	8
12	Lading	Available	8
13	Laff	Available	8
14	Lagor	Not available	10
15	Mabasa	Not available	8
16	Maca	Available	8
17	Macatee	Not available	10
18	Noor	Not available	8
19	Oar	Not available	8
20	Ocha	Not available	8
21	Rabas	Available	12
22	Saba	Available	8
23	Sagon	Available	8
24	Sainz	Available	10
25	Saler	Available	8
26	Salem	Available	8
27	Wadi	Not available	10
28	Mcabe	Not available	8
29	October	Not available	8

The information about the current schedule (OR ID, completion time of the surgeries, number of cases scheduled, case type and complexity) can be seen in Table 9.

Table 9: OR schedule information for the numerical example

OR ID	Number of cases scheduled	Start time, T_j^s	End time, T_j^e	Cardiac cases in the OR?	Complicated cases in the OR?	Resident assigned in the OR?
1	4	7:00	15:40			
2	4	7:00	17:30			
4	3	7:00	16:35			
5	2	7:00	15:20			
6	1	7:00	14:45			Yes
7	3	7:00	15:10			
8	3	7:00	17:10			
9	1	7:00	13:35			
10	1	7:00	15:45			Yes
11	1	7:00	11:35	Yes		
12	2	7:00	14:20			
15	2	7:00	16:45			
16	2	7:00	14:50			
17	3	7:00	17:05			
18	1	7:00	14:25			Yes
19	4	7:00	14:35			
20	4	7:00	18:10			
21	3	7:00	16:40			
22	3	7:00	16:10			
23	2	7:00	17:15	Yes		Yes
24	0	0:00	0:00			
25	0	0:00	0:00			
26 (LI)	2	12:00	14:30			
27 (PULM)	1	7:00	10:00			
28 (MRI/CATLAB/ INR/IN)	1	7:00	12:00			
29 (GI)	2	7:00	15:00			
30 (EP)	0	0:00	0:00			

Based on the input data presented in Tables 7-9, the following sets and parameters are used to solve the proposed MIP models.

- I {1, 3, 4, 5, 6, 7, 8, 11, 12, 13, 18, 19, 21, 22, 23, 24, 25, 26, 27, 28, 29, 31, 32, 32}
- R {1, 2, 3, 4, 5, 6, 11, 12, 13, 16, 21, 22, 23, 24, 25, 26}
- I_H {3, 15, 19, 23, 29, 31, 32, 33}
- O {1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30}
- O_H {11, 23}
- O_d {}
- $O_{\text{zero-case}}$ {3, 13, 14, 24, 25, 30}

O_{GI}	{29}
O_{tenhrs}	{2, 8, 17, 20, 23}
$O_{twelvehrs}$	{20}
$O_{support}$	{1, 2, 4, 5, 6, 7, 8, 10, 12, 15, 16, 17, 18, 19, 20, 21, 22, 23, 29}
$O_{resident}$	{6, 10, 18, 23}
S_1	{Baley, Cook, Delgado, Hernandez, Jordan, Karim, Keith, Lee, Saki, Wachel}
S_2	{Barnes, Oakden}
S_3	{Bonnet, Waber, Louis}
S_{ten}	{Earbyn, Haaker, Labarba, Lagor, Macatee, Sainz, Wadi}
S_{twelve}	{Abas, Rabas}
N	16
M	5

Table 10 shows the schedule achieved by solving the anesthesiologist and nurse anesthetist assignment models. The optimal schedule satisfies all constraints including:

- The anesthesiologists in set S_1 are not assigned to any OR (MIP1: constraints 1 and 4)
- No anesthesiologists are assigned to the ORs that have no scheduled case in them (MIP1: constraints 2 and 5)
- An anesthesiologist is assigned to each OR that has a scheduled case (MIP1, constraints 3, 6, 14, 15)
- The anesthesiologists who can perform cardiac cases (Dr. Modir and Dr. Sabel) are assigned to the ORs with cardiac cases (OR11 and OR23) (MIP1, constraints 7 and 8)
- The anesthesiologist who is requested by a patient is assigned to that operating room (Dr. Landrovski is assigned to OR7) (MIP1, constraint 9)
- At most two operating rooms are assigned to each anesthesiologist (MIP1, constraint 11)
- The anesthesiologists who do not have CRNA or resident support are assigned to only one OR (Dr. Carpenter, Dr. Sabbatino, Dr. Rach, Dr. Cooper, Dr. Modir) (MIP1, constraint 12)
- The total number of ORs without CRNA or resident support (ORs 9, 11, 26, 27, 28) is equal to $M=5$ (MIP1, constraint 13)
- CRNAs are not assigned to the ORs with residents (ORs 6, 10, 18, 23) (MIP2, constraint 2)

- CRNAs are assigned to all ORs, which can have a CRNA support and no resident working in them (ORs 1, 2, 4, 5, 7, 8, 12, 15, 16, 17, 19, 20, 21, 22, 29) (MIP2, constraint 3)
- GI gets two CRNAs (MIP2, constraint 4)
- Other operating rooms gets at most one CRNA (MIP2, constraint 5)
- No CRNA is assigned to the ORs with no case in them (MIP2, constraint 6)

Table 10: Final assignment generated by the proposed MIP models for the numerical example

OR number	Number of cases scheduled	End time, T_j^e	Anesthesiologist	CRNA	Resident
1	4	15:40	Kimber ($x_{18,1} = 1$)	Lading ($z_{12,1} = 1$)	
2	4	17:30	Sabel ($x_{29,2} = 1$)	Haaker (10) ($z_{1,2} = 1$)	
4	3	16:35	Allen ($x_{1,4} = 1$)	Maca ($z_{16,4} = 1$)	
5	2	15:20	Bell ($x_{3,5} = 1$)	Baust ($z_{4,5} = 1$)	
6	1	14:45	Tabak ($x_{31,6} = 1$)		Yes
7	3	15:10	Landrovski ($x_{19,7} = 1$)	Laff ($z_{13,7} = 1$)	
8	3	17:10	Gray ($x_{13,8} = 1$)	Abas (12) ($z_{1,8} = 1$)	
9	1	13:35	Carpenter ($y_{6,9} = 1$)		
10	1	15:45	Allen ($x_{1,10} = 1$)		Yes
11	1	11:35	Modir ($y_{23,11} = 1$)		
12	2	14:20	Racey ($x_{26,12} = 1$)	Earbyn ($z_{5,12} = 1$)	
15	2	16:45	Cox ($x_{8,16} = 1$)	Saba ($z_{22,15} = 1$)	
16	2	14:50	Kimber ($x_{18,16} = 1$)	Sagon ($z_{23,16} = 1$)	
17	3	17:05	Gray ($x_{13,17} = 1$)	Sainz (10) ($z_{24,17} = 1$)	
18	1	14:25	Landrovski ($x_{19,18} = 1$)		Yes
19	4	14:35	Oachs ($x_{24,19} = 1$)	Salem ($z_{26,19} = 1$)	
20	4	18:10	Tabak ($x_{31,20} = 1$)	Rabas (12) ($z_{21,20} = 1$)	
21	1	16:40	Cox ($x_{8,21} = 1$)	Lacko ($z_{11,21} = 1$)	
22	3	16:10	Bell ($x_{3,22} = 1$)	Bauck ($z_{2,22} = 1$)	
23	2	18:10	Sabel ($x_{29,23} = 1$)		Yes
26 (LI)	2	14:30	Sabbatino ($y_{28,26} = 1$)		
27 (PULM)	1	10:00	Rach ($y_{27,27} = 1$)		
28 (MRI/CAT LAB/ INR/IN)	1	12:00	Cooper ($y_{7,28} = 1$)		
29 (GI x 2)	1	15:00	Oachs ($x_{24,29} = 1$)	Baude ($z_{3,29} = 1$), Saler ($z_{25,29} = 1$)	

In both manual assignment by the floor runner and the optimal assignment using the MIP models, the parts of objective function that are related to minimizing the possibility of assigning

anesthesiologists who are at other locations (set S_2) and who are post on-call (set S_3) are equal to zero. The possibility of assigning CRNAs with short working hours assigned to ORs with late completion times is also equal to zero. The fairness of assignments, which is measured by $(U^{max} - U^{min})$, is 59.5 for optimal solution and 83.66 for the manual assignment. This clearly shows the positive effect of optimally assigning the anesthesiologists in making the workload distribution fairer.

4.2 Computational study

As shown in the previous sections, the objective function for the model for anesthesiologists has varying weights for each part of the objective function. The user should determine the objective function weights before solving the models. In this section, the anesthesiologist assignment model is solved with different weight combinations. The solutions are compared according to the performance measures including minimum, average and maximum number of operating rooms assigned to the anesthesiologists, number of anesthesiologists assigned from set S_2 and S_3 , fairness measure, and the objective function value. The values of all input parameters for this model are based on the data gathered from a real life example explained in Section 4.1.

Objective function

$$\text{Min} = w_1 \sum_i \sum_{j \in S_2} x_{ij} + \quad (1)$$

$$w_2 \sum_i \sum_{o \in S_3} x_{ij} + \quad (2)$$

$$\sum_i \sum_j x_{ij} * D_j * h_i + \quad (3)$$

$$w_3 \sum_i \sum_{j \in S_2} y_{ij} + \quad (4)$$

$$w_4 \sum_i \sum_{j \in S_3} y_{ij} + \quad (5)$$

$$\sum_i \sum_j y_{ij} * D_j * h_i + \quad (6)$$

$$\sum_i \sum_j y_{ij} * K_j + \quad (7)$$

$$U^{max} - U^{min} \quad (8)$$

The first and third weights directly affect the number of anesthesiologists assigned from set S_2 (set of physicians who are at other locations of the hospital and are not assigned to ORs unless it is necessary). As the weight increases, the number of anesthesiologists assigned from

set S_2 decreases. The second and fourth weights have also the same effect on the number of anesthesiologists assigned from set S_3 (set of post on-call physicians who could be assigned to operating rooms with earlier completion times).

As explained before, the shortage of nurses (shown by M) affects the anesthesiologist assignments, because the MIP model will assign the same amount of anesthesiologists to work alone in only one operating room, and the remaining anesthesiologists will be assigned to more operating rooms. In order to see the impact of number of CRNAs and nurse shortage on anesthesiologists' workload, the proposed MIP model are solved with different number of nurses. We consider 21 nurses to show the impact of no nurse shortage, 16 nurses to show the impact of current number of available nurses used in the manual assignment, and 11 nurses to show the impact of increased nurse shortage.

Table 11 shows the performance measures for different weight alternatives for 21 nurses, where there is no nurse shortage. Increasing the first and third weights in objective function (w_1 & w_3) decreases the number of anesthesiologists assigned from set S_2 . This is due to the fact that increasing those weights enhances their relative importance in the objective function. The number of anesthesiologists assigned from sets S_2 and S_3 remains zero when the combination of weights becomes (8,1,8,1). It also can be understood from the results that increasing the weights do not have any effect on the fairness (difference between U^{max} and U^{min}) of assignment.

Table 11: Performance measures for different weight alternatives and 21 nurses

Objective function weights	Number of ORs assigned to physicians (minimum, average, maximum)	Total number of physicians assigned	Number of assignment with physicians from set S_2 (physicians who are at other parts of the hospital)	Number of assignment with physicians from set S_3 (physicians who are post on-call)	Fairness measure ($U^{max} - U^{min}$)	Objective function value
(1,1,1,1)	1, 2.15, 3	13	2	0	52.08	1262.83
(2,1,2,1)	1, 2.15, 3	13	2	0	52.08	1264.83
(5,1,5,1)	1, 2.15, 3	13	2	0	52.08	1270.83
(8,1,8,1)	1, 2.15, 3	13	0	0	52.08	1275
(10,1,10,1)	1, 2.15, 3	13	0	0	52.08	1275
(10,2,10,2)	1, 2.15, 3	13	0	0	52.08	1275
(10,5,10,5)	1, 2.15, 3	13	0	0	52.08	1275
(10,8,10,8)	1, 2.15, 3	13	0	0	52.08	1275
(10,10,10,10)	1, 2.15, 3	13	0	0	52.08	1275

Tables 12 and 13 show the performance measures for different weight alternatives for 16 and 11 nurses, respectively. As the nurse shortage increases, the number of operating rooms that should be covered by anesthesiologists working alone also increases. Changing the combination of weights (w_1 & w_3) again decrease the number of anesthesiologists assigned from set S_2 . The difference between U^{max} and U^{min} remains the same as previous results with higher number of nurses.

Table 12: Performance measures for different weight alternatives and 16 nurses

Objective function weights	Number of ORs assigned to physicians (minimum, average, maximum)	Total number of physicians assigned	Number of assignment with physicians from set S_2 (physicians who are at other parts of the hospital)	Number of assignment with physicians from set S_3 (physicians who are post on-call)	Fairness measure ($U^{max} - U^{min}$)	Objective function value
(1,1,1,1)	1, 1.87, 3	15	1	0	52.08	1274.41
(2,1,2,1)	1, 1.87, 3	15	1	0	52.08	1275.41
(5,1,5,1)	1, 1.87, 3	15	1	0	52.08	1278.41
(8,1,8,1)	1, 1.87, 3	15	0	0	52.08	1281
(10,1,10,1)	1, 1.87, 3	15	0	0	52.08	1281
(10,2,10,2)	1, 1.87, 3	15	0	0	52.08	1281
(10,5,10,5)	1, 1.87, 3	15	0	0	52.08	1281
(10,8,10,8)	1, 1.87, 3	15	0	0	52.08	1281
(10,10,10,10)	1, 1.87, 3	15	0	0	52.08	1281

Table 13: Performance measures for different weight alternatives and 11 nurses

Objective function weights	Number of ORs assigned to physicians (minimum, average, maximum)	Total number of physicians assigned	Number of assignment with physicians from set S_2 (physicians who are at other parts of the hospital)	Number of assignment with physicians from set S_3 (physicians who are post on-call)	Fairness measure ($U^{max} - U^{min}$)	Objective function value
(1,1,1,1)	1, 1.65, 3	17	1	0	52.08	1303.33
(2,1,2,1)	1, 1.65, 3	17	1	0	52.08	1304.33
(5,1,5,1)	1, 1.65, 3	17	1	0	52.08	1307.33
(8,1,8,1)	1, 1.65, 3	17	0	0	52.08	1310.16
(10,1,10,1)	1, 1.65, 3	17	0	0	52.08	1310.16
(10,2,10,2)	1, 1.65, 3	17	0	0	52.08	1310.16
(10,5,10,5)	1, 1.65, 3	17	0	0	52.08	1310.16
(10,8,10,8)	1, 1.65, 3	17	0	0	52.08	1310.16
(10,10,10,10)	1, 1.65, 3	17	0	0	52.08	1310.16

Considering the results in Tables 11-13, one can see that there is a tradeoff between the nurse shortage and the total number of anesthesiologists assigned. As nurse shortage increases, the need for anesthesiologists working alone increases. Therefore, more anesthesiologists are assigned to keep the workload reasonable.

CHAPTER 5: CONCLUSION AND FUTURE RESEARCH DIRECTIONS

In this thesis, two mixed integer programming models, which are capable of assigning anesthesiologists and nurse anesthetists to active operating rooms in the anesthesia department, are proposed. The objectives are to balance the workloads for the staff and minimize the possibility of assigning anesthesiologists and nurse anesthetists to operating rooms that are not suitable for them. The proposed models meet all of the requirements and conditions that physicians face with in their daily assignment procedure, such as assigning the providers with specific skills to their relative ORs, considering providers' availabilities and working hours while assigning them, only assigning anesthesiologists to ORs that are close to each other, not to assign an anesthesiologists to multiple ORs with complicated cases, assigning CRNAs to ORs with a physician working at multiple ORS, not assigning any CRNA to ORs with residents, etc. Afterwards, an Excel-based software capable of retrieving the input information from the user and creating results that show the daily schedules for anesthesiologists and nurse anesthetists with the assistance of Visual Basic Application software (VBA) is developed.

The models are solved using real data. Those results were then compared with the assignment created manually by the anesthesia providers at LHMC and it was shown that the optimal assignments created by models are fairer than the one created manually. After that, the anesthesiologist assignment model was solved using different combinations of objective function weights and it was shown that by increasing those weights the possibility for assignment of physicians in sets S_1 and S_2 as well as the fairness in providers' workload decreases.

The next steps for implementation of the created software would be to calculate the optimum values for the objective function weights in anesthesiologist assignment model using the results of manual assignments created by physicians, validate the Excel VBA-based tool by solving assignment problems in the anesthesia department and update the tool based on physicians' feedback. In the long term, the proposed tool should be integrated with the information technology system so that the user does not have to enter the anesthesiologist, CRNA, and surgery information in each OR manually.

As future research, similar models can be utilized to solve staff assignment problems in other healthcare settings. Also, more graphical and user-friendly interfaces can be created for similar purposes so that the user can work with more ease and efficiency.

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