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Nurse Staff Scheduling Optimization Model in the Emergency Room of the Hospital Escuela Universitario

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***Abstract* -** The present study has focused on developing a proposal to optimize nursing staff allocation in the emergency room of the Hospital Escuela Universitario in Tegucigalpa, Honduras, using integer linear programming. The primary objective has been to maximize the number of shifts assigned to all staff. In this context, a thorough analysis of the current allocation process has been conducted, identifying specific areas requiring improvements to ensure an equitable distribution of shifts and address the particular needs of the emergency area. Various tools and methodologies have been employed for data collection and the design of the mathematical model. A case study has been conducted using a mixed approach, with a predominance of quantitative analysis. During this process, variables, and constraints necessary for effectively modelling the problem have been precisely defined. Integer linear programming has been the main tool for developing a mathematical model to optimize shift allocation, utilizing OpenSolver in Microsoft Excel. The validity of the model has been verified through consultations with experts in the field and pilot testing of the instruments used. A significant finding of this study is that the current staff quantity is sufficient to carry out equitable shift assignments, suggesting that no additional hiring is required at the moment. However, it is important to note that the proposal considers the number of nurses, types of shifts, and related constraints as known data, allowing for deterministic modelling.

***Keywords*:** integer linear programming, emergency room, staff allocation, resource optimization, OpenSolver

1. Introduction

In the city of Tegucigalpa, Honduras, the University Teaching Hospital (HEU) is renowned as a leading public healthcare institution, catering to a significant influx of patients on a daily basis, whether they arrive directly or are referred from other healthcare facilities [1]. However, the hospital has long grappled with a chronic issue of inadequate staffing, affecting both physicians and nurses. Consequently, individuals with limited resources are compelled to seek medical assistance despite the prevailing challenges.

In addressing this persistent challenge, [2] a study was conducted in Tegucigalpa, revealing alarming statistics. It was found that a staggering 78.94% of nursing staff in the HEU emergency room exhibit deficient levels of concentration, with 84.21% reporting symptoms such as headaches and fatigue—a clear indication of work-related exhaustion. This concerning trend has resulted in an unsustainable workload for the hospital staff, significantly compromising the quality of patient care. Moreover, individuals experiencing work exhaustion are at heightened risk of making critical errors in medication administration, medical information interpretation, and decision-making processes—all of which are pivotal in the high-pressure environment of an emergency room setting.

In Tunisia, the issue of resource optimization in an emergency room was addressed, primarily focusing on medical staff (physicians and nurses) and beds. A mixed-integer linear program was proposed to determine the optimal number of human resources and beds to enhance patient satisfaction levels and minimize the number of patients waiting [3]. The model was solved using the IBM Ilog Cplex solver.

Similar studies addressing this specific issue have been conducted in various countries. For instance, at Canada's Sacré-Cœur Hospital, a mathematical model was devised to optimize physician allocation in the emergency room [4]. Constraints were classified as mandatory, requiring strict adherence, or flexible, allowing occasional violations. Moreover, considerations were made regarding the types of shifts per week, including those during vacations or national holidays. Upon implementation, it was noted that compared to manual allocation, many constraints were not consistently met, leading to an uneven distribution of shifts.

In Switzerland, a mixed integer linear programming model was crafted utilizing the Gurobi Optimizer solver. This comprehensive model addresses personnel allocation, patient management, resource utilization, and overtime hours, all aimed at minimizing healthcare expenses while enhancing patient care [5]. It encompasses various constraints, including personnel availability, maximum working hours, and task distribution. For future work, the consideration of including uncertainty in patient demand, as well as personnel absences, was contemplated in the model.

Building upon prior research and additional investigation, the present study was conducted. It comprises several significant sections. Firstly, the methodology section delineates the research approach and scope, detailing the instruments and techniques employed for data collection. Subsequently, it identifies dependent and independent variables, and presents the results, including the establishment of the mathematical model with its constraints and variables. Finally, the conclusions section provides an analysis of all the gathered information. Therefore, the main objective of the present study is to design an optimization model for nursing staff allocation in the adult emergency room of the Hospital Escuela Universitario through operations research.

2. Methodology

2.1 Investigative Approach

The mixed-methods approach encompasses a series of research procedures that involve the collection and analysis of both quantitative and qualitative data. This methodology aims to integrate and discuss these two types of data simultaneously to derive broader and more comprehensive conclusions regarding the phenomenon under study [6]. Essentially, it seeks to blend various approaches to achieve a more holistic understanding of the subject matter.

In this study, a mixed-methods approach was adopted, combining quantitative and qualitative elements in both its design and analysis. However, the study leaned more towards the quantitative aspect, with qualitative components serving as supplementary tools. The primary focus was on utilizing quantitative instruments to gather numerical data, which were then analysed using numerical parameters. Nevertheless, it was acknowledged that a qualitative approach was necessary to supplement the analysis, particularly for a more nuanced interpretation of the information. This allowed for a more thorough understanding of the operational dynamics, hospital policies, and constraints within the hospital's emergency room.

2.1.2. Scope of Study

When employing a mixed-methods approach, the study embraces two scopes: the correlational scope for the quantitative aspect, and the case study for the qualitative dimension. Correlational studies aim primarily to grasp the relationships between different concepts, categories, or variables. In this study, the objective was to understand the interrelationships among types of personnel, shifts, and days within the allocation period.

Conversely, a case study entails a thorough analysis of an individual unit, be it a person or a community, focusing on developmental factors in relation to the environment [7]. This study centered on attaining a comprehensive understanding of the current nursing staff allocation process, delving into existing policies, the challenges encountered by personnel, and potential areas for enhancement.

2.2 Techniques and Instruments

In the instruments section, interviews were used to delve into the current scheduling management and obtain feedback on the experience with the current allocation. As for the techniques, two main tools were employed: Microsoft Excel was used for both statistical analysis of the collected data and structuring the nurse scheduling model, serving as an integral platform for these tasks. On the other hand, OpenSolver was utilized to solve the mathematical model generated for the nursing staff of the emergency room at the HEU, ensuring compliance with the established constraints and seeking to optimize the value of the objective cell through the search for the optimal value.

Several other researchers have also leveraged this tool in their studies. In Brazil, it was utilized to optimize the distribution network of a packaged goods company, leading to substantial cost savings across five distribution centers [8]. Similarly, in Peru, it was employed to enhance productivity within a dairy processing company [9]. Meanwhile, in Honduras, particularly within the education sector, a study focused on developing a scheduling tool for school timetables using linear programming [10]. Additionally, in a university setting, it was applied to devise a scheduling model aimed at assigning various classes to different instructors, thereby enhancing student satisfaction [11].

2.3. Variables

2.3.1. Independent Variables

i licensed nurses: {1, 2,…,61}
l nursing assistants: {1, 2,…,68}
j shift type: {1,2,3}
k day of the month: {1, 2,…,31}

2.3.3. Dependent Variables

X_{ijk} binary variable indicating if a licensed nurse of type i is assigned to shift j on day k
Y_{ljk} binary variable indicating if a nursing assistant of type l is assigned to shift j on day k

3. Results and Analysis

3.1 Data Collection: Pilot Interview

The interview instrument was utilized to collect essential information for defining variables and constraints of the mathematical model. However, prior to its implementation, a pilot test of the instrument was conducted involving an expert in a related field to evaluate the clarity and relevance of the questions posed. This pilot test facilitated necessary adjustments in terms of wording and quantity to ensure the instrument's effectiveness.

Following the methodology employed [13], where a single interview was conducted with a representative of an educational institution to explore the allocation process, this study similarly opted for an interview-only approach with the Chief of Emergency Room at the HEU. This decision was based on recognizing the Chief Nursing Officer of the Emergency Room as the authoritative figure responsible for resource allocation within that environment. Consequently, it was anticipated that her insights and experience would yield a comprehensive understanding of the allocation process under scrutiny.

3.2 Data Collection through Interview

The interview aimed to gather insights to comprehend the current process and translate them into variables and constraints. Presently, the allocation of nursing staff in the unified adult emergency room is manually handled for all positions. This responsibility falls on the Chief Nursing Officer during the preceding month, with adjustments made as needed. The process entails identifying the month's days off, assigning shift types to all nurses, and tallying the total staff assigned to each shift per day.

Key information gleaned from the interview helped identify variables such as shift types (A, B, and C), types of staff (licensed nurses and nursing assistants), staff quantity (61 licensed nurses and 68 nursing assistants), and the days considered in the planning period (31 days corresponding to 1 month).
Additionally, the Chief Nursing Officer highlighted important constraints for the mathematical model to ensure compliance with legal requirements. These constraints include:

- One daily shift per nursing staff member
- Maximum of 40 hours worked per nursing staff member per week
- Five mandatory C shifts per month
- Ten days off per month for licensed nurses
- Eleven days off per month for nursing assistants

3.3 Mathematical Model

After analyzing the collected information, the following mathematical model was established, using the following notation:

Table 1: Variable Index

Index	
i	Licenses nurses
l	Nursing assistants
j	Shift type
k	Day of the month
tj	Shift duration in hours

A decision was made to devise a distinct model for each category of personnel, given the considerable number of variables associated with each group. Both models share the common objective of maximizing the total number of shifts worked by all nursing staff, including both licensed nurses and nursing assistants, across the 31-day planning period. These models are designed while considering constraints related to working hours and days off.

$$\max Z = \sum_{i=1}^{I} \sum_{j=1}^{J} \sum_{k=1}^{K} X_{ijk} \tag{1}$$

$$\max Z = \sum_{l=1}^{L} \sum_{j=1}^{J} \sum_{k=1}^{K} Y_{ljk} \tag{2}$$

Both models consider the following restrictions for each type of personnel:

$$\sum_{i=1}^{61} \sum_{j=1}^{3} X_{ijk} \leq 1 \qquad \forall\ k\ \in \{1,2,\dots,31\} \tag{3}$$

$$\sum_{i=1}^{61} \sum_{j=1}^{3} X_{ijk} \leq 1 \qquad \forall\ k\ \in \{1,2,\dots,31\} \tag{4}$$

$$\sum_{k=1}^{31} t_1 X_{i1k} + \sum_{k=1}^{31} t_2 X_{i2k} + \sum_{k=1}^{31} t_3 X_{i3k} \leq H \quad \forall\ i \in \{1,2,\dots,61\} \tag{5}$$

$$\sum_{k=1}^{31} t_1 Y_{l1k} + \sum_{k=1}^{31} t_2 Y_{l2k} + \sum_{k=1}^{31} t_3 Y_{l3k} \leq H \quad \forall\ l \in \{1,2,\dots,68\} \tag{6}$$

$$\sum_{k=1}^{31} X_{i3k} = 5 \qquad \forall\ i \in \{1,2,\dots,61\} \tag{7}$$

$$\sum_{k=1}^{31} X_{l3k} = 5 \qquad \forall\ l \in \{1,2,\dots,68\} \tag{8}$$

$$\sum_{j=1}^{3}\sum_{k=1}^{31} X_{ijk} \leq 21 \qquad \forall\, i \in \{1,2,\dots,61\} \tag{9}$$

$$\sum_{j=1}^{3}\sum_{k=1}^{31} Y_{ljk} \leq 20 \qquad \forall\, l \in \{1,2,\dots,68\} \tag{10}$$

$$\sum_{j=1}^{j-1} X_{i3k} + X_{i1(k+1)} \leq 1 \qquad \forall\, i, \mathrm{k} \tag{11}$$

$$\sum_{j=1}^{j-1} Y_{l3k} + Y_{l1(k+1)} \leq 1 \qquad \forall\, l, \mathrm{k} \tag{12}$$

$$\sum_{j=1}^{j-1} X_{i2k} + X_{i1(k+1)} \leq 1 \qquad \forall\, i, \mathrm{k} \tag{13}$$

$$\sum_{j=1}^{j-1} Y_{l2k} + Y_{l1(k+1)} \leq 1 \qquad \forall\, l, \mathrm{k} \tag{14}$$

$$X_{ijk}, Y_{ljk} \in \{0,1\} \qquad \forall\, i,j,k,l \tag{15}$$

$$X_{ijk}, Y_{ljk} \geq 0 \qquad \forall\, i,j,k,l \tag{16}$$

3.3.1 Model Considerations

- The model solely considers nursing staff from the emergency room of the HEU working on a permanent basis, excluding administrative personnel and nurses on social service.
- The model operates based on the staffing levels provided by the hospital.
- The model is designed for a 31-day month.
- OpenSolver is utilized as the primary tool for model implementation.

3.4 Solutions of the Mathematical Models

3.4.1 Model 1- Licensed Nurses

After establishing the variables, objective function, and constraints, a matrix was developed to serve as the basis for the monthly calendar for all models. The initial purpose of this first model was to represent the original allocation made, as the current sheet in use is difficult to account for and compare accurately. Additionally, during the analysis, an error in the format was identified, where the total number of licensed nurses was calculated as 62 due to the omission of a number.

In this model, the possibility of granting three consecutive days off on weekends per month to each licensed nurse was not considered, as it is mathematically unfeasible. This supports what was mentioned by the interviewee, who pointed out that currently not all employees enjoy this benefit. If we were to ensure at least one weekend off per month for all licensed nurses, upon calculation, only 46 licensed nurses would be available to cover the workweek. Additionally, this would involve delving into nonlinear programming, which is beyond the scope of the present research.

After analyzing the results of the model under the current conditions, an optimal solution of 1,281 assigned shifts was achieved. However, this model does not evenly distribute the average daily number of licensed nurses or assign shift types equitably, with the exception of shift C, of which 5 mandatory shifts are assigned per month.

3.4.2 Model 2- Licensed Nurses

Given that the first model fails to meet the research objectives, it is proposed to add additional constraints to both the daily assignment of licensed nurses and the number of shifts assigned to each nurse during the month. The determination of the number of licensed nurses assigned is based on the experience of the emergency room chief, set a minimum of 9 licensed nurses, while no maximum has been defined due to the perception of insufficient this regard, an upper limit of 15 licensed nurses is proposed. Regarding the number of shifts assigned monthly, it was calculated based on the averages provided by the previous model, establishing a range of 7 to 10 types of shifts A and B per licensed nurse.

Below are the following equations representing the additional constraints.

$$9 \geq \sum_{i=1}^{61} \sum_{j=1}^{3} X_{ijk} \leq 15 \qquad \forall\, k \in \{1,2,\ldots,31\} \tag{17}$$

$$7 \geq \sum_{j=1}^{2} \sum_{k=1}^{31} X_{ijk} \leq 10 \qquad \forall\, i \in \{1,2,\ldots,61\} \tag{18}$$

This model features a total of fewer assignments than the previous model, with a total of 1,235 assignments. However, unlike the previous model, this one establishes limits regarding the assignments. It demonstrates that a more equitable distribution of staff ensures greater fairness in the total number of shift types assigned. Additionally, it complies with the law of assigning two consecutive days off, although not necessarily on specific weekdays.

3.4.3 Model 1- Nursing Assistants

Similar to model 1 for licensed nurses, the possibility of granting three consecutive days off during the weekend was not considered due to mathematical constraints that make it unfeasible. The objective function yields a total of 1,428 assignments. Similarly, the results show a lack of standardization in the total number of daily nursing assistants and inequity in the assignment of shift types.

3.4.4 Model 2- Nursing Assistants

Since the first model does not fully meet the established objectives, a second model has been proposed to address the identified deficiencies. Similar to the case of model 2 for licensed nurses, the averages from the first model have been calculated, resulting in a range of 7 to 9 type A and B shifts per nursing assistant. Regarding the total number of nursing assistants per day in each shift, a minimum of 9 assistants has been established, with a suggested maximum of 16. This leads us to propose the following additional constraints.

$$9 \geq \sum_{l=1}^{68} \sum_{j=1}^{3} Y_{ljk} \leq 16 \qquad \forall\, k \in \{1,2,\ldots,31\} \tag{19}$$

$$7 \geq \sum_{j=1}^{2} \sum_{k=1}^{31} Y_{ljk} \leq 9 \qquad \forall\, l \in \{1,2,\ldots,68\} \tag{20}$$

This model presents a total of 1,332 assignments, establishing limits regarding the assignments. The schedule for this model is presented in Annex 12, followed by the table of total shifts per month.

3.5 Expert Triangulation as a Validation Method

According to [14], triangulation involves using multiple methods or data sources in research to gain a comprehensive understanding of phenomena. It's a strategy to test validity by converging information from different sources. They identified four types of triangulation: methodological, researcher, theoretical, and data source triangulation. [15] highlights that triangulation strengthens confidence in results by revealing previously unknown dimensions of phenomena and stimulating creativity through diverse perspectives.

Throughout the model's development, ongoing communication was maintained with three experts in linear programming. They recommended dividing the model into two parts from the nomenclature stage, considering the complexity of managing 129 individuals. These experts meticulously reviewed and verified the nomenclature, notation, notation, constraints, and particularly the objective function, ensuring its relevance to the research. Additionally, they they advised against incorporating costs, as the hospital lacks overtime policies. It was also decided not to minimize variation between shift types to preserve the model's linearity.

Beyond the input from the subject matter experts, consultations were conducted with the hospital's human resources personnel. These discussions yielded valuable insights into existing labor policies, particularly the regulations governing nursing professionals. This verification process ensured alignment with relevant labor laws and adherence to the policies established by the Hospital Escuela Universitario (HEU).

4. Conclusions

The study identified key factors directly influencing staff allocation in the HEU emergency room. These factors encompass the type of nursing personnel, established shift schedules, and the specific days of the week when these shifts occur. It's worth noting that these elements are closely tied to critical constraints, notably the available staffing levels and the maximum allowable weekly working hours. This initial phase proved pivotal in laying the groundwork for the subsequent development of the optimization model.

Using OpenSolver, four distinct models were crafted: two original versions and two proposed iterations tailored for licensed nurses and aides. Analysis of the original models revealed that the frequency of shifts A and B closely mirrored the empirical allocation method. However, when considering the total number of nurses assigned to these shifts, the models indicated mathematical non-parametrization. This complexity arises due to the variability inherent in these assignments, particularly the practice of randomly assigning three consecutive days off as weekend holidays, posing challenges in defining appropriate linear programming constraints.

Conversely, the proposed models showcased the feasibility of applying linear programming principles to achieve the required allocation. Specifically, by adjusting the assignment of days off to align with statutory regulations and maintaining a balanced distribution of monthly shifts (including types A, B, and C), equity in shift allocations was successfully attained.

Following validation with linear programming experts and hospital human resources personnel, the proposed model was deemed suitable for addressing the complexities of shift allocation. However, its implementation would necessitate revisions to existing practices governing days off allocation. To ensure a comprehensive reflection of real-world dynamics, future iterations of the model would benefit from a thorough review of current staffing conditions, accounting for established practices and policies.

As a general conclusion, an optimization model was devised for nursing staff allocation in the adult emergency room of the University Teaching Hospital. This model sets clear criteria for assigning shifts A, B, and C, and enhances the scheduling of consecutive days off for both types of nursing staff. Moreover, it regulates the daily nurse allocation for each shift, highlighting that hiring more staff currently isn't necessary. Instead, a more effective distribution of shifts and days off is required.

In this shift allocation scenario, the number of nurses, types of shifts, and related constraints are well-known and can be deterministically modelled. However, if the model were subjected to additional highly variable and random constraints, a deterministic approach might struggle to produce optimal solutions. Thus, a more flexible heuristic approach would be better suited to handle such uncertainty and variability effectively.

5. Evolution/Future Work

It's recommended to conduct an operations simulation study to better understand the demand dynamics of the emergency room and the availability of staff. Currently, the room's capacity is defined by the number of available beds, and patients are admitted based on bed availability. However, critical patients may sometimes exceed the total capacity.

By using simulation, we can establish a relationship between patient influx and nursing staff availability, considering the different sections of the emergency room and the time each nurse spends on various tasks. This would enable the development of a more comprehensive staffing allocation model, not only assigning shifts but also assigning specific roles to each nurse. This approach would enhance patient care traceability and optimize resource utilization.

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