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Case Report

Case Study on Streamlining Surgical Operations: A Mathematical Approach to Operating Room Scheduling and Surgeon Allocation

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Abstract

Operating rooms (ORs) represent one of the most critical and resource-intensive cost centers in any hospital. Their efficient management is paramount to both financial stability and patient care quality. Inefficient OR scheduling often leads to significant issues, including high operational costs, staff burnout due to overtime, and increased patient wait times. The main objective of this study is to develop and present a model aimed at increasing the strategic utilization of ORs, with the dual goals of minimizing associated operational costs and achieving significant cost savings. The research is grounded in a practical case study at the ABC Hospital. A primary contribution of this work is the meticulous collection and analysis of a comprehensive dataset from ABC Hospital, detailing the specific duration data for a wide variety of surgery types. This empirical data forms the foundation for our modeling approach. The approach itself centers on an optimization framework designed to address several key challenges simultaneously. The model is focused on minimizing the combined costs of regular OR opening hours and all associated overtime costs. Beyond cost, the study analyzes the complex task of sequencing surgeries within each OR to maximize throughput and efficiency. A crucial component of this analysis is the development of a robust system for assigning specific surgeries to the respective surgeons, aligning surgeon availability and specialization with the surgical schedule. By addressing the dual problems of cost minimization and procedural scheduling, this study provides a practical, data-driven framework. The anticipated outcomes include actionable recommendations for ABC Hospital that could lead to significant cost reductions, enhanced resource allocation, and a more predictable and efficient surgical environment for both patients and staff.

Keywords

Operations Research, Scheduling Problem, Linear Programming Problem, Decision-making

1. Introduction

Scheduling theory, a distinct discipline within Operational Research originating in the 1950s, addresses the optimal allocation of finite resources to activities over time. This decision-making process is fundamentally concerned with solving problems of sequencing, timetabling, and optimal arrangement. The applications of this theory are extensive, extending

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beyond its traditional roots in manufacturing and computer systems to diverse sectors such as agriculture, health care, and transportation.

A "schedule" specifies the sequence of jobs assigned to each machine in a processing system. This is governed by standard constraints: a machine is restricted to processing a single job at any given time, and a job cannot be processed by multiple machines simultaneously. Specific scheduling environments may introduce further complexities, such as variable job release times or the allowance of pre-emption, where a job may be interrupted by another.

2. Operations Research in Healthcare Systems

Healthcare systems are currently facing a dual challenge of rising operational complexity and escalating costs, driven largely by an aging population. This environment necessitates new approaches to disease prevention, diagnostics, and care planning, while also accommodating the growth of services like home healthcare and telemedicine.

The feasibility of a systems engineering approach is increasing thanks to the development of advanced medical technologies. The growing availability of healthcare data, coupled with advances in ICT and robotics, enhances operational efficiency, safety, and diagnostic capabilities. In parallel, innovative Operations Research (OR) techniques are being developed to optimize a wide range of applications, including operating room scheduling, emergency department staffing, radiotherapy planning, and long-term care logistics.

However, the simple transference of management models from other industries has proven inadequate. The failure of many 'lean' or 'quality control' projects, which did not account for the specificities of healthcare, underscores the need for original, industry-specific research to effectively leverage these new technological and analytical tools.

Scheduling in Healthcare System

Planning involves the establishment of objectives and the formulation of strategies to achieve them. Specifically, healthcare planning endeavors to supply appropriate and sufficient healthcare infrastructure to populations with the greatest need. In nations facing significant resource constraints and supporting a large populace (particularly a growing elderly demographic), such as India, the application of robust healthcare planning is crucial. Furthermore, as life expectancies extend and birth rates decline, supplementary budgetary and healthcare provisions are required to address escalating demands. Consequently, there is a profound obligation to ensure the optimal utilization of these resources, preventing waste, as healthcare is a critical domain impacting human life. To this end, operational research (OR) has been increasingly adopted as a methodology to optimize resource allocation and control expenditures. OR methodologies are applied to diverse problems, from the tactical distribution of beds in emergency departments and the staffing of nurses in intensive care units, to strategic decisions like hospital site selection and the forecasting of future service demand.

The objective of healthcare management systems is the rationalization of both technical and administrative workflows to enhance the efficiency, productivity, and quality within healthcare organizations. Among the most significant resources requiring efficient management are operating theatres (OTs). OTs represent high-cost centers that simultaneously serve as primary drivers of revenue. The daily functioning of these theatres is contingent upon the availability of staff, physical space, and necessary medical equipment. A principal challenge in this management context is the development of effective scheduling protocols designed to maximize the utilization rate while adhering strictly to technical, safety, and quality-related constraints. For several decades, the problem of scheduling in operating rooms has been a focal point of considerable research inquiry.

Escalating healthcare expenditures compel hospitals to pursue cost reduction measures concurrently with enhancements in care quality. As operating rooms are the single largest source of both revenue and expenditure, hospital administration is increasingly focused on the efficacy of scheduling and planning. The present study comprises an analysis of recent scholarly work concerning operating room planning and scheduling. The majority of literature surveyed, published from 2000 onward, was assessed based on several criteria: patient characteristics, defined performance metrics, the solution methodologies employed, considerations of problem uncertainty, the practical applicability of the findings, and the specific planning strategies addressed by the solution.

Hospitals, entities whose primary output is service, are increasingly adopting strategic measures in response to rising health demands and a competitive landscape. Consequently, hospital management is mandated to decrease costs and enhance financial standing. Operating theatres generate approximately two-thirds of a hospital's income while representing around 40% of its expenses. From this financial perspective, OTs claim the largest portion of both revenue and costs. For this reason, enhancing the productivity of operating rooms significantly impacts the financial and, ultimately, the ethical performance of the institution. As a consequence, operating rooms are the most compelling and focal areas within hospitals. Such performance enhancements are directly and proportionally linked to improvements in service quality and patient satisfaction.

The problem of operating room scheduling is considered a specialized branch of optimization. Over the last four decades, a cautious research focus has been maintained on planning and scheduling studies aimed at attaining goals like performance and productivity within the OT. Within the literature, a broad spectrum of approaches has been developed by researchers for the solution process, subsequent to problem identification. Solutions to these scheduling problems have been proposed that incorporate varied performance criteria. In addition to addressing numerous other healthcare management facets, OR researchers have provided significant contributions to areas such as drug treatment planning, the prevention and control of infectious diseases, and organ donation logistics.

3. Literature Review

Hare WL, et al., developed models and algorithms to improve earthwork operations in road design using mixed integer linear programming in 2011. Kim S, et al., described sample average approximation in 2015. Lamiri M, et al., developed a model for operating room planning with elective and emergency demand for surgery using stochastic processes in 2008. [1, 16, 9].

Li L, et al., devised a model for rolling horizon surgery scheduling in 2016. Mancilla C., et al., discussed sample average approximation approach to stochastic appointment scheduling and sequencing in 2012. Min D, et al., investigated scheduling elective surgery under uncertainty and downstream capacity constraints in 2010. M'Hallah, et al., discussed scheduling of operating rooms through simulation in 2014. [2, 15, 8, 11].

Perrson M, et al., devised a model to support surgery management at a Swedish hospital in 2009. Saadouli H, et al., discussed scheduling operating rooms and recovery beds in an orthopaedic surgery department using stochastic optimization in 2015. Santibanez, et al., demonstrated block scheduling of surgeries in a wide array of hospitals in 2007. Testi A, et al., discussed a model of three phase approach for operating theatre schedule in 2007. Wang Y, et al., developed an algorithm for solving operating theatre planning problem under stochastic demand and surgery cancellation risk in 2014. [12, 7, 4, 1, 10].

The efficient management of Operating Rooms (ORs) is paramount in healthcare, with literature highlighting that optimization is crucial for addressing issues like high costs, staff burnout, and patient wait times. Foundational work by Blake and Donald established the efficacy of integer programming for OR time allocation, which was later expanded upon by Xiang and Li, who specifically incorporated real-life constraints and the comprehensive operational cost into the scheduling objective. Recognizing the dynamic nature of the OR environment, Addis et al. introduced a flexible rolling horizon approach for scheduling and rescheduling, underscoring the need for adaptability. Furthermore, the complexities of integrating personnel and handling variability are central to the field; Beliën and Demeulemeester utilized a branch-and-price approach to simultaneously optimize nurse and surgery schedules, while Devin applied stochastic programming to the nurse scheduling problem to account for uncertainty. Finally, the challenge of unpredictable surgery durations was addressed by Mancilla and Storer, who developed a sample average approximation approach for stochastic appointment sequencing, providing a robust methodology for maximizing throughput and efficiency despite inherent variability. Collectively, these studies demonstrate a strong academic grounding in applying advanced optimization techniques to address the multifaceted problems of OR resource allocation, cost minimization, and staff integration [3, 5, 6, 13, 14].

4. Methodology

4.1. Operating Room Scheduling

The initial phase of daily surgery scheduling involves planning the Operating Room (OR) assignments. In this study, the OR schedule for the subsequent day was formulated at the conclusion of each operational day. The primary objective guiding the assignment of surgeries to ORs was the dual minimization of anticipated overtime and the total number of active ORs. This multi-objective goal was quantified and consolidated into a singular cost function. The scheduling model was subsequently conceptualized as a deterministic problem, utilizing expected values for the parameters.

4.2. Notations

We used the following notations in the mathematical model:

Indices and sets:

I → the set of ORs with index *i*

J → the set of surgeries with index j

I_j → the set of ORs that meet requirements of surgery *j*

Parameters

C^0 → the per-minute overtime cost

C_i^f → the fixed cost for opening OR *i*

O_i → the overtime in OR *i*

P_{ij} → the surgery duration of surgery *j* in OR *i*

Decision Variables

x_i → equals 1 if OR *i* is open, 0 otherwise

y_{ij} → equals 1 if surgery *j* is assigned to OR *i*, 0 otherwise

5. Operating Room Scheduling Model

The model incorporates several real-world constraints. First, it addresses the heterogeneity of operating rooms (ORs); surgeries have specific requirements based on cleanliness levels and fixed equipment, restricting which ORs are suitable for which procedures. Second, a distinct fixed cost is associated with opening each OR. The parameter p_{ij} is defined as the processing duration of surgery j in OR i. To enforce the compatibility constraint, p_{ij} is assigned a prohibitively large value (i.e., a penalty) if surgery j cannot be performed in OR i. The OR scheduling problem was then formulated as follows:

$$Min \sum_{i\in I} C_i^f x_i + C^0 \sum_{i\in I} O_i \quad (1)$$

Subject to constraints:

$$\sum_{i \in I_j} y_{ij} = 1, j \in J, \quad (2)$$

$$y_{ij} \le x_i, i \in I, j \in J \quad (3)$$

$$O_i \ge 0, i \in I \quad (4)$$

$$x_i, y_{ij} \in \{0,1\} \quad (5)$$

$$i \in I, j \in J$$

The objective function (1) is designed to minimize the total cost, which comprises two components: the fixed costs associated with the number of operating rooms (ORs) that are opened, and the costs incurred from staff overtime.

The constraints are:

1. Constraint (2) ensures that each surgery is assigned to exactly one operating room that satisfies all of its specific requirements.
2. Constraint (3) defines the mathematical relationship between the two sets of decision variables used in the model.
3. Constraints (4) are used to assign the correct overtime value to its corresponding intermediate variable (likely calculating the positive-only duration beyond a standard shift).
4. Constraint (5) imposes the binarity condition, restricting the decision variables to integer values of either 0 or 1.

6. Data Collection

Researchers may study how surgeries are scheduled within a given OR, looking at factors such as the time of day, day of the week, or surgeon preferences. They may investigate whether certain types of surgeries are clustered together or spread out over time.

Surgery time directly correlates with costs incurred by the healthcare system. It can also be an indicator of the quality of care provided. Longer surgery times may suggest more complex cases or potential complications, while shorter times may indicate efficiency and skill. Researching surgery time helps healthcare providers identify areas for improvement in patient care and surgical outcomes.

In all types of surgery were considered for the study like general, surgical oncology, ENT, Plastic, Neural and gastroenterology. The following data were collected from ABC Hospital, Trichy for the year 2020-2021.

No. of Operation Rooms: 5

Number of Surgeons: 12

Average Duration of Surgery: 220 mins.

Overtime Cost: Rs. 120 per minute

Table 1. *Analyzing the surgery durations and cost.*

Type of Surgery	Fixed Cost (Rs.)	No. of Surgeons
General Surgery	45000	5
Surgical Oncology	45000	4
ENT, Head, Neck Surgery	45000	4
Plastic Surgery	45000	5
Neural and Spine Surgery	60000	8
Surgical Gastroenterology	45000	8

The standard operating duration (i.e., regular time) for an OR is 420 minutes. Any work exceeding this threshold is classified as overtime, which incurs a cost of Rs 120 per minute.

7. Problem Formulation

Objective function

$Min \sum_{i \in I} C_i^f x_i + C^0 \sum_{i \in I} O_i$

Notations

C_i^f: Fixed cost for opening OR i.

x_i : equals 1 if OR i is open, 0 otherwise.

C^0: the per-minute overtime cost.

O_i: the overtime in OR i.

General Surgery

Given:

Fixed time = 2 hours

Duration = 2 hours 27minutes

Fixed cost for the surgery (C_1^f) = Rs. 13,000

Overtime per minute cost (C^O) = Rs. 120

Overtime of the surgery (O_1) = 27minutes

Solution:

Cost for the surgery = Rs. (13,000 + 120(27))

= Rs.16,240

Surgical Oncology

Given:

Fixed time = 3 hours

Duration of the surgery = 3 hours 50minutes

Fixed cost for the surgery (C_2^f) = Rs.19,500

Overtime per minute cost (C^O) = Rs. 120

Overtime for the surgery (O_2) = 50minutes

Solution:

Cost for the surgery = Rs. (19,500 + 120(50))

= Rs. 25,500

ENT Surgery

Given:

Fixed time = 5 hours

Duration of the surgery = 5hours 36minutes

Fixed cost for the surgery (C_3^f) = Rs. 32,500

Overtime per minute cost (C^0) = Rs. 120
Overtime of the surgery (O_3) = 36 minutes
Solution:
Cost for the surgery = Rs. (32,500 + 120(36))
= Rs. 36,820
Neural and Spine Surgery
Given:
Fixed time = 7 hours
Duration of the surgery = 6hours 40minutes
Fixed cost for the surgery (C_4^f) = Rs.60,000
Overtime per minute cost (C^O) = Rs. 120
Overtime of the surgery (O_4) = 0
Solution:
Cost for the surgery = Rs. (60,000 + 120(0))
= Rs.60,000.
Surgical Gastroenterology
Given:
Fixed time = 5 hours
Duration of the surgery = 5hours 8minutes
Fixed cost for the surgery (C_5^f) = Rs.32,500
Overtime per minute cost (C^0) = Rs. 120
Overtime of the surgery (O_5) = 8minutes.
Solution:
Cost for the surgery = Rs. (32500 + 120(8))
= Rs.33,460.
The constraints of the model are expanded.

$$\sum_{i\in I_j} y_{ij} = 1\,, j \in J$$

$$y_{11} + y_{21} + y_{31} + y_{41} + y_{51} = 1$$

$$y_{12} + y_{22} + y_{32} + y_{42} + y_{52} = 1$$

$$y_{13} + y_{23} + y_{33} + y_{43} + y_{53} = 1$$

$$y_{14} + y_{24} + y_{34} + y_{44} + y_{54} = 1$$

$$y_{15} + y_{25} + y_{35} + y_{45} + y_{55} = 1$$

$$y_{ij} - x_i \le 0, y_{11} - x_1 \le 0,$$

$$y_{12} - x_1 \le 0, y_{13} - x_1 \le 0$$

$$y_{14} - x_1 \le 0, y_{15} - x_1 \le 0,$$

$$y_{21} - x_2 \le 0, y_{22} - x_2 \le 0$$

$$y_{23} - x_2 \le 0, y_{24} - x_2 \le 0,$$

$$y_{25} - x_2 \le 0, y_{31} - x_3 \le 0$$

$$y_{32} - x_3 \le 0, y_{33} - x_3 \le 0,$$

$$y_{34} - x_3 \le 0, y_{35} - x_3 \le 0$$

$$y_{41} - x_4 \le 0, y_{42} - x_4 \le 0,$$

$$y_{43} - x_4 \le 0, y_{44} - x_4 \le 0$$

$$y_{45} - x_4 \le 0, y_{51} - x_5 \le 0,$$

$$y_{52} - x_5 \le 0, y_{53} - x_5 \le 0$$

$$y_{54} - x_5 \le 0, y_{55} - x_5 \le 0$$

$$y_{ij} \le x_i\,, i \in I, j \in J$$

$$O_1 \ge 0 \Longrightarrow 27 \ge 0$$

$$O_2 \ge 0 \Longrightarrow 50 \ge 0$$

$$O_3 \ge 0 \Longrightarrow 36 \ge 0$$

$$O_4 \ge 0 \Longrightarrow 0 \ge 0$$

$$O_5 \ge 0 \Longrightarrow 8 \ge 0$$

$$O_i \ge 0\ i \in I$$

Using the given data, the model is formulated
Objective function

$$\text{Min } 13000x_1 + 19500x_2 + 32500x_3 + 60000x_4 + 32500x_5 + 145200O_i$$

Subject to the constraints,

$$\sum_{i,j\in\{1,2,3,4,5\}} y_{ij} = 1$$

$$y_{ij} - x_i \le 0$$

$$1 \le i, j \le 5$$

8. Result Analysis

Upon solving the formulated model with an optimization package (LINGO Optimization Software), the results indicate a reduced cost of zero for the first decision variable. The optimal solution, as determined by the model, achieves a total cost reduction of Rs. 13,000. The detailed solution for the problem is presented as follows.

Table 2. *Minimized surgery cost.*

Variables	Objective Coefficient	Min. Objective Coefficient	Variables	Objective Coefficient	Min. Objective Coefficient
x_1	13000.00	0.00	y_{31}	0.00	-19500.00
x_2	19500.00	13000.00	y_{32}	0.00	-19500.00
x_3	32500.00	13000.00	y_{33}	0.00	-19500.00
x_4	60000.00	13000.00	y_{34}	0.00	-19500.00
x_5	32500.00	13000.00	y_{35}	0.00	-19500.00
O_i	14520.00	0.00	y_{41}	0.00	-47000.00
y_{11}	0.00	-13000.00	y_{42}	0.00	-47000.00
y_{12}	0.00	-13000.00	y_{43}	0.00	-47000.00
y_{13}	0.00	-13000.00	y_{44}	0.00	-47000.00
y_{14}	0.00	-13000.00	y_{45}	0.00	-47000.00
y_{15}	0.00	-13000.00	y_{51}	0.00	-19500.00
y_{21}	0.00	-6500.00	y_{52}	0.00	0.00
y_{22}	0.00	-6500.00	y_{53}	0.00	0.00
y_{23}	0.00	-6500.00	y_{54}	0.00	0.00
y_{24}	0.00	-6500.00	y_{55}	0.00	0.00
y_{25}	0.00	-6500.00			

Table 3. *Current Cost versus Optimized Cost.*

Type of Surgery	Current Cost (Rs.)	Optimized Cost (Rs.)
General Surgery	45000.00	13000.00
Surgical Oncology	45000.00	13000.00
ENT, Head, Neck Surgery	45000.00	19500.00
Plastic Surgery	45000.00	32500.00
Neural and Spine Surgery	60000.00	60000.00
Surgical Gastroenterology	45000.00	32500.00

The results summarized in Table 3 clearly illustrate the proposed model's effectiveness in optimizing the fixed costs associated with OR operations. The table contrasts the baseline or current scenario with the model's optimized solution, demonstrating that the model successfully reduces the total number of active ORs needed to process the same surgical caseload. This optimization is achieved by creating a more consolidated and efficient schedule, thereby proving the model's capacity to enhance resource allocation and generate significant fixed cost savings.

9. Conclusion

The case study solved an issue with surgery durations in the operating room scheduling and surgeon assignment. ABC hospital provided real-time surgery duration statistics from various departments. More real-world constraints, such as the resources required during the surgical period have been considered. The cost is reduced by Rs. 13000. In addition, unpredictable variables such as emergency arrival and surgery cancellation is included in the modelling process to make it more practical.

10. Scope for Future Studies

We are able to expand the study to include any kind of situation involving decision-making which incorporate staff preferences, such as preferred shifts or days off, into the scheduling process to improve employee satisfaction and work-life balance. Additionally, factor in considerations for staff well-being, such as minimizing consecutive long shifts or ensuring adequate rest periods between shifts.

Abbreviations

OR	Operating Rooms
ICT	Information and Communication Technology
ABC Hospital	Assured Best Care Hospital
ENT	Ear, Nose, and Throat

Author Contributions

Arivudai Nambi Jenifer Christinal: Conceptualization, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing

Dhasaiyan Surjith Jiji: Conceptualization, Data curation, Formal Analysis, Resources, Software, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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