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Operations Research in Healthcare: A Review

***S Priyan**

Department of Mathematics, Mepco Schlenk Engineering College, Sivakasi 626005, Virudhunagar DT, Tamilnadu, India.

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***Corresponding author:** S Priyan, Department of Mathematics, Mepco Schlenk Engineering College, Sivakasi 626005, Virudhunagar DT, Tamilnadu, India, Email: jaisilpriyan@gmail.com

Abstract

A brief review of operations research (OR) applications to problems of health care systems are made in this article. It demonstrates the possibilities which exist for improving the operational, tactical and strategic decision-making of health care systems through the use of operations research approaches. This paper aims to raise the awareness of healthcare managers with regard to realistic OR applications

Commentary

Operations research is a term that can be used with mathematical and statistical methods and computer systems, which characterizes the orientation, interdisciplinary philosophy, which aims to quantify the relevant aspects of the situation in the modeling and manipulation of the model approach to develop decisions, plans, and policies. The systematic methodology of OR focuses on the problems developed conflicting objectives, strategies and alternatives. OR is, ultimately, the scientific method, which is applied to complex tasks to assess the overall impact of different policy options to consider actions, providing a better basis for making business decisions. The OR approach to solve the problem comprises the following six sequential steps:

i. Formulate the problem,

ii. Construct a mathematical model,

iii. Derive the solution from the model,

iv. Test the model

v. Establish control over the solution, and

vi. Implement the final results, (Figure1) shows this schematically (Figure 1).

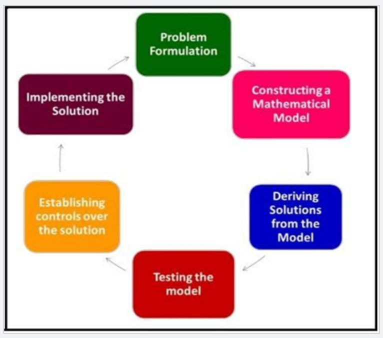

Figure 1: Sequential steps of OR approach.

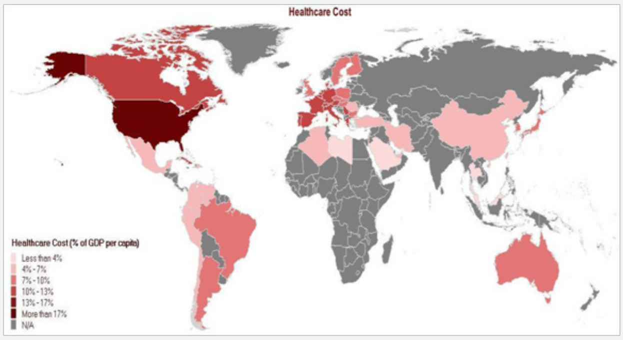

Figure 2: Healthcare cost among all countries.

Health care is the number one domestic industry in the United States and one of the largest industries in the developed and developing countries, as well as it is a service-oriented industry. It is a particularly significant service industry given not only the criticality of quality and safety in delivering patient care [1], but also the associated cost involved as it is expected to account for 20% of gross domestic product (GDP) or $4 trillion in the USA in 2015 [2]. Figure 2 compares the total expenditure on health care among several countries, as a percentage of the GDP. These concerns extend beyond the USA, leading to increasing research interest in global healthcare operations [3]. OR provides a broad range of methodologies that can help health care systems to significantly improve their operations. Technologies, tools and theories of decision-making OR is many different topics and issues in health care. There are at least three reasons why operations research is relevant to health. To improve programme outcomes in relation to medical care or prevention, to assess the feasibility of new strategies or interventions in specific settings or populations, and we have to advocate policy change [4] (Figure 2).

Healthcare has become one of India's largest sectors both in terms of revenue and employment. Healthcare comprises hospitals, medical devices, clinical trials, outsourcing, telemedicine, medical tourism, health insurance and medical equipment. The Indian healthcare sector is growing at a brisk pace due to its strengthening coverage, services and increasing expenditure by public as well private players. Indian healthcare delivery system is categorized into two major components public and private. The Government, i.e. public healthcare system comprises limited secondary and tertiary care institutions in key cities and focuses on providing basic healthcare facilities in the form of primary healthcare centers (PHCs) in rural areas. The private sector provides majority of secondary, tertiary and quaternary care institutions with a major concentration in metros, tier I and tier II cities. India's competitive advantage lies in its large pool of well-trained medical professionals. India is also cost competitive compared to its peers in Asia and Western countries. The cost of surgery in India is about one-tenth of that in the US or Western Europe. The comparison of a few Indian major states with highest healthcare cost is given in (Figure 3).

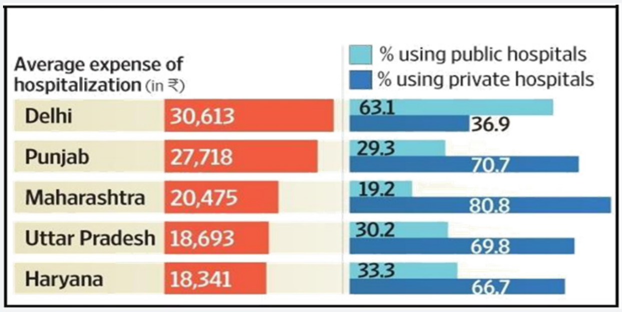

Figure 3: States with highest healthcare cost in India.

Demographic change and increasing health expenditures in the world make the healthcare research a hot topic. Hospitals in the world are becoming larger to take advantage of the scale economy but also become more complex to design and to operate. Ageing population makes constant diseases increasingly significant and leads to the need of better disease prevention, diagnostic, treatment planning and proactive cares. Patients are more and more concerned by healthcare safety and traceability. Healthcare systems are also changing and new health services such as home healthcare and telemedicine are growing. Most hospitals used to empiric management are not prepared for and innovative systems engineering approaches are needed. Recent development of advance medical technologies makes the systems engineering approach possible. The increasing availability of healthcare relevant data makes possible better disease prevention, diagnostic and healthcare system operations. Innovative OR techniques have been designed for a broad range of healthcare applications such as operating room planning, emergency department staffing, breast cancer screening, radiotherapy treatment planning, home healthcare planning, long-term care planning and scheduling.

Facing these challenges, the very first attempts of the hospitals are to apply modern management techniques from other industries. This leads to numerous hospital projects on lean management, quality control, inventory control, etc. Most of these projects had limited impacts due to their strong dependence on experiences of consulting firms gained from other industries and hardly took into specific features of. Hospitals realized more and more the need of original research taking into specific features of healthcare industry. Various scientific communities quickly embraced major healthcare challenges from different perspectives. Emerging hot topics of the robotics & automation community include lab automation, lab-on-chip, surgical navigation, nanoscale drug delivery, medical imaging analysis, etc. Other communities such as OR and Industrial Engineering have been very active in healthcare management research. Major Operations Research and Industrial Engineering journals publish more and more papers in healthcare and OR/IE conferences often have very popular sessions in healthcare such as surgery planning/scheduling, nurse rostering, emergency department analysis, ambulance location/dispatching and so on.

Operations research is increasingly recognized as essential to strengthen health programs. For example, expanded stop tuberculosis (TB) strategy research clearly acting as a key element of successful programs of TB. It has various definitions depending on the scenario, scientists, and the type of search. The International Union against TB and Lung Disease and many of its research partners define OR as research into strategies, interventions, tools or knowledge that can enhance the quality, coverage, effectiveness or performance of the health system or programme in which the research is being conducted [4]. Mistry et al. [5] derived a local agenda for OR: modeling the effects of newer technologies, active case detection, and changes in timing of activities, and mapping hotspots and contact networks; modeling the effects of drug control, changing the balance of ambulatory and inpatient care, and adverse drug reactions; modeling the effects of integration of TB and HIV diagnosis and management, and preventive drug therapy; and modeling the effects of initiatives to improve infection control.

Healthcare OR is not a new field; many health care researchers and planners use concepts and methodologies which, in the business world, are often associated with the practice of operations research. These concepts and methodologies most often deal with problems in the areas of: Healthcare operations improvement; Inventory and Supply chain management; Facility location and layout; Prevention, detection and treatment of diseases; Resource allocation; Clinical diagnosis and decision making; and Treatment design and planning. In the context of matter and the flow of patients and healthcare logistics management operations offer a wide range of applications for

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the analysis of operations research techniques. We review below the applications area of OR in healthcare.

Operations Research in Healthcare: Literature Review

An area that has received considerable attention among OR scholars is workforce scheduling, and in particular, nurse rostering. The problem of working hours of construction for nurses to meet fluctuations in demand is extremely difficult. Service plans must comply with the requirements of the work of nurses distinguish permanent and temporary staff are qualified to provide holidays and day, night and nurses evenly over the weekend and set preferences for class officers. Linear, mixed integer and goal programming with constraint programming methods have been developed to generate nurse rosters [6]. Reviews of literature on nurse rostering are available in Burke et al. [7] and Lim et al. [8].

Appointment scheduling has also been a rich research area over the past decades (e.g. see Gupta and Denton [9]). The process of assigning time slots for serving out- and inpatients arises in diagnostic and treatment units deals with uncertain service times, no-shows, cancelations, and walk-ins. A good appointment schedule keeps patient waiting times short and minimizes staff overtime taking into account the patient load and the available resources (i.e. staff, rooms, and equipment)? In view of this numerous authors developed models with the objective of

i. How many patients to schedule?

ii. How to allocate appointment slots throughout working day?

iii. What is the optimal sequencing of heterogeneous patients.

Recently, Granja et al. [10] developed an optimization model based on simulation approach to the patient admission scheduling problem using a linear programming algorithm. Richard et al. [11] provided an improved method for solving the so-called dynamic patient admission scheduling (DPAS) problem. Atlie et al. [12] presented an exact method for Patient Admission Scheduling (PAS) problem based on a recursive logic-based Benders' decomposition where each sub problem is formulated as an integer linear program. Turhan et al. [13] addressed two Mixed Integer Programming based heuristics namely Fix-and-Relax and Fix-and-Optimize where PAS problem instances are decomposed into sub-problems and then the sub-problems are optimized.

Kidney dialysis therapy initiation for evaluating cost and effectiveness is investigated in Lee et al. [14]. They used Approximate Dynamic Programming and Simulation to determine an optimal therapy and a strategy for maximizing patient welfare. Chen [15] proposed the kidney allocation problem. He assumed that the decision has to be made within a fixed time horizon because a kidney is perishable and the kidneys are limited. He addressed that the objective of kidney allocation problem is to determine the allocation rule to maximize the total expected value achieved. The arrival, demand pattern of patients is random. When we replace kidneys with airline tickets and patients with travelers, we get the airline yield management problem. When we replace kidney and patient by job and worker respectively, it has the typical scheduling problem. Recently, Thamer et al. [16] developed a risk score to assist shared decision making for kidney dialysis initiation. Then Bagshaw et al. [17] addressed strategies for the optimal timing to start renal replacement therapy in critically ill patients with acute kidney injury

Operating theater planning and scheduling (OTPS) has also received much attention in the past 60 years. The strategic (long term) planning level addresses capacity planning given a forecast of patient demand. Typically, the operating theaters and the time allocated to each activity of the department at the time. The tactical (mid-term) planning level deals with the creation of weekly/monthly (rough) schedules for elective surgeries. Operational planning, the operational plan for the next day, generating a sequence of operations in each operating room early and distribution activities and some resources. Finally, the online planning level deals with rescheduling previously planned surgeries as a result of unforeseen events such as delays, emergencies, and cancelations. The rich and still growing literature on OTPS covers a wide range of OR methodologies (heuristic approaches, and simulation) for deterministic and stochastic environments [6]. Reviews of literature up to 2010 on Operating Theater planning and scheduling are available in Cardoen et al. [18]. Recently, Wang et al. [19] investigated an operating theater allocation problem with uncertain surgery duration and emergency demand. In Wang et al. [19], the operating room allocation problem with cancellation risk is mathematically formulated as follows:

$$J = \sum_{r \in R} c^f x_r + c^v E_w\left(\sum_{r \in R} O_r^w\right)$$

subject to

$$y_{ir} \le x_r \quad \forall i \in I, \forall r \in R$$

$$\sum_{r \in R} y_{ir} = 1 \ \forall i \in I$$

$$O_r^w = \left(\sum_{i \in I} y_{ir} d_i^w + e_r^w - T\right)^+ \quad \forall r \in R, \forall w \in \Omega$$

$$P\left(\sum_{i \in I} y_{ir} d_i + e_r > T + H\right) \le \beta \ \forall r \in R$$

$$x_r, y_{ir} \in \{0,1\} \ \forall i \in I, \forall r \in R$$

Strategic operating theater planning belongs to the group of resource allocation and capacity planning problems. This group involves decisions concerning the mix and volume of patients treated by a hospital and the amount, capability, and type of resources for the delivery of healthcare. Hospital layout planning is also at the strategic level, but has received much less attention. The goal is to design a hospital, a clinic or a department in order to minimize the movements of patients and accompanying resources such as medical staff and equipment [6]. Quadratic integer programming models were proposed by Butler et al. [19]

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and Elshafei [20] for problems arising in this area.

Patient transportation is a variant of the dial-a-ride problem (DARP) and concerns finding a set of minimum-cost routes and schedules for a feet of ambulances (or hospital staff) to transport (or escort) inpatients between nursing wards and diagnostic units. Hospital-specific constraints (e.g. different priorities of requests, needs special equipment and support medical staff during transport and handling of incomplete knowledge in advance) significantly complicate the development of high-quality vehicle routes and schedules. The latter is often controlled by the imposition of the travel time of the patient and minimizing deviations from the desired times for pickup and delivery [21]. By its nature DARP combined extremely difficult to solve, which has contributed to the development of new OR, in particular the new (meta-) heuristic methods allowed [6]. Beaudry et al. [22] and Kergosien et al. [23] proposed tabu search based approaches, while Hanne et al. [24] embedded an evolutionary algorithm in a software application designed to support all phases of the transportation flow including request booking, scheduling, dispatching, monitoring, and reporting. Recently, Knyazkov et al. [25] illustrated the evaluation of Dynamic Ambulance Routing for the Transportation of Patients with Acute Coronary Syndrome in Saint-petersburg. Zhang et al. [26] addressed a real-life public patient transportation problem derived from the Hong Kong Hospital Authority (HKHA), which provides ambulance transportation services for disabled and elderly patients from one location to another.

Aiming at improving the efficiency and reliability of ambulance service, several location models for ambulance stations have been proposed in the OR literature. Well-known approaches to this problem are coverage model and median model. Coverage model looks for the location to maximize the (deterministic or probabilistic) covered demand of ambulance calls. Hence this model can be thought of reliability oriented model. On the other hand in median model the objective is to minimize the total traveling distance of the ambulances from the station to the scene of call. This model gives more weight to the efficiency of ambulance operation [27]. Morohosi [27] addressed the comparison of those optimization models through actual patient call data from Tokyo metropolitan area to show the characteristics of each model and investigate a possibility of improvement in ambulance service.

Problem of patients overflow in wards is addressed by Teow [24] The demand of hospital's inpatient beds by medical specialties changes according to patients' volume over time. With no adjustments to the allocation of beds, the growing mismatch will result in unnecessary patients' overflow. This will lead to poor patient care, travel health workers redundant and the waiting bed. Hence, hospitals need to periodically review their bed allocation by specialties. The bed reallocation exercise is typically a zero-sum game: some specialties will end up with more beds while others with fewer beds. Teow [24] suggested the structure of the patients overflow problem. He first established bed demand for each specialty using patient-day. He stated that the objective of the problem is to assign the beds (i.e. decision variables) such that the specialties will end up with equitable bed occupancy rates (i.e. outcome), subject to number of beds available (i.e. constraint). Litvak et al. [28] presented a mathematical method for computing the number of regional beds for any given acceptance rate. In Litvak et al. [29], for blocking probability, they computed the famous Erlang loss formula

$$B(c, \rho) = \rho^c / c! \Big/ \sum_{k=0}^{c} \rho^k / k! \text{ where } \rho = \lambda \mu^{-1}$$

is the load, with λ the call arrival rate, and μ-1 the mean call length based Equivalent Random Method (ERM), and they schematically depicted (Figure 4) the patient flows for two ICUs (Figure 4).

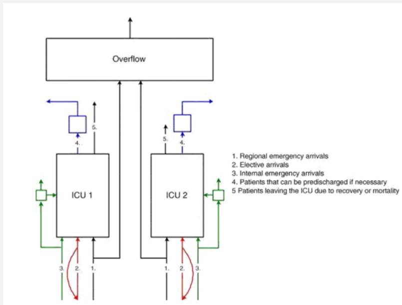

Figure 4: Overview of the ERM including all patient streams [28].

Outpatient appointment scheduling in health care has been researched over the last 50 years. Various scheduling rules have been proposed in different research works Bailey [30] and Cayirli [31]. A good appointment schedule is one that trade-offs patients waiting time for clinics overtime, constrained by the patient load and staffing. Operations research researchers use techniques such as queueing theory and discrete event simulation to propose various appointment strategies under different clinics settings. Some planning strategies can be very complex. Although the list of applications for logistics and research hospital management operation is far from over, above shows the range of possibilities in the field of operations research in hospitals [29].

Optimization issues in healthcare have become noticeably significant and attract keen interest from the OR community. Chen [32] addressed the optimization and decision support in Brachy therapy treatment planning using OR techniques. He expressed that the planning means finding a pattern of sources that is consistent with do simetric constraints in brachy therapy. He formulated the following objective (0-1 mixed integer programming) for the problem of Brachy therapy treatment planning and suggested the Branch and bound method to solve it: Objective = Rewards - Penalties, where the rewards are the effect of the treatment and the penalties are the side-effect on the surrounding healthy tissues. The graphical illustration of the Brachy therapy treatment is shown in (Figure 5).

Figure 5: Graphical illustration of the Brachy therapy treatment [32].

Minimization of the total treatment time in cancer radiotherapy using multileaf collimators is studied by Wake et al. [14]. The approach considers a Mixed Integer Program that happens to be a modification of a cutting-stock problem formulation. Maillart et al. [33] developed a Markov chain model for investigating the proper frequency of mammography screening. They analysed a broad range of screening policies and discussed computational results. Lee and Zaider [34] described a clinical decision support system for treatment planning in Brachy therapy (placement of radioactive seeds inside a tumour) and used Mixed Integer Program for optimization. Recently, Holder [35]) gave a comprehensive discussion of linear and non-linear programming models for Intensity Modulated Radiotherapy Treatment (IMRT). Nightingale et al. [36] surveyed the current practices of preparation and management of radical prostate radiotherapy patients during treatment.

Accurate demand forecasting is indispensable in healthcare planning, it results providing the input to numerous optimization problems. Cote and Tucker [37] discussed four common methods for forecasting demand for healthcare services: percent adjustment, 12-month moving average, trendline and seasonality. Xue et al. [38] analysed the continued growth of the end-stage renal disease population in the United States. They forecasted up to the year 2010 using historical data with stepwise autoregressive and exponential smoothing models. The accuracies of various forecast methods were evaluated by Jones et al. [39]. They used data from daily patient arrivals at the emergency departments of three different hospitals and considered the following methods: time series regression, exponential smoothing, and seasonal autoregressive integrated moving average and artificial neural network models.

Hospital capacity planning is full of challenging problems for OR practitioners. Green and Savin [40] used OR-based analyses to address the increasingly critical hospital capacity planning decisions. They used a queuing model formulation and gave examples of how OR models can be used for deriving significant insights and operational strategies. Figure 6 shows the example of Hospital capacity alternative. A cooperative solution approach for hospital capacity to treat emergency patients in the Netherlands is proposed in Litvak et al. [41]. Adan et al. [42] addressed the problem faced at a cardiothoracic surgery center for optimizing resource utilization. They modeled it as a Mixed Integer Program having stochastic lengths of stay. Burdett & Kozan [43] proposed a multi-objective optimization (MOO) approach to perform a system wide analysis of public hospital resources and capacity. Recently, Burdett et al. [44] derived a mixed integer linear programming approach to perform hospital capacity assessments. They developed the following optimization model

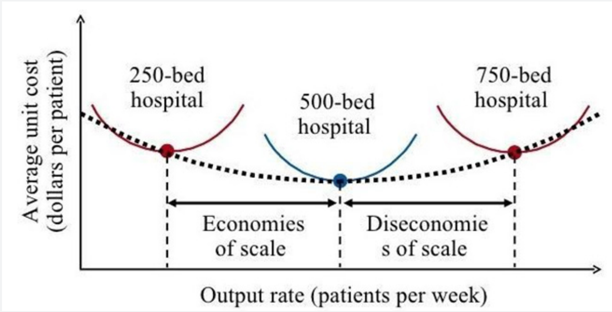

Figure 6: Example of Hospital capacity alternative.

Minimize= $\sum_{m} \sum_{i\in[1,I]} \delta_{m,i} \cdot \dot{y}_{m,i}$ subject to some realistic constraint (Figure 6).

Increase in longevity, escalating health-care costs and the emergence of new diseases in recent years have forced medical decision-makers to focus strongly on preventive and specialized. According to Rais and Viana [45], optimization problems related to the prevention of diseases concern mostly vaccine selection. The vaccine selection algorithm has been extensively studied as it was first introduced in Jacobson et al. [46]. Wu et al. [47] formulated the annual vaccine-strains selection problem as a stochastic dynamic program. On the other hand, Earnshaw et al. [48] addressed a resource allocation problem for HIV prevention and developed a linear-programming model for improving on past allocation strategies.

Unlike many industries, healthcare managers have to manage very complicated distribution networks and inventory management problems without proper guidance on efficient practices. This is because most hospital administrators and pharmacy managers are doctors with expert knowledge in medicine, and are not supply chain professionals. Hence, given the high costs, coordination, constraints, and perishability of pharmaceuticals, more study is necessary to help health care managers in setting optimal supply chain management policies. Operations research provides a wide range of methodologies that can help hospitals and other health care systems to significantly improve their operations. Kelle et al. [49] provided decision support tools that improve operational, tactical, and strategic decision-making supply chain management under an inventory

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policy that involves periodic review. Amir et al. [50] developed a generalized network oligopoly model for PSC competition that takes into account product perishability, brand differentiation, and discard costs. Priyan & Uthayakumar [51] designed the supply chain management strategies for a pharmaceutical company and a hospital. Priyan & Uthayakumar [52] framed an optimal inventory management strategies for healthcare supply chain in a fuzzy–stochastic environment. Nematollahi et al. [53] derived an economic and social collaborative decision-making on visit interval and service level in a two-echelon pharmaceutical supply chain.

Conclusion

A brief review of operations research (OR) applications to healthcare system are addressed in this paper. The purpose of this paper is to identify the existing literature on the wide range of operations research (OR) studies applied to healthcare, and to classify studies based on application type and on the OR technique employed. Based on this review, we recognized that commonly used OR approaches fall into four categories: mathematical programming (deterministic and stochastic), heuristics, queuing theory, and simulation.

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