Operating Room Capacity Planning Decisions

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Abstract—Operating rooms are important assets for hospitals as they generate the largest revenue and, at the same time, produce the largest cost for hospitals. The model presented in this paper helps make capacity planning decisions on the combination of open operating rooms (ORs) and estimated overtime to satisfy the allocated OR time to each specialty. The model combines both decisions on determining the amount of OR time to open and to allocate to different surgical specialties. The decisions made are based on OR costs, overutilization and underutilization costs, and contribution margins from allocating OR time. The results show the importance of having a good estimate of specialty usage of OR time to determine the amount of needed capacity and highlighted the tradeoff that the OR manager faces between opening more ORs versus extending the working time of the ORs already in use.

Keywords—capacity planning, contribution margins, operating room, overutilization

I. INTRODUCTION

OPERATING ROOM (OR) is the greatest source of revenue for hospitals [6]. It is estimated that revenue generated from ORs account for an estimated 40% of total revenue [12]. Because of the increasing demand for health care and competition for resources; in addition to OR contribution to hospitals revenue, decisions related to allocating OR capacity or expanding the capacity of the OR are of great importance and greatly impacts the quality and cost for the different stakeholders involved; namely, patients, surgeons, and hospital administrators. In many hospitals, surgery planning and scheduling is carried out in the following steps: A surgery planner or decision maker in the first step will determine the amount of available capacity, which is the OR time and how much of that capacity to allocate to elective cases which will be scheduled in advance or to emergency cases which will be performed as soon they arrive. The elective case capacity of OR time is allocated to the different specialties based on demand and historical use of OR time. Blake et al. [5] developed an integer programming model and post-solution heuristic to allocate OR time to different departments based on each department requirement and assigning penalty for undersupply. Strum et al. [18] and Strum et al. [19] used a minimal cost model of underutilization and overutilization to determine the optimal amount of OR time to allocate to each specialty.

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Zhang et al. [20] used a finite-horizon mixed integer programming approach for allocating OR capacity; the developed model determines a weekly OR allocation template that minimizes inpatient cost measured as their length of stay.

The second step in surgery planning after allocating the OR time to specialties is to assign the OR time for each specialty or department to the different surgical groups. Different papers in the literature suggest different models to assign OR time to surgical groups [2,3,4,10]. Blake et al [4] used integer programming to assign block time to surgical groups while Dexter et al. [10] used a time series analysis to forecast the total hours of elective cases of allocation of OR time for surgical groups.

The last step in surgery planning is to assign operations to rooms for each surgical group. Ozkarahan [16] used goal programming to allocate surgeries to ORs based on room utilization, surgeon preferences, block restrictions, and intensive care capabilities.

During surgery planning and scheduling, OR time is assigned and allocated mainly based on demand by department, specialties, and surgical groups and on the available OR time. Hospitals try to assign as much as they can from the available OR time to achieve high usage and utilization to meet the increasing demand for health care services and reduce costs while improving quality of care. Several papers in the literature studied OR scheduling use of demand and OR utilization as the basis to allocate OR time [2,3,4,16]. Integer programming and goal programming were the common methods used in these papers.

A new direction in the literature argued that OR time should be assigned and allocated based on contribution margins [7,8,14]. Contribution margin is defined as the hospital revenue generated by a surgical case minus all hospitalization variable labor and supply costs. The reason Macario et al. [14] advised to use contribution margin is the result of their study on the variation of contribution margin per hour of OR time among surgeons where they found that that the contribution margin per hour was negative for 26% of the cases. Dexter et al. [7] and Dexter et al. [8] have also found that contribution margins per hour of OR time varied more than 1000% among surgeons. However despite the argument to use contribution margins, the OR time is still allocated heavily based on OR utilization. Assigning OR time using contribution margins only will only result in assigning the surgical group with the highest contribution margin in as many OR time blocks as they want which does not help the OR planner to achieve the desired balance in the schedule.

The financial measures of OR such as cost, profitability, and contribution margin are considered mainly when capacity expansion decisions are to be made [9,13]. Lovejoy et al. [13] built a model to determine how the hospital can expand its capacity by investigating three performance criteria; wait to

get on schedule, schedule procedure start-time reliability, and hospital profits. Dexter et al. [9] considered the problem of allocation of OR time where the strategic decision had been made to increase the number of ORs with a contribution margin being used as the criteria to allocate operating groom time.

It is worth noting that the most important element for consideration is not profitability but rather the contribution margin, which reflect both the labor and supply costs. Contribution margin is a more equitable and balanced number that can be contributed directly to surgeon, service, or procedure consumption. Resnick et al. [17] pointed that surgeons contribute significantly to hospital margin with certain specialties being more profitable than others. Payer mix, the penetration of managed care, and negotiated contracts as well as a number of other factors all have an impact on an individual hospital's margin. Hospital managers and doctors have been trying to understand each individual factor that comprises the total cost of providing health care and are willing to learn new and innovative techniques that would enhance the productivity and reduce the cost of health care delivery [11].

This paper is concerned with making strategic decisions regarding the planning of the ORs. The decisions involve capacity decisions and OR time allocation decisions. The developed model is solved for both weekly and daily target OR times for each specialty; and for each case, different levels of overtime cost were considered.

The organization of the paper is as follows. In section 2, the methodology and solution approach are introduced. In section 3, the data used in testing the model are described and results are presented along with discussion on our findings. Finally, conclusions are given in section 4, together with suggestions for future work.

II. Mythology and solution approach

Integer programming model was developed in this work to combine OR capacity decisions with OR time allocation decisions. Capacity decisions involve determining the combination of how many ORs should be open and how much overtime, if any; those ORs will be open for to meet the OR demand. The capacity decisions are based on the cost to open the ORs in addition to OR overutilization cost and underutilization cost. The contribution margin which results from opening the ORs and assigning them to the different specialties is also taken into consideration when making capacity decisions.

OR time allocation decisions involved determining the amount of OR time that must be allocated to the different specialties to minimize the underutilization cost and overutilization costs in addition to improving the contribution margins from assigning operating room time. The allocation decisions attempts to meet a target value for the amount of operating room time to allocate to each specialty; the target values are estimated using the historical usage of operating room time for each specialty and the overtime and undertime costs; the target values are calculated using the suggested

approach by Strum et al. [18] and Strum et al. [19]. The time horizon can be every six months or annually depending on variability in demand for the OR time.

Specialties weekly usage of OR time will be used to estimate the target values for OR time requirement for each specialty.

Mathematical model
Model parameters
Subscripts

s specialty; takes on values from 1 to g

i operating room; takes the values from 1 to n

d   day of the week; takes the values from 1 to 5 which represents Monday to Friday

Decision Variables

X_s amount of operating room time to allocate to specialty s

Y_{isd} room opening decision. 1 if operating room i on day d is open and assigned to is open for specialty s and 0 if closed

Z_{isd} amount of overtime in operating room i on day d open for specialty s

Deviation variables

t_s^-, t_s^+ negative and positive deviation between the target weekly operating room time for specialty s and amount of time allocated to that specialty

UT_s amount of undertime from allocating OR time to specialty s

Coefficients

CM_s contribution margin from assigning 1 hour of operating room time to specialty s

TCM_s target contribution margin per hour from assigning time of operating rooms that can perform cases for specialty s to specialty s

C_s^R cost of opening an operating room for specialty s

C_s^o cost of working overtime in an operating room assigned to specialty s

C_s^u cost of working undertime in an operating room assigned to specialty s

δ^+ maximum allowed positive deviation percentage from target weekly operating room time for specialty s

δ^- maximum allowed negative deviation percentage from target weekly operating room time for specialty s

Right hand side values

OT_i amount of overtime operating room i can be open for on day d

TT_s target weekly operating room time for specialty s

R_{is} takes value of 1 if cases for specialty type s can be performed in operating room i. Each operating room can service different specialties but can be open only for one

The model

$$\min \left(\sum_{d=1}^{5} \sum_{s=1}^{g} \sum_{i=1}^{n} C_s^R * Y_{isd} \right)$$
$$+ \left(\sum_{d=1}^{5} \sum_{s=1}^{g} \sum_{i=1}^{n} C_s^o * Z_{isd} \right)$$
$$+ \left(\sum_{s=1}^{g} (C_s^o * t_s^-) + (C_s^u * t_s^+) \right)$$
$$+ \left(\sum_{s=1}^{g} (C_s^u * UT_s) \right)$$
$$+ \left(\sum_{s=1}^{g} \left(\left(\sum_{d=1}^{5} \sum_{i=1}^{n} ((8 * Y_{isd}) + Z_{isd}) \right) \right.\right.$$
$$\left.\left. * (TCM_s - CM_s) \right) \right)$$

Subject to

$$X_s + t_s^- - t_s^+ = TT_s \quad \forall s \tag{1}$$
$$t_s^+ \le \delta^+ * TT_s \quad \forall s \tag{2}$$
$$t_s^- \le \delta^- * TT_s \quad \forall s \tag{3}$$
$$\sum_{d=1}^{5} \sum_{i=1}^{n} (Z_{isd}) + \sum_{d=1}^{5} \sum_{i=1}^{n} (8Y_{isd}) \ge X_s \quad \forall s \tag{4}$$
$$\sum_{d=1}^{5} \sum_{i=1}^{n} (8Y_{isd}) \le X_s + UT_s \quad \forall s \tag{5}$$
$$\sum_{s=1}^{g} Y_{isd} \le 1 \quad \forall i, \forall d \tag{6}$$
$$Y_{isd} \le R_{is} \quad \forall i, \forall s, \forall d \tag{7}$$
$$\sum_{s=1}^{g} Z_{isd} \le OT_{id} \quad \forall i, \forall d \tag{8}$$
$$Z_{isd} \le Y_{isd} * OT_{id} \quad \forall i, \forall s, \forall s \tag{9}$$
$$Y_{isd} \in \{0,1\} \; \forall i, \forall s, \forall d$$
$$Z_{isd} \ge 0 \; \forall i, \forall s, \forall d$$
$$X_s, t_s^+, t_s^- UT_s \ge 0 \; \forall s$$

The objective function has five terms and measures an overall performance of cost. The terms in the objective function are:

- Cost of opening ORs: the first term in the objective function reflects the cost of opening an OR that can perform specialty s cases to specialty s.
- Cost of working overtime: the second term in the objective function is the cost of an OR opened to specialty s working overtime.
- Undertime and overtime cost penalty: the third item in the objective function is a penalty cost on the deviation from the target weekly OR time for specialty s. For negative deviation there will be overtime cost penalties and for positive deviation there will be undertime cost penalties. The reason penalties are assigned is because the assigning the exact amount of target weekly OR time for specialty s will result in minimum overutilization and underutilization costs because the target time value was calculated based on it.
- Undertime cost from opening an OR for a specialty and the specialty will use only part of the time in that room.
- Contribution margin loss from assigning OR time: the last item is a penalty which represents the loss from assigning the OR time to specialties that yield contribution margin less than targeted contribution margin.

Constraint (1) will try to match the amount of OR time allocated for each specialty with the amount targeted for that specialty. Constraint (2) and (3) will give the OR manager control over how much deviation is allowed from the target OR time for each specialty. Constraint (4) will ensure that the amount of open ORs time where cases for specialty s can be performed is enough for the allocated OR time to that specialty s. Constraint (5) is to calculate the amount of undertime in cases where the amount of open OR time for a specialty is more than the allocated OR time for that specialty.

Constraint (6) is unique assignment constraint to make sure that each OR on each day if it is open then it will be open only for one specialty. Constraint (7) is concerned with ensuring that an OR will be open for specialty s only if it can perform cases for that specialty. Constraint (8) will limit the amount of overtime each OR will be open for to what is allowed. Constraint (9) is to make sure that an OR will not have overtime hours for specialty s unless that OR is open and open for that specific specialty

III. DATA, RESULTS, AND DISCUSSION

A. Data

The data used in this paper is based on information derived from interviews with two local hospitals in Arizona-USA, operating suite settings from Marcon et al. [15] and a sample solution from Amblitel [1]. Data used to test the model are considered reasonable estimates for a small to midsized hospital's surgical suite.

We assume there are three service types (S1, S2, and S3) which represent Orthopedics, Ophthalmology, and General surgery and the surgical suite has ten ORs [15]. Each OR can serve one or more certain types of specialties but can only be assigned to one specialty. For each OR there is a limit on the maximum amount of overtime that an OR can be used on each day. There is a fixed opening cost for each room that depends on the specialty it is going to be open for as well as an overtime and undertime costs that are related to that OR and specialty. For each specialty there is a target amount of OR time that must be assigned to that specialty to minimize the underutilization and overutilization costs. The target amount of OR time is determined using the approach suggested by Strum et al. [18] and Strum et al. [19] where the target value should be the value that gives the minimum overutilization and underutilization costs. They have developed a model where the minimum cost solution can be determined by knowing the usage probability distribution and relative hour cost of under and overutilization.

From the historical data for each specialty we can determine the probability distribution of OR demand (weekly usage and daily usage). We have assumed normal distribution for specialties usage of OR time. After determining the probability distribution, we have determined the target value as $100 \left(1 + \frac{C_s^u}{C_s^o}\right)^{-1}$ percentile of the probability distribution. For example, if the overtime cost is twice the undertime cost then the target value will be 67th percentile of that specialty usage probability distribution function. For the daily target OR time we used the probability distribution for each specialty for each day and for the weekly target OR time we have added the daily distribution for each specialty over all the week days and calculated the target value. The model also will give the decision maker an option to determine what negative and positive deviations from the target value of OR times for each specialty are acceptable. The OR planner sets a target value for the contribution margin and for each specialty there will be contribution margin that was determined as an average of contributions margins from all surgeons who perform cases for each specialty. Target contribution margins are determined from historical data and any increase in variable costs. Surgeons' contribution margins were obtained from sample solution from Amblitel [1]

B. Results and discussion

After generating the data for the weekly and daily target OR time for each specialty, we ran the model using different values for the OR overtime costs. Table 1 and Table 2 show the results for the weekly and daily runs consecutively with Figure 1 showing a sample result for the Master Surgery Schedule (MSS) for the case when overtime cost equals 1.5 of regular time.

From Table I and Table II we can see that the higher the cost of overtime, the target values for operating time will subsequently be higher. This means more ORs will be open and more ORs will be open for overtime which drives the cost

up. In cases where overtime cost is high, we advise to study the feasibility of adding more rooms to the capacity.

TABLE I
MODEL RESULTS USING WEEK TARGET VALUES OF OPERATING GROOM TIME FOR SPECIALTY. 50 ORs AND 110 HOURS OF OVERTIME ARE AVAILABLE EACH WEEK

$\left(1 + \frac{C_s^u}{C_s^o}\right)^{-1}$	Target OR time	Allocated OR time	# of open ORs	# of overtime hours open	Objective function value
50th	392	392	43	48	$90000
56th	400	400	49	8	$92390
60th	405	405	49	13	$95300
67th	416	416	50	16	$100650
75th	428	428	50	28	$113800

TABLE II
MODEL RESULTS USING DAILY TARGET VALUES OF OPERATING GROOM TIME FOR SPECIALT. 50 ORs AND 110 HOURS OF OVERTIME ARE AVAILABLE EACH WEEK

$\left(1 + \frac{C_s^u}{C_s^o}\right)^{-1}$	Target OR time	Allocated OR time	# of open ORs	# of overtime hours open	Objective function value
50th	392	373	42	56	$87700
56th	409	391	44	38	$96921
60th	420	399	47	30	$104780
67th	441	427	50	32	$118600
75th	467	449	50	45	$145950

There is a significant difference between the daily and weekly target values for OR time which highlights the importance of having better estimates for the amount of OR time. The less variation we have in the daily estimate of the probability distribution of OR usage the less difference we will have between the daily and weekly target. The difference will also highlight negotiating with the department to have their OR time allocated to them based on their weekly usage rather than daily usage and to adjust their allocations of OR time to their surgical groups accordingly. If the OR planner decides to use weekly target values for OR time then it will result in lower overall cost and lower overtime hours.

IV. CONCLUSION

In this paper we developed a model to combine decisions of allocating OR time to the different specialties with decisions on deciding on the combination of open ORs and overtime to satisfy those allocations. Our decisions are based on OR cost, overutilization cost, underutilization cost, and contribution margins from allocating OR time. The model will give the OR decision maker a tool to plan the capacity and activities of the surgical suite. Results from testing the model highlighted the importance of having a better estimate of specialties usage of OR time and its impact on the cost and capacity decisions of the surgical suite. The model also highlighted the tradeoff between the overtime cost and adding more capacity to the surgical suite by opening more rooms.
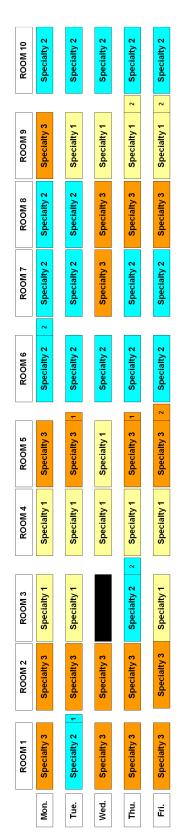
Fig. 1 sample Result Master Surgery Schedule (MSS) for Overtime Cost Equal 1.5 Regular Time

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