Int. J. Computer Aided Engineering and Technology, Vol. 16, No. 1, 2022

Technology for improved operating room scheduling – a case of Kilimanjaro Christian Medical Center of Tanzania

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Abstract: Optimal scheduling of surgeries can result in efficient utilisation of the limited available operating rooms. Considering that operation theatres are an expensive investment, the optimal usage of these facilities will ensure that the dividend from the investment on the facilities is maximised. The integration of proper technology in the scheduling process can aid the creation of optimal schedules of patients who want to undergo surgeries leading to minimisation of patient waiting times under conditions of limited available operating facilities and specialised equipment. This work seeks to model the scheduling of surgeries at Kilimanjaro Christian Medical Center, a referral hospital located on the northern corridor of the Republic of Tanzania. We model the operation room scheduling problem as an integer

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linear programming problem. The model is solved using Torsche toolbox with the help of MATLAB routines and functions by considering appropriate configurations like resources, task parameters and optimisation criterion.

Keywords: optimisation; scheduling; surgery; torsche; $C_{\max}$.

Reference to this paper should be made as follows: Mtonga, K., Kumaran, S., Jayavel, K. and Mikeka, C. (2022) 'Technology for improved operating room scheduling – a case of Kilimanjaro Christian Medical Center of Tanzania', *Int. J. Computer Aided Engineering and Technology*, Vol. 16, No. 1, pp.1–13.

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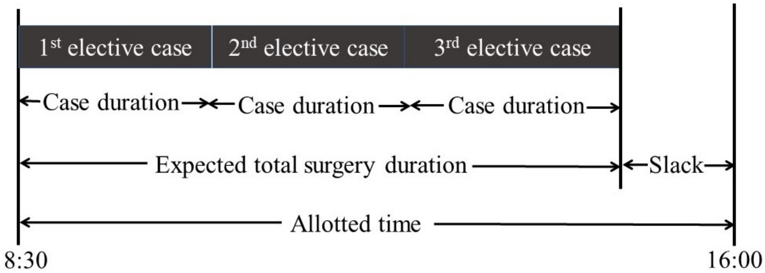
1 Introduction

Operating theatre (OT) planning and scheduling remains an important subject of research (Shuwan et al., 2019, 2020). Considering that many patients undergo surgical interventions in their care pathway, the importance of the OT cannot be overemphasised. Despite their importance, the OT also remains one of the most expensive departments within the health facility, hence planning and scheduling ensures optimal use of this resource. Furthermore, it is important that the waiting time of patients on the waiting list has to be minimised (Dexter et al., 2004). Decisions involving planning can be classified into; strategic, tactical and operational (Anthony, 1965). For healthcare settings, the operational level planning is split into an online and offline operational level, with the former involving the controlling and monitoring of the process in real time and the latter involves advance short decision making (Hans et al., 2011). Tactical level planning involves using patient demand (e.g., surgery appointment requests) to address resources usage. Tactical level planning focuses beyond the surgery sequencing, rather the level verifies whether the planned surgeries will cause resource conflicts for the OT and the subsequent hospital departments (e.g., wards) or for medical instruments. Creation of the master surgical schedule is done at this level (Ruth and Frannklin, 2008).

OT scheduling is classified into several types of strategies (Hongyin et al., 2006), namely; open scheduling, block scheduling and modified block scheduling. Under open scheduling strategy, surgical cases are assigned to an operating room at the convenience of the surgeon; whilst under block scheduling, specific surgeons or groups of surgeons are assigned a set of time blocks, either for some weeks or months into which they can schedule their surgical cases (Ya et al., 2011). Unlike the block scheduling where surgeons own time blocks such that they cannot be released, in the modified block scheduling, the scheduling is flexible, i.e., some time is blocked and some is left open, or unused block time is released at an agreed-upon time before surgery.

Figure 1 Elective surgical time line



The scheduling of OT for emergency surgery is complex due to the different patient arrival patterns and a further need for the patient to wait the minimum possible time before proceeding to OT. Furthermore, for many hospitals, there usually is a reserved operating room on standby for emergency surgery. Hence, in this work we consider the scheduling of OTs for elective surgery. Normally, elective surgery patients will make surgery appointments and will arrive as per the appointment time (Dexter and Traub, 2002). Upon arrival, the nurse prepares the patient for surgery, after which he/she is taken to the operating table. Once the surgery is successfully performed, the patient is taken to the recovery ward. The length of stay in the recovery ward will vary from patient to patient depending on varied factors. Figure 1 shows a general outlay surgical time line for elective surgeries. Each surgery will have a duration time and the slack time (i.e., the reserved capacity) which ensures that overtime is accommodated (Erwin and Peter, 2012).

The problem of operating room scheduling has received considering attention from researchers (Mehdi et al., 2009; Sangdo and Wilbert, 2014; Dexter et al., 1999, 2012, 2010; McIntosh et al., 2006), with approaches such as; queuing models, simulation models, heuristic approaches, deterministic and stochastic mathematical programming models widely used to investigate this problem (Tancrez et al., 2013; Liu et al., 2018; Panos et al., 2013; Kavitha and Venkumar, 2017; Muthiah and Rajkumar, 2017). However, as highlighted by Rym et al. in their work titled 'The planning and scheduling of operating rooms: a simulation approach', some of these models are very complex such that their application requires advanced mathematical programming knowledge; a factor that hinders their adoption by healthcare professionals (Anwar and Rym, 2014). Furthermore, in Sub-Saharan Africa, despite the existing challenge of limited availability of surgical facilities (Sam et al., 2009), much of the research on surgical services has focused on social aspects of the situation rather than on optimised use of the existing infrastructure. Some of the focus of recent research include; assessment of factors driving cancellation of surgeries (Martin et al., 2017), the assessment of cost and emotional impact of cancellation of elective surgeries (Pittalis et al., 2019), studies into how to scale up safe surgeries (Prin et al., 2018), and assessment of factors affecting starting delays in OTs (Assumpta, 2017). This research seeks to bridge this gap by presenting a simple OT optimisation model and further introduce technological tools that healthcare professionals and hospital administrators can use to ensure the optimal use of the limited, yet costly and important surgical facilities.

As pointed out, despite being costly, operation theatres play a crucial role in the provision of healthcare to patients since it is here where the surgical solutions are tried. A typical OT comprises several operating rooms and one or more recovery rooms where recuperating patients will be moved upon completion of the surgery. There are also waiting rooms where patients will be prepared for surgeries. The movement of patients from one section to the other during the entire process needs to be as seamless as possible. This work seeks to study the scheduling problem of operation theatres at the Kilimanjaro Christian Medical Centre (KCMC), an academic tertiary referral hospital (KCMC, 2021). We formulate the OT theatre allocation as an optimisation problem and use the Torsche – a time optimisation, resource scheduling toolbox for MATLAB to solve the problem, where solving implies finding an optimal schedule (Leite, 2010). Below we give an overview of the healthcare system in Tanzania with a focus on the situation at KCMC.

2 Surgery service delivery in Tanzania

In many developing countries surgical care is extremely limited. Tanzania is one such country where millions are in need of surgical care but can hardly access it (Weiser et al., 2008). According to the World Health Organization survey of Tanzanian's primary healthcare services, it was discovered that suturing was routinely available at all medical facilities, against the 35 listed basic interventions. Unfortunately, these medical facilities serve a population of over 23 million with only 64 surgeons, across multiple sub-specialties. These facilities clearly lack the ability to provide a full complement of surgical services (Tom et al., 2011). This puts a burden on a few referral hospitals in the country that have the infrastructure and equipments available and hence have a capacity to deliver emergency care. It is therefore these tertiary referral facilities that are more likely to provide surgical care in its entirety to all patients in need (Tim et al., 2013).

This research uses secondary data of the KCMC, an academic tertiary referral hospital located on the northern corridor of the Republic of Tanzania. Figure 2 shows the data source and general flow of this study. The rural areas of the northern corridor of Tanzania has a population of over 11 million and comprises provinces of Kilimanjaro, Tanga, Arusha, Manyara and Singida (KCMC, 2021). Despite availability of primary medical facilities and other smaller providers of care in the region, this area is primarily served by a single major academic tertiary referral hospital, the KCMC. Usually, the facility is overwhelmed by the enormous demand for surgical services in the region, such that for example; 90% of the population in need of orthopaedic surgery are unable to access the service. The orthopaedic department at KCMC alone sees over 11,000 admitted and outpatient patients per year. Of the annual inpatient census, over 95% require surgical intervention of which less than 60% actually receive surgical care, with the average time to surgical intervention being greater than ten days (Ajay et al., 2016). This clearly demonstrates the existing discrepancy between supply and demand. This mismatch between demand and supply can be attributed to, among other factors; limited physical resources, work-flow issues, OT case mix and patient financial burden (Leshabari et al., 2008; Geoffrey et al., 2017).

Figure 2 Data source and general study flow (see online version for colours)

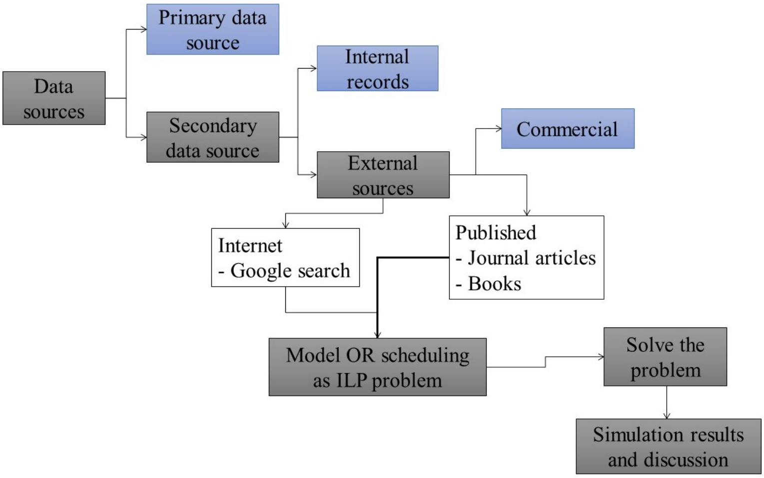


Table 1 Five months analysis of payment methods, operating days, case volume and cancellations for KCMC

Surgery type	*Payment methods*			*Operating days*	*Case volume*	*Cancellation*
	Cash	*Insurance*	*NL/others*			
General	104	11	124	104	244	64
Gynaecology	70	71	3	74	144	33
Orthopaedics	161	132	39	122	323	76
Septic	105	91	12	110	208	65

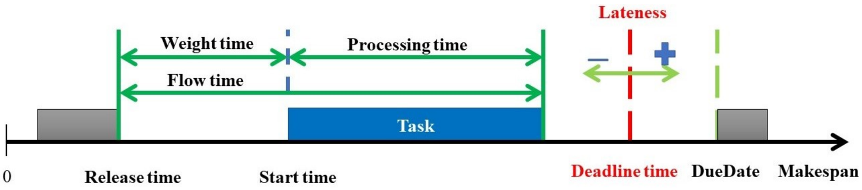
At KCMC tertiary referral hospital, there are five main operating suites, namely; multi-disciplinary emergency surgery, general surgery, orthopaedic surgery, multi-disciplinary septic surgery and gynaecology. At the end of each case, a surgical staff manually records activities of the OT and the records are stored in the administrative rooms in the surgical wards. In this work we use secondary data to demonstrate how technology on scheduling can be used to improve efficiency in the scheduling of the operating rooms at KCMC. In the work titled ‘Understanding surgical care delivery in Sub-Saharan Africa: a cross-sectional analysis of surgical volume, operations, and financing at a tertiary referral hospital in rural Tanzania’, Rajaguru et al. assessed the operations and financing of the main OTs at KCMC through a retrospective review of operating report books. Table 1 summarises the findings from their five months analysis of payment methods, operating days, case volume and cancellations for KCMC selective surgeries (Rajaguru et al., 2019).

Primarily, this work makes use of data as reported in Rajaguru et al. (2019). We derive the mean duration of a surgery procedure and based on this value we schedule the operation rooms such that they all operate nearly the same duration. The rest of this work is organised as follows. We model the scheduling of OTs in Section 3. We solve the derived scheduling optimisation problem and present a discussion of simulation results in Section 4. We end the paper with some concluding remarks and directions for further research in Section 5.

3 OT scheduling and TORSCHE toolbox

Scheduling of OTs can aid in addressing specific objectives that can lead to improved service delivery. Some possible objectives for scheduling may include; minimising patient waiting time, minimising total idle times of operating rooms or minimising $C_{\max}$, i.e., time of completion of last surgery. It is well known that the planning and scheduling of the processes of an operating room area is a very complex task. The complexity is a consequence of the many constraints that need to be met, some of which are opposite in their objectives. These constraints includes; the availability of the surgeon, anaesthetists, and supporting staff. To minimise the patient waiting time and also ensure that there is no overload on any of the resources, it is important that all operating stations function nearly the same duration.

Figure 3 TORSCHE task parameters description (see online version for colours)



Developed by the Czech Technical University in Prague, time optimisation, resources, scheduling (TORSCHE) toolbox for MATLAB supports solving integer linear programming (ILP) problems. In TORSCHE, a task is a data structure, defined with all scheduling process parameters such as; processing time, arrival time, starting time, release time, deadline, due date, etc. Figure 3 is a graphical representation of task parameters in TORSCHE. Below we briefly discuss each of these task parameters.

- *Release time (or ready time):* This is time at which a task becomes ready for execution represented as; r_{Task_j}. If $r_{Task_j} = 0 \; \forall \; Task_j$, it implies that all tasks have the same release time.
- *Start time:* This is time when the execution of $Task_j$ is started, represented as S_{Task_j}.
- *Due date:* This is a time limit $\left(d_{Task_j}\right)$ by which the task should be completed. Associated with the due date are penalty functions that are defined.
- *Deadline time:* This is a *hard* real-time limit $\left(\bar{d}_{Task_j}\right)$ by which a task becomes ready for execution and must be completed.

- *Processing time:* This is time for a task execution, denoted as; P_{Task_j}, where $Task_j = \{task_{j1}, task_{j2}, \cdots, task_{jTask_j}\}$.
- *Completion time:* This is time $\left(C_{Task_j}\right)$ when the execution of a task is finished.
- *Lateness:* This is the time difference in executing a certain task and earliness finishing time operations before meeting the deadline, defined as $L_{Task_j} = C_{Task_j} - d_{Task_j}$.
- *Makespan:* This is time at which the task is finished and it is calculated as; $C_{\max} = \max C_{Task_j}$.
- *Weight (or priority):* This is the priority $\left(\omega_{Task_j}\right)$ of the task.
- *Flowtime:* This is the period required for completing the task. It is the sum of waiting and processing times, i.e., $F_{Task_j} = C_{Task_j} - r_{Task_j}$.

  The performance optimality criterion below is used to evaluate schedules;

  $$\text{Schedulelength(Makespan)}C_{\max} = \max C_l, \tag{1}$$

  where mean flow time is defined as;

  $$\bar{F}_{Task_j} = \frac{1}{n}\sum_{j=1}^{n} F_j \ , \tag{2}$$

  with maximum lateness given by;

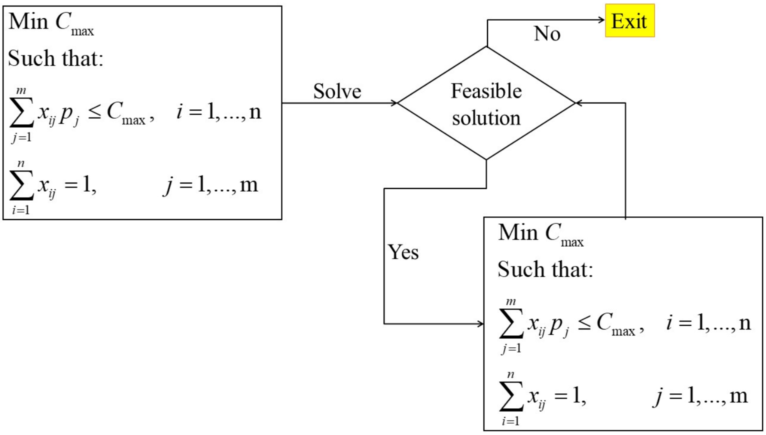
  $$L_{\max} = \max L_l. \tag{3}$$

Our goal is to demonstrate how this tool can be used to solve the problem of scheduling surgeries in the operating rooms of the OT at KCMC so as to optimise time. We formulate the operation room assigning problem as an ILP problem and solve it using the $P||C_{\max}$ scheduling algorithm. The objective of $P||C_{\max}$ scheduling algorithm is to assign a set of independent tasks to parallel identical processors in order to minimise schedule length and preemption is not allowed. The algorithm finds optimal schedule using ILP. This problem is known to be NP hard in the strong sense and is called the $P||C_{\max}$ problem. Recall that at KCMC the OT has five operating rooms (or theatres). Based on data reported in Rajaguru et al. (2019) we drive Table 2. Note that, although cases are treated as independent, however, in practice this may not be the case (Austin et al, 2014).

Table 2 Details of procedures carried out in 5 months at KCMC

Theatre	*Operating days*	*No. of cases*	*Complete procedure mean*	*Operating day length*	*Mean duration/procedure*
General	104	244	2.35	5:52 hrs	2.35 hrs/proc
Gynaecology	74	144	1.95	5:02 hrs	2.6 hrs/proc
Orthopaedics	122	323	2.65	6:12 hrs	2.3 hrs/proc
Septic	110	208	1.89	4:20 hrs	2.22 hrs/proc

Figure 4 Flow of how the scheduling problem is solved (see online version for colours)



For a typical OT scheduling, the basic requirement is that the total duration of surgeries on each of the operating beds is nearly the same with no priority for any of the surgeries. All the operating beds are considered to be equal, in the sense that any surgery could be assigned to any of the beds. However, in real scenarios, the scheduling of the entire surgical process might produce an overhead when different surgeries are scheduled in a surgical bed. Disregarding this however, the OT scheduling problem can be mathematically, formulated as follows:

$$\min C_{\max} \tag{4}$$

Subject to:

$$\sum_{j=1}^{n} x_{ij} p_j \leq C_{\max} \quad i = 1, \cdots, m \tag{5}$$

$$\sum_{i=1}^{m} x_{ij} = 1 \quad j = 1, \cdots, n, \tag{6}$$

where p_j is the duration for which j^{th} operating room is in use, n represents operating rooms and m represents surgeries to be scheduled such that if surgery j is scheduled in room i, $x_{ij} = 1$ else $x_{ij} = 0$. Here, the goal is to minimise the schedule length by assigning a set of surgeries (i.e., independent tasks) to operating rooms (i.e., parallel identical processors). Since the tasks are independent, the execution of a particular task will never get precedence over others. The problem is solved using ILP implemented in TORSCHE Toolbox for MATLAB. Figure 4 shows the flow of how the problem is solved in TORSCHE. Recall that the problem is solvable if a feasible solution (i.e., schedule) exists.

4 Simulation results and discussion

We simulate the scheduling of five operating rooms of an OT. Table 3 summarises the simulation environment.

Table 3 A summary of simulation environment

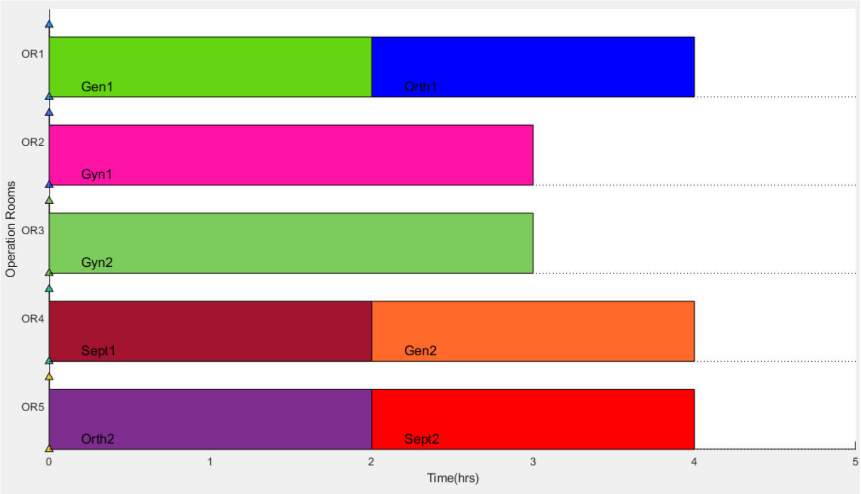
Simulation tools	*Description*
Laptop	Intel(R) Core(TM) i5-5300U CPU @2.30 GHz 2.29 GHz
Operating system	Windows 10 Pro 64-bit
MATLAB	R2018b
TORSCHE	Release 0.4.0

Recall that the problem $P||C_{\max}$ is known to be NP hard in the strongest sense. However, the right hand side $C_{\max}$ is found by some approximation algorithms. Below we briefly describe some of these algorithms (Jacek et al., 2001).

- *Longest processing time (LPT):* LPT is a list scheduling (LS) algorithm's strategy that requires an arrangement of tasks in order of non-increasing processing time p_j.
- *Shortest processing time (SPT):* With SPT, the processes are arranged in the ascending order with respect to their processing times and are assigned to the next available processor in that order.
- *ILP:* Note that in equations (5) and (6), for the unknowns m, n; x_{ij} can take only integer values namely; 1 or 0 and is subjected to $m + n$ linear constraints. In addition to the above unknowns, $C_{\max}$ which is also an integer is an unknown. Hence, this problem is an ILP problem solved by using branch and bound algorithm.

The 'mean duration/procedure' column in Table 2 shows the mean time (in hours) taken to complete a procedure. Comparing the 'operating day length' for each surgery type, we see that each operation room carried out an average of 2 surgeries per operation day. To produce meaningful simulation results as depicted in Figure 5, we considered the scheduling of 2 surgeries for each surgery type. The surgeries were named as: SurgeriesToSchedule = 'Gen1' 'Gen2' 'Gyn1' 'Gyn2' 'Orth1' 'Orth2' 'Sept1' 'Sept2', where mean duration for 'Gen1' and 'Gen2' is the same as in Table 2, similarly for 'Gyn2', 'Orth1', 'Orth2', 'Sept1' and 'Sept2'. Hence, Figure 5 shows the scheduling of eight surgeries in the five operation rooms. From the generated schedule, it is found that operating rooms 1, 4 and 5 are utilised for 4 hours whiles 2 and 3 are utilised for 3 hours. From the figure it is noted that roughly, there is a 1 hour difference in total operation time between the operation rooms which is far less than the mean completion time of any type of the procedures. Hence, this shows that the surgeries were evenly distributed between the operation rooms.

Figure 5 TORSCHE scheduling of eight surgeries in five ORs (see online version for colours)



5 Conclusions

Sub-Saharan Africa healthcare systems are stretched by demand for surgical services. This work highlights the situation at KCMC, an academic tertiary referral hospital in northern Tanzania. While highlighting the importance of surgical interventions in the provision of quality healthcare, this work has also highlighted the challenges faced with surgical facilities. Since surgical department represents an expensive investment, it is important that they are used wisely so as to harvest optimal dividends from the investment on the facilities. Optimal scheduling of surgeries remains one of the way through which efficient utilisation of the limited available operating rooms can be achieved. Optimal scheduling of surgeries can further lead to reduced waiting times for patients on the waiting list. This work has demonstrated how the use of appropriate technologies can be used to achieve scheduling of limited operation rooms. We modelled the operation room scheduling problem as an ILP problem and used the TORSCHE toolbox in MATLAB to solve the problem. The toolbox managed to solve the problem by producing a schedule of patients in the limited operation rooms at the health facility. Our future work will consider using primary data to develop a procedure completion time prediction system using machine learning techniques. Such a system can be used by hospital managers to plan and schedule surgeries and achieve optimal usage of surgical facilities.

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