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Optimizing Cash Flows and Minimizing Simultaneous Turnovers in Operating Room Scheduling

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I am submitting herewith a thesis written by Mohit Shukla entitled "Optimizing Cash Flows and Minimizing Simultaneous Turnovers in Operating Room Scheduling." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Industrial Engineering.

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Optimizing Cash Flows and Minimizing Simultaneous Turnovers in Operating Room Scheduling

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I would like to dedicate my degree and thesis to my parents, Saroj and Sanjay Shukla and my sister, Nitya Shukla. Without their unwavering support, this would not be possible.

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To master any discipline, you must first master discipline itself.

Abstract

Currently, the scheduling of surgical suites follows either an open booking or block booking framework. Under block booking, medical departments (or surgeons) that provide certain types of services (e.g. opthalmology, orthopedics, cardiology) are assigned fixed blocks of time that are used to divide access to the operating rooms (ORs) among different specialties. Two integer-programming based methods of generating block schedules are investigated in this research. The first approach focusses on optimizing cash flows, an area not studied previously within the OR scheduling domain. Results indicate that while there is some utility of this approach in improving the liquidity of a healthcare facility, its contribution towards increasing overall revenues is marginal. The second approach aims to minimize simultaneous turnovers of operating rooms. Although reduction in turnover times is a frequently studied area in literature, the solution presented here is novel in its attempt to minimize the occurrences of turnovers in two or more rooms at the same time, which places a strain on shared resources and leads to delays in planned start times of procedures. Results for this approach are promising in reduction of turnover times and consequently, workload on resources required to perform turnovers. Both approaches begin with the study of existing schedules to derive key insights into the chosen target parameters and then propose alternative schedules to optimize the aforementioned objectives. The proposed methods are designed to be minimally disruptive so as to remain feasible in real life scenarios.

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Chapter 1

The Scheduling Problem

1.1 Introduction

Operating rooms (OR) are a hospital's largest cost and revenue center and have a major impact on the performance of the hospital (Macario et al., 1995; Healthcare Financial Management Association et al., 2003). Managing the OR is hard due to conflicting priorities and preferences of its stakeholders on one hand (Glouberman and Mintzberg, 2001) and due to the scarcity of costly resources on the other (Cardoen et al., 2010). They are expensive to build, maintain and operate and consequently patients are charged anywhere from $22 to more than $133 per minute for booking an OR. From the perspective of either the hospital or a patient, the efficient utilization of OR time available is of paramount importance and is often the make or break factor for a hospital.

Whether scheduling a single room or an OR suite comprised of multiple rooms, hospital managers and administrators must determine their priorities and make decisions congruent with those priorities. There are several conflicting factors to be considered which make the task of scheduling extremely complicated. A survey of OR directors in US conducted by Hamilton and Breslawski (1994) classifies some factors considered during the scheduling process. They are listed in table 1.1 and their relative priorities vary from case to case. Institutions in one category (block scheduled) regard the number of ORs available, equipment limitations, block times assigned and the hospital scheduling policy as most important. In the other category (first-come-first-served or open scheduled), institutions give paramount importance to the number of ORs, estimated room set up duration, case duration and equipment restrictions.

Table 1.1: Factors considered in OR Scheduling

Related to	Factors
Surgeons	surgeon's desired start times, surgeon's assigned start times, surgeon's sequence of cases, late arrivals of surgeons, surgeon's room preferences, surgeon/service priorities, block times assigned, cancellations by surgeon over time, procedure add-ons by surgeon's over time, emergency additions by surgeons' over time, late arriving patients according to surgeon over time etc.
OR schedule	number of elective surgeries scheduled, type of elective surgeries scheduled, estimated surgery durations, possibility of cancellations in the schedule, possibility of additions to the schedule, potential for emergency additions, estimated room clean up duration, estimated room set up duration.
Resources	number of beds in postanesthesia care unit, number of ORs, regular time available in the OR, hospital scheduling policy, room restrictions due to size, availability of beds in intensive care unit.
Equipment, supplies	late arrivals of equipment, late arrivals of supplies, room restrictions due to equipment, room restrictions due to supplies, equipment limitations, supply limitations.
Patients	incomplete charts, late arrivals of patients.
Miscellaneous	room utilization figures over time, political factors e.g. only certain surgeons may use new equipment, one surgeon cannot follow another surgeon.

The findings clearly show that the task of OR scheduling is every bit as complicated as it is crucial. Given the importance and the complexity of decisions which must balance many competing priorities, OR assignment is a widely studied area of operations research.

A large body of literature exists on assessing and improving operating theatre management practices. Magerlein and Martin (1978) review the literature on surgical demand scheduling and categorize reported scheduling systems into those that schedule patients in advance of the surgical date (termed advance scheduling) and those that schedule available patients on the day of the surgery (termed allocation scheduling). Blake and Carter (1996) elaborate on this taxonomy and add the domain of external resource scheduling, which they define as the process of identifying and reserving all resources external to the surgical suite necessary to ensure appropriate care for a patient before and after a surgery. Furthermore, they divide each domain into a strategic, administrative or operational level and identify a need to integrate OR scheduling with other hospital operations. Przasnyski (1986) structures the literature on OR scheduling based on general areas of concern, such as containing costs or scheduling specific resources. Various reviews on OR management as part of global health care services can be found in Boldy (1976); Pierskalla and Brailer (1994); Smith-Daniels et al. (1988) and Yang et al. (2000). A thorough and recent review of OR scheduling literature is given by Cardoen et al. (2010), who evaluate the literature on multiple descriptive fields that are related to either the problem setting (e.g. performance measures or patient classes) or technical features (e.g. solution technique or uncertainty incorporation).

The general outline of the work presented in this thesis is as follows: the rest of this chapter describes the process of scheduling, situates the scope of this work and explains some concepts and terms used in later sections. Chapter 2 describes the optimization strategy based on considering cash flows, whereas chapter 3 describes the work done on minimizing simultaneous turnovers.

1.2 Overview of the Scheduling Process

OR scheduling is typically started by addressing two fundamental concerns: type of patients and type of OR planning strategy.

Managers, in general must plan to accomodate two types of patients: elective cases, where the surgery dates are planned in advance, and non-elective cases, such as emergencies or urgent cases which need to be performed at short notice. This creates an interesting problem. On the one hand, all the available OR time should be allocated to surgeries in advance in order to most efficiently utilize it. On the other hand, a certain capacity must be reserved for unforseen cases, which may or may not be utilized completely.

Before the surgery schedule is constructed, a decision has to be made about the operating theatre planning strategy. The 3 principle strategies followed in US hospitals are:

- *Open Scheduling*: Under this strategy, surgeons ask for OR time by submitting their cases to the scheduler, who accomodates their request subject to availability on a first-come-first-served basis. Surgeons/specialties are free to schedule their cases on any day, based solely on availability. This strategy, also known as the 'first-come-first-served' rule or the 'any workday' rule by Dexter and Traub (2002), obviously favors surgeons/specialties who schedule appointments in advance. On the other hand, other specialties such as General, Cardiac etc. who are unable to make long term predictions or need to schedule appointments at short notice are at a disadvantage (Patterson, 1995).

- *Block Scheduling*: Under this strategy, every surgeon or specialty is assigned one or more *blocks* of time during a week or month, into which they schedule their cases. In the absence of block-release policies, the surgeon(s)/specialty owns the block and can choose to not release the block, even if they have no cases to schedule into it. The advantage of this system is that hospital administration may make equitable distributions of available OR time amongst all competing sides, based on a chosen metric such as revenues generated, surgeries performed, length of waiting lists etc. However, unless unutilized time is released in advance, OR utilization may suffer.

- *Modified Block*: Under this strategy, block scheduling is modified in one of two ways: either some time is blocked while some is left open, or unused block time is released at an agreed-upon time before surgery, such as 72 hours. This method has the potential to balance the needs of all specialties (ones which can book in advance and ones which cannot) but requires constant monitoring of release times and block assignments in order to maximize utilization (Patterson, 1995).

Most hospitals tend to follow a modified block scheduling system, which combines features of first come, first served and block formats. Major specialties and surgeons are assigned blocks, with some time left open for those who cannot schedule far in advance. In addition, unreserved block time is released at a predetermined time ahead of the schedule, such as 72 or 96 hours and becomes available for anyone else to utilize. Another effective approach is to keep one or more *Overflow* rooms, which are ORs acting as buffers to accomodate last minute requests.

1.3 Scope of this Research

The focus of this research is on block scheduling for elective procedures, which is an important criteria in OR literature because of two reasons. First, the arrival rate of unplanned or emergency procedures tends to fluctuate due to a variety of factors, and is thus highly stochastic in nature. Focusing on such procedures introduces a large uncertainty in predictions of annual revenue, expected costs and even personnel requirements. On the other hand, elective procedures are much easier to plan based on historical data. It is prudent for hospital administrators to use elective procedures as key baseline indicators for planning purposes, so as to make reasonably accurate assumptions about expected revenues and required resources.

Second, most hospitals reserve some buffer capacity to deal with unplanned cases in different ways, e.g. block-release policies, overflow rooms, partial open scheduling etc. Such decisions are beyond the scope of this research since they are deeply intertwined with each hospital's objectives and available resources, and thus vary from one to another. Instead we focus on block scheduling because as indicated by Patterson (1995), block and modified block scheduling are the most popular strategies followed in U.S hospitals. Their results also indicate an increasing predisposition towards complete block scheduling as the size of a hospital increases, presumably because of the relative ease in planning and implementation.

Within block scheduling, we restrict our effort on the **Master Scheduling** phase of planning, which is explained in the following section.

1.4 Block Scheduling

The surgical scheduling process for elective cases involves activities from determining the OR time to be allocated in a hospital through to the actual scheduling of individual cases. From a process analysis perspective, usually this process under a block-booking system has three stages (Blake and Donald, 2002; Beliën and Demeulemeester, 2004; Santibáñez et al., 2007), as depicted in Fig. 1.1:

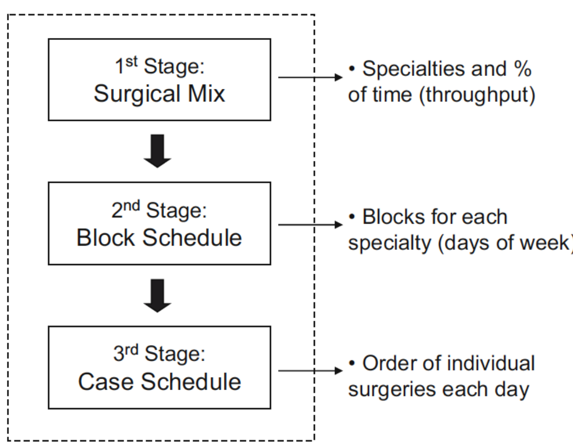

Figure 1.1: Stages in the surgical scheduling process

1. *Mix planning*: The first stage divides the OR time available among the surgical specialties.

2. *Master scheduling*: The second stage, also termed 'block booking', develops the block schedule, specifying which specialty will use which OR on which day.

3. *Patient mix*: The third stage schedules individual cases on a daily basis.

Decisions in these three stages are highly interrelated and not taken in isolation, although not necessarily at the same time, especially because of the complexity of the overall problem and the timing and the planning horizons considered in each stage. While the scope of this research is restricted to the second stage, i.e. master scheduling, a brief description of all three steps is outlined in the following sections.

1.4.1 Mix Planning

This is a long term decision, usually revisited on an annual basis. In this stage, the hospital management working in conjunction with the subcommittee determines the gross number of OR hours that will be made available for allocation. This is a function of the budget provided by the hospital for perioperative nursing vis a vis all activities connected with performing surgical procedures. Nurse managers then develop a few alternative scheduling arrangements which meet the gross number of hours and are feasible in terms of the nurses' collective agreement. This yields a template which indicates the number of ORs available on each day of the planning horizon and the duration for which they are available (Blake and Donald, 2002).

The management then decides the amount of time that will be allocated to each competing surgical department/specialty or surgeon, usually based on a chosen measure of performance such as utilization. This is a complex and often contentious process because while the allocation has to remain congruent with the hospital's chosen parameter, it should also be equitable to reduce conflicts between surgical departments.

Research towards case mix planning in a hospital setting is rather scant. Hughes and Soliman (1984) present a linear programming approach to this problem. A linear goal programming approach is presented by Blake and Carter (2002) to set the case mix and volume for physicians and to translate case mix decisions into a set of practical changes for physicans. Historical utilization is a common parameter to divide block time amongst surgeons/specialties. This approach tends to result in higher OR utilization rates and assuming that higher utilization implies higher revenue, can be considered a useful tactic. However, this is not always be the case. Macario et al. (2001) present contribution margin as an alternate parameter to allocate block time. Rather than trying to increase surgical volume, they suggest allocating more time to surgeons with higher contribution margins (revenue per unit of OR time) and vice-versa. While this approach has the potential to improve profitability, its applicability is dependant on the goals of the hospital administration. Current demands can also be the parameter to decide the mix (Shylo et al., 2012). It is not uncommon for administrators to reevaluate this decision at regular intervals, for instance to reduce the amount of time allocated to a specialty with higher rate of cancellations and assign it to another or redistribute amongst multiple specialties in order to increase utilization. Once the decision is made, the next step is the development of the master schedule.

1.4.2 Master Scheduling

Master Scheduling is a medium term decision, and typically performed a few times annually. The *master schedule* assigns fixed blocks of time to various surgeon(s)/specialties that provide certain types of services (e.g. Ophthalmology, Orthopedics, Cardiology), thus dividing the access to the ORs. This is also known as 'block booking'. In some senses, the master surgical schedule (MSS) can be thought of as being equivalent to the aggregate production plan in a manufacturing environment. Because it defines the number and types of procedures that will be performed by a hospital over the medium term, the MSS defines the aggregate resource requirements, such as the demand for nurses, drugs, diagnostic procedures, laboratory tests and perioperative nurses (Blake et al., 2002). A sample *master schedule* is shown in 1.2.

	OR 1			OR 2		
Week 1	**7:30-12:00**	**12:00-15:00**	**15:00-18:00**	**7:30-12:00**	**12:00-15:00**	**15:00-18:00**
Monday				7.5 (7:30-15:00)		
Tuesday						
Wednesday	9.5 (8:30-18:00)			6.5 (8:30-15:00)		
Thursday	7.5 (7:30-15:00)			7.5 (7:30-15:00)		
Friday	7.5 (7:30-15:00)					
Week 2						
Monday				7.5 (7:30-15:00)		
Tuesday	10.5 (7:30-18:00)			7.5 (7:30-15:00)		
Wednesday	9.5 (8:30-18:00)			6.5 (8:30-15:00)		
Thursday	7.5 (7:30-15:00)					
Friday	7.5 (7:30-15:00)					
Week 3						
Monday				7.5 (7:30-15:00)		
Tuesday						
Wednesday				6.5 (8:30-15:00)		
Thursday	7.5 (7:30-15:00)			7.5 (7:30-15:00)		
Friday	7.5 (7:30-15:00)					
Week 4						
Monday				7.5 (7:30-15:00)		
Tuesday	10.5 (7:30-18:00)					
Wednesday	9.5 (8:30-18:00)			6.5 (8:30-15:00)		
Thursday	7.5 (7:30-15:00)					
Friday						

Room Unavailable | Urology | Orthopedics | General | Plastics

Figure 1.2: Sample of current schedule part

The characterestics of the master schedule vary on case-by-case basis, decided by the priorities and guidelines of the hospital administration. In general, it should:

- Equitably divide OR time based on historical utilization, demand, profitability of surgeon(s)/specialty or any other parameter of interest to the hospital.

- Be cyclical within a planning horizon as far as possible and certainly across successive planning horizons.

Despite potential inefficiencies because of unbalanced block schedules, this framework is widely accepted because of its convenience for both surgeons and managers (Blake et al., 2002). Various authors have studied the process of block allocation based on various performance parameters.

1.4.3 Patient Mix

The third stage has more of an operational focus. In this stage, individual surgeries are scheduled within the assigned blocks of the master schedule. Research in this area focuses on optimal assignment and sequencing of procedures.

Dexter and Traub (2002) examine two approaches of scheduling elective cases in hospitals (earliest vs. latest start time) where surgeons and patients choose the day of the surgery. They note that the *earliest start time* approach maximizes efficiency when a service has nearly filled its regularly scheduled hours of OR time while the *latest start time* approach performs better at balancing workload among services' OR time. Guinet and Chaabane (2003) tackle a problem of planning for N patients within an operating theatre over a medium term horizon from the perspective of patient satisfaction and resource efficiency and suggest a heuristic solution method.

Weiss (1990) studies sequencing decisions in the two-surgery context and show, using stochastic dominance arguments, that for certain selective choices of distributions, the optimal solution is in order of increasing variance of surgery durations. In line with this, Denton et al. (2007) show that a simple sequencing rule based on surgery duration variance can be used to generate substantial reductions in surgeon and OR team waiting, OR idling and overtime costs. Further research on incorporating the variability in durations of surgical procedures *(scheduled vs actual)* is performed in Shylo et al. (2012) who present an optimization framework for batch scheduling within a block booking system that maximizes the expected utilization of OR resources, subject to a set of probabilistic capacity constraints. Zhao and Li (2014) draw comparisons between mixed integer non-linear programming and constraint programming approaches to scheduling elective surgeries in multiple ORs under ambulatory surgical settings.

1.5 Relevance

The scope of scheduling problems presented in the literature is vast. Cardoen et al. (2010) present a thorough review of the literature on OR scheduling divided into various categories based on the research objectives followed by individual authors. Some of these include:

- Performance measures: waiting time, throughput, utilization, leveling, makespan, patient deferrals, financial measures and preferences
- Patient characterestics: elective and non-elective patients
- Decision delineation: assignments of date, time, operating room or allocation of capacity

The focus of the research presented in this thesis is on performing master scheduling using integer-programming (IP) to optimize two distinct objectives not examined previously:

1. Optimizing cash flows from an OR suite
2. Minimizing simultaneous turnovers of ORs

Cash flow is chosen as one of the decision objectives because to the best of our knowledge, no work in the past has been done to incorporate liquidity and time value of money in OR scheduling decisions. Past work considers other financial parameters such as contribution margins or variable costs to make decisions about OR capacity allocation or expansion (Dexter et al., 2001, 2002a,b,c; Dexter and Ledolter, 2003; Dexter et al., 2005). Furthermore, the scope of all previous research lies in the mix planning stage i.e. allocating OR time to specialties to optimize the chosen financial metric. Given the OR time available for allocation and the amount to be allocated to each specialty, this research is designed to develop alternate master schedules to achieve our objectives. Since cash flow is considered a critical factor in project management and economics, its utility as a decision criteria for OR scheduling is worth exploring, in the very least to establish whether or not there is value in implementing such an approach in real life.

Minimizing simultaneous turnovers can be thought of as a project management problem striving to improve utility given a limiting resource, which in this case is OR time available. In order to maximize the utilization of the OR, it is ideal to minimize delays and stick as close to the planned surgery schedule of the day as possible. A common source of delays in operating theatres is from *Turnovers* i.e. the various processes that must be performed in an OR after the completion of one procedure before the start of the next procedure. The ideal OR turnover or preparation time between one operation and another is classified as of high performance if up to 25 minutes; of medium performance if between 25 and 40 minutes and not good if more than 40 minutes (Dexter, 2000; He et al., 2012; Macario, 2006; Surgery Management Improvement Group, 2012). However, preparation times in OR suites are often found to be higher and prone to large variation. For instance, at a public hospital in Brazil the delays were found to be as large as 119.8±79.6 minutes (Costa Jr et al., 2015). The problem is exacerbated by the limited availability of staff and equipment required to perform turnovers as they are often shared between one or more rooms. For instance if two ORs finish their procedures at approximately the same time and share turnover crews, the room that finishes second would have to wait for the crew to complete its activities in the other room, thus delaying its planned activities. There is a gap in the literature here that we address in this research. We simulate the daily operations of multiple rooms in order to quantify *Overlaps* in room turnovers and then redesign the master schedule to minimize the same. To the best of our knowledge, this combination of factors has not been studied previously in OR literature. Previous work in this area tends to be from a medical perspective in attempting to better plan and execute the procedures.

In both approaches, we deliberately do not make recommendations on altering OR time available or reapportioning time allocated to specialties currently because any changes in an OR schedule are disruptive and therefore extremely complicated to implement. One of the motivations of this project was to create minimally disruptive solutions which would prove effective. Therefore, we restrict our focus on only revising the master schedules to achieve the chosen objectives.

1.6 Terminology

Before proceeding further, certain commonly used terms used frequently are defined here:

1. Surgeon/Specialty/Department: A surgeon is a single person performing surgeries whereas surgical specialty/department represents a surgical group such as General, Orthopedics etc. In this thesis, they are used interchangeably to represent entities to which block time is allocated.

2. Block: Blocks are the principle components of a master schedule. A block is a period of time within a given interval for which an OR is available for allocation. They have two principle attributes: start time and duration. An OR schedule is composed of different kinds of blocks. For instance, table 1.2 lists some blocks available for assignment at a facility and table 1.3 depicts a skeletal time table based on those blocks.

Table 1.2: Example of available blocks

Block ID	Duration (hours)	Day	OR	Interval
1	4.5	Monday	2	7:30-12:00
2	9.5	Wednesday	1	8:30-18:00
3	6.5	Wednesday	2	8:30-15:00
4	7.5	Thursday	1	7:30-15:00
5	7.5	Thursday	2	7:30-15:00
6	7.5	Thursday	1	7:30-15:00

3. Master Schedule or Block Schedule: is the time-table that defines block assignments on various days. It is constructed by dividing the available blocks

Table 1.3: Master schedule based on available blocks

Day	OR 1 7:30-12:00	OR 1 12:00-15:00	OR 1 15:00-18:00	OR 2 7:30-12:00	OR 2 12:00-15:00	OR 2 15:00-18:00
Monday	-	-	-	Block[1]	-	-
Tuesday	-	-	-	-	-	-
Wednesday	Block[2]			Block[3]		-
Thursday	Block[4]		-	Block[5]		-
Friday	Block[6]		-	-	-	-

amongst the requesting specialties. For instance, the blocks within the skeletal master schedule above (table 1.3) are assigned to 3 specialties to create a master schedule or block schedule, as represented in table 1.4. In this schedule, Plastics is assigned OR 2 on Monday from 7:30-12:00. On Wednesday, General is assigned OR 1 for the entire day (7:30-18:00), while Plastics is assigned OR 2 from 7:30-15:00. All blocks with a '-' imply that the OR is not available for allocation during that period, which might be because it is assigned to some other duty at that time or because of resource constraints.

Table 1.4: Example of a Master Schedule

Day	OR 1 7:30-12:00	OR 1 12:00-15:00	OR 1 15:00-18:00	OR 2 7:30-12:00	OR 2 12:00-15:00	OR 2 15:00-18:00
Monday	-	-	-	Plastics[1]	-	-
Tuesday	-	-	-	-	-	-
Wednesday	General[2]			Plastics[3]		-
Thursday	General[4]		-	Ortho[5]		-
Friday	General[6]		-	-	-	-

The terms *block schedule* and *master schedule* are used interchangeably from here on. The term *Block Scheduling* is still used in its orginal context as an OR scheduling strategy.

Chapter 2

Optimizing Cash Flow Using Block Scheduling

2.1 Introduction

The average operating margins (i.e. profits) of hospitals decreased from 6.3% in 1997 to 2.7% in 1999 as per OR Manager (2000) and more recent reports by Dunn and Becker (2013) indicate they currently stand at 2.5%. Moody's Investor Services (2000) reported that in 1999, 43% of not-for-profit hospitals had negative operating margins. Since operating rooms (OR) are a hospital's largest cost and revenue center (Macario et al., 1995; Healthcare Financial Management Association et al., 2003), their profitability is crucial and hence the subject of constant research. Various authors have focused on improving various aspects of OR management. A common parameter for instance, is to maintain relatively high utilization of ORs. In the context of block scheduling, where surgeon(s)/specialities are assigned specific *blocks* of time during a week in which to schedule their procedures, this is done by studying historical utilization of allocated block time and then reallocating the time to surgeons/specialties which tend to *run short* by taking time from the ones which do not end up utilizing all the allocated time. A comprehensive review of

OR scheduling literature categorized by research objectives, which are in turn based on criteria commonly used by adminstrators to gauge OR performance and make strategic and operational decisions, is given by Cardoen et al. (2010). The financial criteria considered most commonly are contribution margins and variable costs. This research introduces *Cash Flow* and *Net Present Value (NPV)* as financial objectives of an integer-programming (IP) approach to block scheduling of elective surgeries.

Cash flow refers to the net inflow and outflow of money from an enterprise. It is one of the most fundamental aspects of all business operations and representative of the financial health of an institution. Cash flows are used to quantify the liquidity or the *Cash Availability* of an organization, that is the amount of capital that the organization possesses at any given time. Obviously the greater the amount of the cash available to an organization, the better its financial health.

Another important aspect of project management is the Net Present Value (NPV) of revenues. NPV is used in capital budgeting to analyze the profitability of a projected investment or project. Determining the value of a project is challenging because there are different ways to measure the value of future cash flows. Due to the time value of money (TVM), money in the present is worth more than the same amount in the future. This is both because of earnings that could potentially be made using the money during the intervening time and because of inflation. In other words, a dollar earned in the future is not worth as much as one earned in the present. The discount rate element of the NPV formula is a way to account for this. Companies may often have different ways of identifying the discount rate. Common methods for determining the discount rate include using the expected return of other investment choices with a similar level of risk (rates of return investors will expect), or the costs associated with borrowing money needed to finance the project. For example, if a retail business wants to purchase an existing store, it will first estimate the future cash flows that the store will generate and then discount those cash flows into one lump-sum present value amount. Let's say that amount is $500,000. If the offered price for the store is less than that, say $300,000, then the purchasing company is likely to accept the offer. This investment will yield a net gain of $200,000 and is a positive NPV investment. Conversely, if the offered price is greater than $500,000, the purchaser is unlikely to buy the store as the acquisition presents a negative NPV proposition and will reduce the overall value of the retail company.

As stated earlier, NPV is the difference between the present value of future cash inflows and the present value of future cash outflows. The NPV of a future cash flow is calculated as:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_o$$

where,

C_t = net cash inflow during period t

C_o = total initial investment costs

r = discount rate, and

t = number of time periods

A positive net present value indicates that the projected earnings generated by a project or investment (in present dollars) exceed the anticipated costs (also in present dollars). Generally, an investment with a positive NPV is profitable and one with a negative NPV results in a net loss.

The expectation at the outset of this approach is to two-fold:

- To examine three distinct cash flow scenarios and their effect on cash availability
- To explore the difference in NPV of the revenues earned between the three scenarios

This chapter is organized in the following way: section 2.2 presents related work in OR literature; sections 2.3 and 2.4 introduce the problem and the solution methodology; a numerical instantiation of the proposed approach is presented in 2.5 and finally the overall findings are discussed in 2.6.

2.2 Literature Review

Previous research in the OR scheduling domain, based on financial considerations is somewhat limited to the consideration of variable costs and/or the contribution margins from various surgeons/specialties. Dexter et al. (2001) tested, using discrete-event computer simulation, whether increasing patient volume while being reimbursed less for each additional patient can reliably achieve an increase in revenue when initial adjusted OR utilization is 90%. They found that increasing the volume of referred patients by the amount expected to fill the surgical suite (100%/90%) would increase utilization by $< 1\%$ for a hospital surgical suite (with longer duration cases) and 4% for an ambulatory surgery suite (with short cases). The increase in patient volume would result in longer patient waiting times for surgery and more patients leaving the surgical queue. With a 15% reduction in payment for the new patients, the increase in volume may not increase revenue and can even decrease the contribution margin for the hospital surgical suite. The implication was that for hospitals with a relatively high OR utilization, signing discounted contracts to increase patient volume by the amount expected to fill the OR can have the net effect of decreasing the contribution margin (i.e. profitability).

Dexter et al. (2002a) researched allocating OR time based on contribution margin (revenue minus variable costs) and using linear programming showed that reallocating OR time among surgeons could increase the overall hospital margin for elective surgery by 7.1%. They also warn that this would not be as simple as taking OR time from surgeons/specialties with low contribution margins and giving it to those with higher margins because different surgeons used differing amounts of hospital ward and ICU time. To achieve substantive improvement in a hospitals perioperative financial performance despite restrictions on available ORs, hospital wards or ICU time, contribution margin per OR hour should be considered (perhaps along with OR utilization) when OR time is allocated. Dexter and Ledolter (2003) and Dexter et al. (2005) incorporate contribution margins and the uncertainty associated with predicting them into making strategic decisions, namely expansion of OR capacity. In Dexter et al. (2002b), the authors showed that changing OR allocations among surgeons without changing total OR hours allocated can increase hospital perioperative variable costs by up to approximately one third. Thus, at hospitals with fixed or nearly fixed annual budgets, allocating OR time based on an OR-based statistic such as utilization can adversely affect the hospital financially. The OR manager can reduce the potential increase in costs by considering not just OR time, but also the resulting use of hospital beds and implants.

Dexter et al. (2002c) obtained accounting data for all outpatient or same-day-admit surgery cases during one fiscal year at an academic medical center. Linear programming was then used to find the mix of OR time allocations to surgeons that would maximize the contribution margin or minimize variable costs.

To the best of our knowledge, Cash-flow and NPV and their effect on the financial health of a hospital have not been studied previously as objectives of block scheduling. Past work considers other financial parameters such as contribution margins or variable costs to make decisions about OR capacity allocation or expansion. Furthermore, their scope lies in the mix planning stage i.e. allocation of OR time and its apportioning between various competing specialties. Instead, this research is designed to extract information about the amount of time available for allocation and the amount of time to be allocated to each specialty from an existing master schedule and then develop alternate master schedules to achieve our objectives. Since cash flow is considered a critical factor in project management and economics, its utility as a decision criteria for OR scheduling is worth exploring, in the very least to establish whether or not there is value in implementing such an approach in real life. While the primary focus of the approach is on cash flows, the consequent effects on the NPV of revenues are also reported.

Cash flows and NPV are important parts of resource-constrained project-scheduling problems studied in literature. Without positive cash flows, basic obligations such as payments to suppliers, payrolls etc. cannot be met (Pate-Cornell et al., 1990; Uhrig-Homburg, 2005). Russell (1970) first introduced the cash flow criterion to resource-constrained project-scheduling problems and proposed a model named max-NPV, which sought to optimize the overall NPV of the project, based on discounted cash inflows and outflows. Chen et al. (2010) presented an ant colony optimization approach for optimizing discounted cash flows. Li et al. (2013) developed a decision support system subject to variable developer and bank payment schedules, based on considerations of NPV in estimation of net cash inflows and outflows. Some surveys on consideration of cash-flows in project planning are given by Brucker et al. (1999); Herroelen et al. (1997, 1998); Özdamar and Ulusoy (1995) and Tavares (2002). Dror and Trudeau (1996) applied cash flow considerations to an inventory routing problem and proposed that it would be more advantageous for the company to set deliveries for a large percentage of customers based on the present value of cash flow. OR time allocation, as represented by block schedules can also be thought of as an inventory routing problem which could be optimized based on considerations of cash flow and NPV.

The solution methodology is restricted deliberately to only revising existing master schedules so as to ensure the approach remains as non-disruptive as possible:

- Total amount of OR time available for allocation is not altered by the addition or removal of existing blocks. As indicated earlier, this is a strategic decision (long-term) mix planning decision subject to budgetary, capacity and staffing constraints.

- Total amount of OR time allocated to various specialties is not reapportioned. This is again, a mix planning decision.

We only look to alter current master allocations. In other words, we tackle only the question of *when* time should be allocated to each surgeon/specialty, and not *how much* time is available for allocation and *how much* is allocated to each surgeon/specialty. These restrictions ensure that the proposed solutions do not increase any variable, fixed or staffing costs and possibly only require adjustments to surgeon schedules. Any changes in the OR environment tend to be difficult to implement and one of the motivations of this research was the development of relatively easy to implement solutions.

2.3 Problem Statement

A set of blocks B in ORs R available for allocation in a planning horizon of D days must be assigned to a set of specialties S subject to coverage and duplicate assignment constraints. This is a binary integer problem, where the decision variable represents the mapping of blocks to specialties. The overall profit-rate of the day (overall profit divided by total hours available on day) is used as the objective function. Four cash flow scenarios are studied:

- **Baseline**: For implementation in real life scenarios, a baseline scenario is constructed using the values of expected revenue derived from the simulation model and then generating cash flows and overall revenues based on the current master schedule. The IP model is not used in this stage, and this scenario simply represents the current cash flow as per an existing master schedule and simulated values of expected revenues.

- **A1**: a *Business-as-usual* scenario, designed to mimic the baseline scenario where no consideration is given to cash flow. When applying the solution to a real-world problem, this approach should closely emulate the daily revenues being earned according to the existing schedule. The purpose of this scenario is to test whether the IP is able to replicate the current cash flow patterns of a given real life schedule vis a vis the baseline scenario. This serves as validation that the final results of the approach are only due to modifications in the cash flow pattern and not due to any other external factor. In terms of both cash flow and

NPV, the A1 scenario should therefore be quite close to the baseline scenario of a real life instance.

- **A2**: an *Increasing* revenue pattern, where a higher portion of the overall revenue is earned in the later stages of the planning horizon. This is accomplished by modifying the block schedule to favor higher cash flows later in the planning horizon as opposed to earlier. From a cash flow and NPV perspective, this can be intuitively thought of as the worst scenario.

- **A3**: a *Decreasing* revenue pattern, where a higher portion of the overall revenue is earned in the initial stages of the planning horizon. This is accomplished by modifying the block schedule to favor higher cash flows earlier in the planning horizon as opposed to later. Intuitively speaking, this scenario should have the best performance in terms of NPV since the larger proportion of earnings are accrued earlier and thus have a greater time period to accumulate interest. Furthermore, this is the preferable scenario in terms of cash availability as the overall revenue increases more quickly as compared to the other scenarios. Again, while the overall revenue is the same in all scenarios, this scenario would create better liquidity for the institution across the planning horizon.

The A1, A2 and A3 scenarios are induced by modifying the coefficients of the objective function and consequently, alternative master schedules are produced. Based on the allocations, the revenues over a period of one year are calculated and discounted in order to determine the NPV of the overall annual revenue arising from any given master schedule.

2.4 Solution Methodology

This section details the the methodology to devise altenate master schedules to optimize cash flows and NPV of the daily revenues generated over a year. It is comprised of the following steps:

1. Generating Expected Revenues: A large number of blocks of each type and for each specialty are simulated, in order to determine mean expected values of revenue from each block type for each specialty.
2. Integer Programming Model: Using the expected revenue from assigning any block to a particular specialty, an IP-model was devised to generate master schedules to optimize cash flows.

2.4.1 Generating Expected Revenues

The first step is to calculate the expected revenue from each block type B when allocated to specialty S. This value is assumed to be consistent across all rooms R and all days D. These values can then be used to calculate revenues based on an existing master schedule. Given a list of surgeries performed by a specialty and the revenue from each of those procedures, a large number of blocks (vis a vis 10,000) of each type for each department are generated using algorithm 1. Based on the simulation, for each block we know: the length of the block, number of surgeries in block and expected revenue from the block. After that, a small number of blocks of the same type are selected using random sampling (algorithm 2) and the mean of these blocks is considered as the mean revenue for a given block-specialty combination. The second stage of sampling vis a vis algorithm 2 incorporates a greater degree of randomization in the experiment, but can be removed from the solution approach since it does not significantly alter the results.

Algorithm 1 attempts to fill every block by random sampling and quits at the first failed attempt i.e. when the datasample picks a surgery which cannot be fit into the current block. As a result, some blocks are left without any procedures. Realistically speaking, this could be the case if there are no requests which fit a particular block, although unlikely. Seed values are specified for each block type, for instance the 3 hour block uses seed '1', 3.5 hour block uses '2' and so on. The seed values are used to generate random numbers during sampling of surgeries from their respective pools.

Algorithm 1: Simulating surgical blocks

Input: Pool of surgeries performed by specialty under consideration in previous year data (excluding procedures for which pricing data is not available), length of block to be generated (l), number of sample blocks to be generated (m), number of sampling failures allowed (K), duration of overtime allowed (o) and turnover time (p).

Output: m surgical blocks for the specialty under consideration

```
Let C be the current block
C ← ∅
while Length of C ≤ (l + o) do
    Set k = 0
    Randomly select a procedure from given pool of surgeries and add to C.
    Increment length of C by length of procedure chosen and turnover time.
    if Length of C > l then
        Remove last added procedure from C
        Increment k by 1
    if k > K then
        Break
return Current block C
Reduce length of C by p, since no cleaning occurs after the completion of all
  procedures.
Commit current block to block array.
return Current block C
Repeat for m iterations.
```

Algorithm 2: Generating revenues from surgical blocks

Input: Pool of surgery blocks of type b constructed for specialty s, including the value of expected revenue from every block, number of blocks, N of type b available for allocation over the planning horizon.

Output: Expected revenue to the hospital if block type b is assigned to surgical specialty s

```
Draw N samples and record mean revenue value for block type b for specialty
  s.
return Mean revenue from block b when allocated to specialty s
Repeat for 100 iterations.
```

The seed is specified so that the sampling for each block is similar across experiments (for instance over differing values of overtime) but dissimilar from the other blocks. In other words, it provides a measure of replicability of the output data. In this way, expected revenue resulting from the allocation of a given block to a given specialty are estimated.

NOTE: The costs used are derived from Medicare's website. In the case of surgeries, the figures that are considered as 'revenue' from any procedure are what Medicare uses when paying for the professional services of physicians and other enrolled health care progessionals in private practice, services covered incident to physician's services (other than certain drugs covered as incident to services), and other diagnostic and radiology services.

2.4.2 IP-Model

The IP model used is described below.

- *Parameters*

  1. S: number of specialties under consideration.
  2. B: number of block types under consideration.
  3. D: number of days in the planning horizon.
  4. R: number of ORs available.
  5. M: Maximum number of blocks that can be assigned to one specialty on one day.

- *Indices*

  1. s: Index of specialties, $s = 1, ...S$.
  2. b: Index of blocks, $b = 1, ...B$.
  3. d: Index of days in planning horizon, $d = 1, ...D$.
  4. r: Index of available rooms,$r = 1, ...R$.

- *Indexed Parameters*

1. ${N_b}^s$: Minimum number of blocks of type b that must be assigned to specialty s in the planning horizon.
2. H_d: Total number of blocks (of all types) available for assignment on day d.
3. E^s_{bdr}: Expected revenue if block b on day d in room r is assigned to specialty s.
4. A_d: Coefficient values, calculated using the linear function:

$$A_d = A_{d-1} + 50 * (d - 1) \quad \forall d \in D \tag{2.1}$$

- *Decision Variable*: Binary variable X^s_{bdr},

$$X^s_{bdr} = \left\{ \begin{array}{ll} 1, & if\ block\ b\ on\ \ day\ d\ in\ room\ r\ is\ assigned\ to \\ & specialty\ s \\ 0, & otherwise \end{array} \right\}$$

- *Decision Expression:* Overall profit on day d,

$$P_d = \sum_{s=1}^{S} \sum_{b=1}^{B} \sum_{r=1}^{R} X^s_{bdr} E^s_{bdr} \quad \forall\, d \in D \tag{2.2}$$

- *IP-Formulation*

$$Minimize\ \sum_{d=1}^{D} \frac{P_d}{H_d} A_d \tag{2.3}$$

Subject to

$$\sum_{s=1}^{S} X^s_{bdr} = 1 \quad \forall\, b \in B, d \in D, r \in R \tag{2.4}$$

$$\sum_{d=1}^{D} \sum_{r=1}^{R} X^s_{bdr} \geq N^s_b \quad \forall\, s \in S, b \in B \tag{2.5}$$

$$\sum_{b=1}^{B} \sum_{r=1}^{R} X^s_{bdr} \leq M \quad \forall\, s \in S, d \in D \tag{2.6}$$

The objective function (2.3) is comprised of minimizing the sum across the planning horizon of the product of profit rate of the day (profits earned divided by number of hours available for allocation on given day) and the coefficient (A_d) for that day. The coefficient A_d guides the program to find solutions which:

- simulate a business-as-usual scenario, where no preference is given to the cash flow across all the days of the planning horizon, or
- simulate an increasing scenario, where the master schedule generated favors placing the most profitable blocks as late in the schedule as possible, or
- simulate a decreasing scenario, where the master schedule generated favors placing the most profitable blocks as early on as the schedule as possible.

Constraint 2.4 ensures every block is only assigned to one specialty, 2.5 ensures each specialty receives the required number of blocks of each type and 2.6 ensures that no specialty is assigned more than a certain number of blocks on each day. The approach is applied to a real life hospital, as elaborated in the following section.

2.5 Numerical Instantiation

The proposed solution approach was applied to data obtained from the Veteran's hospital, Pittsburgh. The 4 busiest departments at the hospital vis a vis, General, Orthology, Urology and Plastics were considered. While the actual schedule cycles over a 5-week period, this research was limited to 4 weeks in order to improve the cyclicity of the schedule. The list of surgeries (or procedures) performed by each department over the course of one year was provided by the hospital administration and the revenue for each of those procedures was obtained online (https://www.cms.gov/apps/physician-fee-schedule/search/search-criteria.aspx/). The procedures and costs are mapped to each other using the CPT code assigned to each procedure. For instance, the procedure with CPT code 11406 generates $245.23

in revenue. The current master schedule followed at the hospital was also provided, which was used to construct two kinds of schedules: the *Expanded* and the *Condensed* schedule, which are explained in the following sections. The number and type of blocks currently assigned to each specialty and overall are applied to constraints 2.5 and 2.6.

2.5.1 The Expanded Schedule

A sample of the current schedule at the hospital for 2 rooms over one week is shown in figure 3.3 while the full schedule for 9 rooms over 4 weeks is presented in appendix A.1.

	OR 1			OR 2		
Week 1	**7:30-12:00**	**12:00-15:00**	**15:00-18:00**	**7:30-12:00**	**12:00-15:00**	**15:00-18:00**
Monday				7.5 (7:30-15:00)		
Tuesday						
Wednesday	9.5 (8:30-18:00)			6.5 (8:30-15:00)		
Thursday	7.5 (7:30-15:00)			7.5 (7:30-15:00)		
Friday	7.5 (7:30-15:00)					
Week 2						
Monday				7.5 (7:30-15:00)		
Tuesday	10.5 (7:30-18:00)			7.5 (7:30-15:00)		
Wednesday	9.5 (8:30-18:00)			6.5 (8:30-15:00)		
Thursday	7.5 (7:30-15:00)					
Friday	7.5 (7:30-15:00)					
Week 3						
Monday				7.5 (7:30-15:00)		
Tuesday						
Wednesday				6.5 (8:30-15:00)		
Thursday	7.5 (7:30-15:00)			7.5 (7:30-15:00)		
Friday	7.5 (7:30-15:00)					
Week 4						
Monday				7.5 (7:30-15:00)		
Tuesday	10.5 (7:30-18:00)					
Wednesday	9.5 (8:30-18:00)			6.5 (8:30-15:00)		
Thursday	7.5 (7:30-15:00)					
Friday						

Room Unavailable | Urology | Orthopedics | General | Plastics

Figure 2.1: Sample of current schedule part

As is evident from the schedule, the rooms are not always available. The color on the schedule indicates the specialty to which the room is currently assigned. Additionally each block carries the duration for which it is assigned to said specialty.

Each day of the week is divided into 3 periods: morning or 7:30 to 12:00; afternoon or 12:00 to 15:00; and evening or 15:00 to 18:00. There are 85 blocks varying in the location, start time and duration available for allocation. Each block is currently assigned to some specialty. A summary of these blocks is given in tables 3.2 and 3.3 below, a more expanded list is available in the appendix.

Table 2.1: Types and number of blocks available for assignment

Block Type	Duration	Number of blocks available in 4 weeks
I	3	8
II	3.5	4
III	4.5	10
IV	5	10
V	6.5	7
VI	7.5	26
VII	9.5	4
VIII	10.5	16
Total		85

Table 2.2: Expanded schedule over 4 weeks

Speciality	Blocks assigned of type							
	I	II	III	IV	V	VI	VII	VIII
General	4	0	2	0	1	12	4	4
Orthopedics	0	0	4	2	4	4	0	8
Urology	4	0	0	8	0	6	0	4
Plastics	0	4	4	0	2	4	0	0

The allocations defined within this schedule are summarized in figure 3.4 for illustration purposes.

2.5.2 The Condensed Schedule

As seen in the master schedule, each day in the planning horizon is comprised of the morning, afternoon and evening period. Various blocks of varying lengths are used

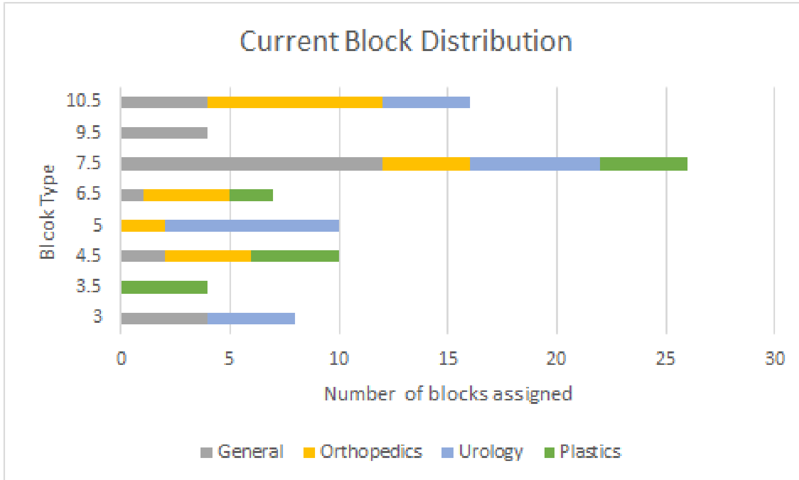

Figure 2.2: Distribution of Blocks amongst the Specialties

to cover various time intervals during the day. Blocks larger than 5 hours can be considered as combinations of the smaller blocks. For instance, a 9.5 hour block in the hospital starts at 8:30 and ends at 18:00. It can therefore be considered as the combination of a 3.5 hour block (8:30-12:00), a 3 hour block (12:00-15:00) and another 3 hour block (15:00-18:00). The 8 block types mentioned in the master schedule can be broken down in a similar fashion into their constituent blocks. This simplfies the process of simulation and optimization (by reducing the number of decision variables) and lends more flexibility to the optimization model in terms of block allocations made to fulfill coverage requirements. Table 3.4 details the breakdown of the type and number of each constituent block of the 4 largest blocks vis a vis 6.5, 7.5, 9.5 and 10.5 hour blocks. Using only 4 types of blocks, the *Expanded Schedule* can be reduced to the *Condensed Schedule*, given in tables 3.5 and 3.6.

2.5.3 Results

Two sets of revenue optimization experiments were conducted, one on the expanded and one on the condensed schedule. The expected revenues for each block type and

Table 2.3: Breakdown of long blocks

Block Type	Current Block Duration	Number of constituent blocks		
		4.5	3.5	3
V	6.5	0	1	1
VI	7.5	1	1	0
VII	9.5	0	1	2
VIII	10.5	1	0	2

Table 2.4: Types and Number of Blocks available for assignment

Block Type	Duration	Number of blocks available in 4 weeks
I	3	81
II	3.5	15
III	4.5	52
IV	5	10

Table 2.5: Condensed Schedule over 4 weeks

Speciality	Blocks assigned of type			
	I	II	III	IV
General	33	5	18	0
Orthopedics	24	4	16	2
Urology	18	0	10	8
Plastics	6	6	8	0

specialty were constructed using the random sampling methods outlined in section 2.4.1, given in table 2.6.

Using the aformentioned expected values, the cash flows for the four scenarios mentioned in section 2.3 are constructed. The daily revenues for the 4 scenarios under the expanded and the condensed schedules are given in tables 2.7 and 2.8 respectively. From these tables, it is evident that the cash flows for the baseline and A1 scenarios are close to each other and do not favor any trend in the cash flow pattern. The A2 and A3 cash flow scenarios on the other hand, form increasing and decreasing trends respectively. The daily revenues reported above were assumed to stay constant across all planning periods and discounted to day 1 using an annual compound interest rate

Table 2.6: Expected Revenues

Block Type	Duration (hours)	Specialty General	Orthopedics	Urology	Plastics
I	3	$635.88	$953.48	$470.22	$740.98
II	3.5	$770.73	$1179.47	$563.96	$898.77
III	4.5	$1042.67	$1484.95	$785.05	$1131.88
IV	5.0	$1140.08	$1669.41	$890.17	$1274.02
V	6.5	$1543.72	$2181.32	$1246.12	$1649.28
VI	7.5	$1787.94	$2554.82	$1455.19	$1894.92
VII	9.5	$2298.37	$3265.32.24	$188756	$2391.28
VIII	10.5	$2547.22	$3615.24	$2113.14	$2641.91

of 2% (equivalent to a daily interest rate of 0.0054%). Finally, the discounted cash flows were used to estimate the overall annual revenues, summarized in table 2.9.

2.6 Conclusions and Discussion

The use of two financial criterion: cash flow and NPV as the deciding factors in master scheduling was explored.

Cash Flow:

From the perspective of cash flow, the A3 approach is definitely superior to all others. Since a larger proportion of the monthly revenue is earned earlier on in each planning period, a greater amount of cash is available for most of the planning period. The overall costs incurred with this approach can be assumed to remain the same because no changes are introduced with respect to the blocks available or the staffing requirements. In that case, the hospital would be in better financial health and better able to settle its dues in time. Where applicable, this approach would also reduce the need to borrow capital in order to meet expenses, given that most goods, services and utilities require payment towards the beginning of every month. The merits of transitioning from a Baseline/A1 scenario to either the A2 or the A3 scenario are represented by figures 2.3 and 2.4, which contrast **cumulative** cash flows across one

Table 2.7: Daily Revenues under the Expanded Schedule

	Scenario			
Day	**Baseline**	**A1**	**A2**	**A3**
1	$11,887.47	$12,634.04	$9,325.29	$12,207.86
2	$2,547.22	$2,113.14	$2,113.14	$3,615.24
3	$5,736.59	$5,631.03	$5,631.03	$7,047.87
4	$5,689.03	$5,457.60	$5,023.51	$8,724.88
5	$6,763.57	$5,362.80	$5,362.80	$8,475.35
6	$0.00	$0.00	$0.00	$0.00
7	$0.00	$0.00	$0.00	$0.00
8	$10,218.06	$10,188.96	$8,435.12	$11,010.86
9	$5,102.04	$3,568.33	$3,568.33	$5,403.18
10	$8,449.95	$7,917.91	$7,385.87	$8,449.95
11	$8,243.85	$8,979.07	$8,018.04	$9,086.05
12	$10,361.06	$11,075.98	$9,683.40	$10,202.13
13	$0.00	$0.00	$0.00	$0.00
14	$0.00	$0.00	$0.00	$0.00
15	$11,887.47	$12,634.04	$11,687.08	$9,747.27
16	$2,547.22	$2,113.14	$2,113.14	$2,113.14
17	$7,280.31	$7,917.91	$8,449.95	$7,917.91
18	$7,144.22	$8,979.07	$8,979.07	$7,578.30
19	$6,763.57	$5,362.80	$7,696.11	$5,362.80
20	$0.00	$0.00	$0.00	$0.00
21	$0.00	$0.00	$0.00	$0.00
22	$10,218.06	$10,188.96	$10,903.88	$8,102.36
23	$2,547.22	$2,113.14	$3,615.24	$2,113.14
24	$8,449.95	$8,449.95	$9,229.19	$7,280.31
25	$7,144.22	$7,578.30	$10,619.80	$6,811.46
26	$10,361.06	$11,075.98	$11,502.16	$8,092.09
27	$0.00	$0.00	$0.00	$0.00
28	$0.00	$0.00	$0.00	$0.00

month between various scenarios. Cumulative revenue on any day is the total revenue earned by a hospital from all the specialties in all the days of the planning horizon leading up to that day.

The daily cumulative revenues in the A2 scenario are usually lower than those in the baseline scenario whereas the daily cumulative revenues in the A3 scenario are usually higher than those in the baseline scenario. Although the monthly revenues

Table 2.8: Daily Revenues under the Condensed Schedule

	Scenario			
Day	**Baseline**	**A1**	**A2**	**A3**
1	$11,442.16	$12,130.68	$8,525.55	$12,340.87
2	$2,314.42	$1,725.48	$1,725.48	$3,391.91
3	$5,471.18	$4,613.01	$4,613.01	$7,506.87
4	$5,082.57	$4,567.33	$4,567.33	$7,843.76
5	$6,430.85	$5,187.70	$4,672.46	$7,356.39
6	$0.00	$0.00	$0.00	$0.00
7	$0.00	$0.00	$0.00	$0.00
8	$9,772.74	$10,337.60	$7,819.30	$10,604.14
9	$4,752.85	$2,980.75	$2,980.75	$4,628.17
10	$8,097.33	$7,309.47	$6,900.74	$8,506.06
11	$7,521.00	$8,620.47	$7,706.92	$9,062.75
12	$9,911.94	$10,326.97	$9,282.26	$9,510.64
13	$0.00	$0.00	$0.00	$0.00
14	$0.00	$0.00	$0.00	$0.00
15	$11,442.16	$12,340.87	$10,870.91	$10,185.75
16	$2,314.42	$1,725.48	$2,314.42	$1,725.48
17	$6,877.79	$7,181.43	$8,378.02	$6,900.74
18	$6,337.84	$8,620.47	$9,027.29	$7,706.92
19	$6,430.85	$4,672.46	$7,356.39	$4,856.38
20	$0.00	$0.00	$0.00	$0.00
21	$0.00	$0.00	$0.00	$0.00
22	$9,772.74	$10,159.17	$10,604.14	$7,564.42
23	$2,314.42	$1,725.48	$3,391.91	$1,725.48
24	$8,097.33	$7,462.12	$9,041.52	$5,853.96
25	$6,337.84	$8,620.47	$9,541.89	$6,153.92
26	$9,911.94	$10,326.97	$11,314.09	$7,209.76
27	$0.00	$0.00	$0.00	$0.00
28	$0.00	$0.00	$0.00	$0.00

in all three cases are the same (because the same number of blocks of each type are assigned to every specialty in all the scenarios), daily revenues in the A2 approach are on average, 11.68% lower than those in the baseline scenario while those in the A3 scenario are on average, 10.69% higher than the baseline scenarios, when considering the expanded schedule. A similar result is observed with the condensed schedule (figure 2.4) and the difference in daily cumulative revenues in the baseline vs. A2 and

Table 2.9: Actual and Discounted Revenues from the Expanded and Condensed Schedules

	Condensed Schedule	Expanded Schedule
Base Actual	\$1,828,246.95	\$1,941,448.01
Base Discounted	\$1,810,438.71	\$1,922,534.71
A1 Actual	\$1,828,246.95	\$1,941,448.01
A1 Discounted	\$1,810,403.16	\$1,922,514.27
A2 Actual	\$1,828,246.95	\$1,941,448.01
A2 Discounted	\$1,810,299.97	\$1,922,413.98
A3 Actual	\$1,828,246.95	\$1,941,448.01
A3 Discounted	\$1,810,562.59	\$1,922,643.26

the baseline vs. A3 scenario is found to be -14.67% and 12.95% respectively.

Maximizing revenue:

The impact of NPV calculations on daily revenues was not found to be significant enough to warrant adoption of the approach. Over the course of 1 year, whether the expanded schedule is considered or the condensed, the impact on the overall revenue is minute. For instance, it would be advantageous to earn as much revenue as possible as early in every planning period as possible, so as to minimize the impact of the depreciation of money with time. Then, the A3 approach would be preferable over all other approaches. In practice, we see from table 2.9, the annual revenue of the A3 cases is only slightly better than all other approaches, in both the condensed and expanded schedules. Given that the differences are minute, we conclude that the NPV approach does not significantly improve the annual revenue, and would not be recommended if the end goal was maximization of revenue. However, it should be noted that these results are subject to two important considerations: the interest rate considered and the data for the costs of surgeries. Cash flow and NPV calculations are critically dependent on these values, and higher profit margins (function of amount

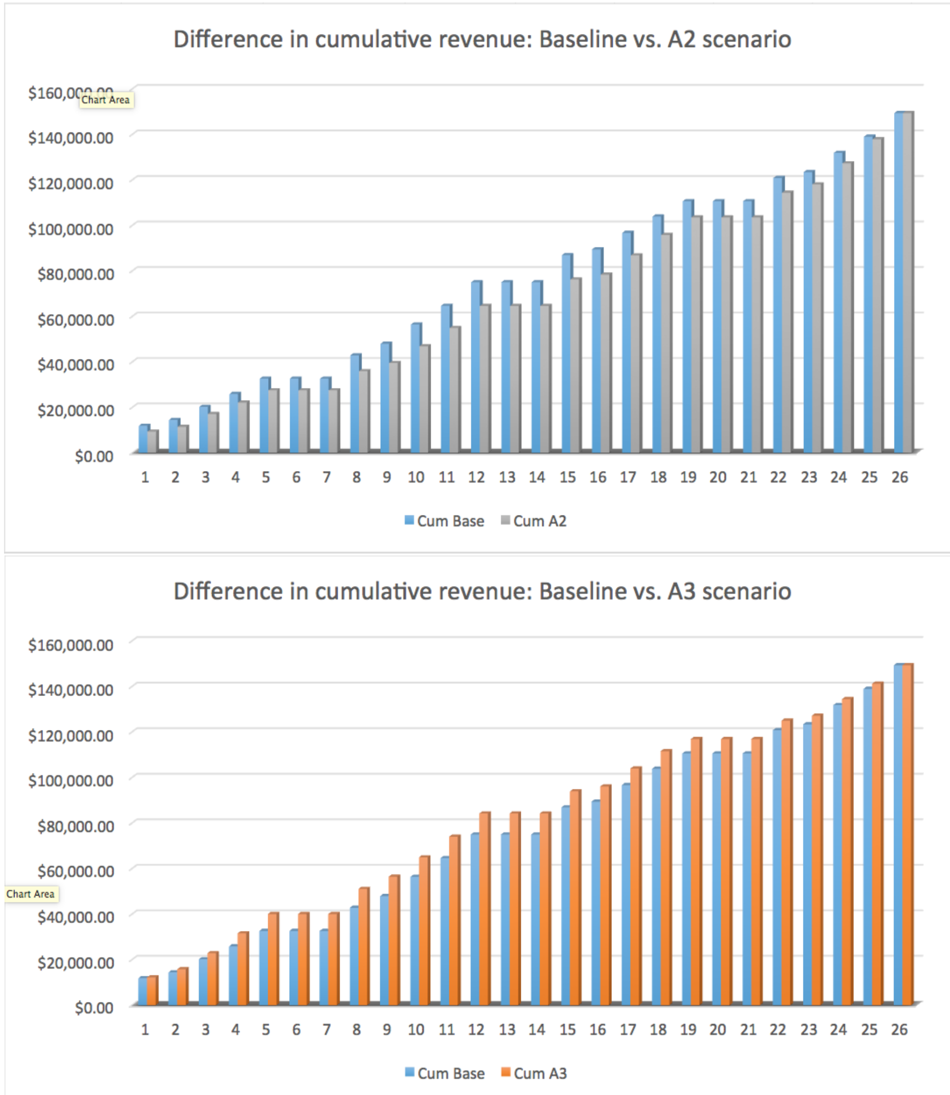

Figure 2.3: Expanded Schedule Results

billed to customers) could significantly improve these results.

The use of financial criteria represents a difficult choice for OR planning committees: while it would be ideal to accomodate as many patients as possible for achieving patient centered care, hospitals do have to consider their financial health for long term sustainability. Decisions must be made on a case-by-case basis to strike a balance. For-profit hospitals obviously must favor their financial performance, but

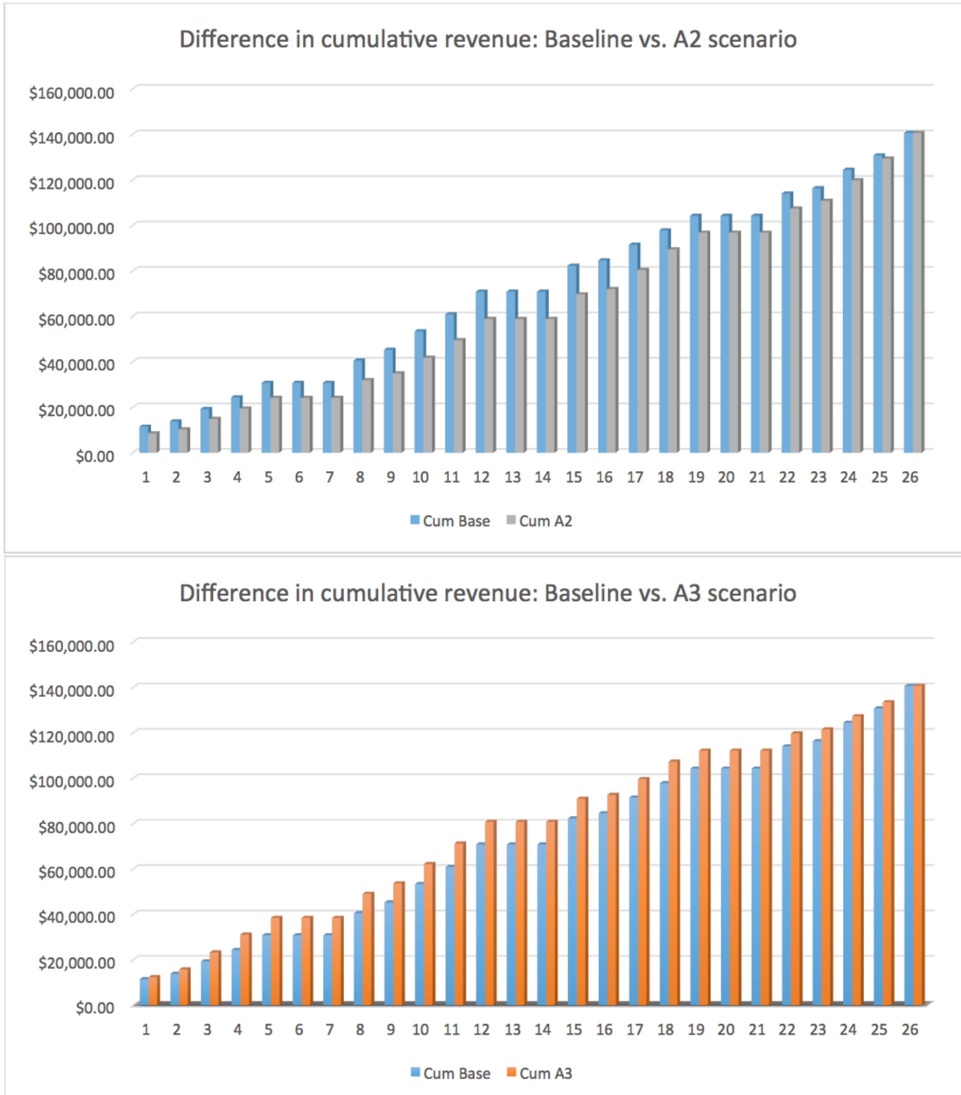

Figure 2.4: Condensed Schedule Results

even not-for-profit institutions cannot completely ignore such considerations in order to avoid budget cuts and consequent problems. The contribution of this research lies towards enriching the literature of OR scheduling based on financial criteria and providing a methodology which can be applied easily to any institution to improve its liquidity and to some extent, overall revenues. In conjunction with a contribution-margin or similar approach to mix planning, this method can be beneficial in the long run for ensuring the sustenance and growth of an OR suite.

Chapter 3

Minimizing Simultaneous Turnovers using Block Scheduling

3.1 Introduction

The single largest cost center of a hospital delivering surgical care is the Operating Room (OR) suite (Macario et al., 1995; Healthcare Financial Management Association et al., 2003). Regular and overtime salaries of OR staff account for most OR costs, particularly at hospitals with salaried nurse anesthetists and/or anesthesiologists (Dexter and Macario, 1996). Consequently in many hospitals, an OR manager or a governing body has the authority and the directive to organize care for surgical patients at the least cost. OR managers must therefore try to maximize "labor productivity" by using the least number of staff necessary to care for the patients (Dexter et al., 1999). It is a logical extension to assume that minimizing the workload on staff would be a desirable outcome, from the administrative and the employee perspective.

The time in operating theaters is categorized either as operative time or non-operative time. The former represents the time for which the OR is in use for performing surgical procedures and depends on factors such as patient, case characterestics, surgeon ability etc. The latter represents all other times when the OR is open but not being operated in, and is typically quantified as *Preparation or Turnover time*. This interval starts counting with the exit of a patient from the OR and the entrance of the next patient, and it covers some actions, such as patient transport, removal of surgical instruments, filling out forms, collection of biological materials, sterilization (cleaning) of the OR and replacement of materials (surgical and anesthetic) for the next operation (Costa Jr et al., 2015). Unlike operative times which exhibit large variations because they are dependent on multiple factors, non-operative times (preparation or turnover) do not depend on many factors and are expected to show only small variations. Furthermore, it would be reasonable to expect turnover times across diverse facilities to be fairly homogenous to expected values reported in literature. The ideal OR preparation time between one operation and another is classified as of high performance if up to 25 minutes; of medium performance if between 25 and 40 minutes; not good enough if more than 40 minutes (Dexter, 2000; He et al., 2012; Macario, 2006; Surgery Management Improvement Group, 2012). However, turnover times in OR suites are often found to be higher and prone to large variation. For instance, at a public hospital in Brazil the delays were found to be as large as 119.8±79.6 minutes (Costa Jr et al., 2015).

Large and variable turnover times create a multitude of planning problems for hospital planners. From the perspective of resource constraints, the availability of turnover resources i.e. the staff and equipment required is a major contributing factor to the size and variations in turnover durations. The logic behind this reasoning is as follows: an OR suite is comprised of multiple ORs conducting surgeries in parallel. All ORs need to be turned over after each procedure. Every time two or more rooms with shared turnover resources finish their planned procedures at approximately the same time, there is a delay caused due to the availability of turnover resources. For instance, consider the scenario shown in figure 3.1. OR 1 and OR 2 are scheduled to conduct surgeries in parallel, starting at the same time and must share a common turnover crew between them.

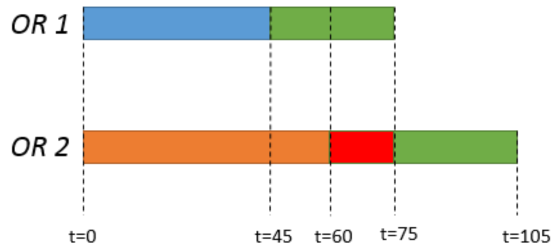

Figure 3.1: Overlap between two rooms

The surgeries in both rooms start at the same time i.e. t=0 (beginning of the block). The procedure in OR 1 is completed at t=45 at which point, the turnover crew shared between these two rooms is assigned to OR 1. The procedure in OR 2 is completed at t=60, at which turnover may commence in this room. However, since the crew is already occupied in OR 1, OR 2 must wait for the time being. At t=75, the cleaning crew is done with OR 1 and commences the cleaning process in OR 2. At t=105, the next procedure can commence. It is obvious that while no delays occur in OR 1, OR 2 has already incurred a delay of 15 minutes. This delay is what we term as an **Overlap** which to summarize, is a period of time in which two rooms require turnover in parallel. As the day progresses, such delays only get compounded, unless cancellations occur or surgerical procedures are completed sooner than anticipated. The former is not a preferable scenario and the latter is unlikely. Overlaps such as the one shown above reduce the operational efficiency of the OR suite, which utilize a limited number of turnover crews between multiple rooms. In order to quantify the overall delays caused by Overlaps, we devise a consolidated metric termed as **Simultaneous Turnovers**, defined as the sum of all overlaps occuring within an OR suite. A more formal definition is provided in later sections.

If the problem lies with a shortage of staff responsible for turnovers, then the solution would be as simple as to hire more staff. But this would incur additional costs, and might not be as effective given that the requirement for the extra staff might be critical on one day when the number of procedures performed is high in the OR suite and insignificant on other days when only a few procedures are performed. Minimizing simultaneous turnovers would reduce the load on the turnover crews and potentially reduce costs of hiring more turnover staff by improving the utilization of the present staff. Ancilliary benefits would include reducing delays in planned start times of procedures, leading to lower overtimes and further reducing costs. Therefore, the objective investigated in this research is minimizing simultaneous turnovers between all the rooms in an OR suite scheduled for procedures on any given day.

The solution methodology is restricted deliberately to only revising existing master schedules so as to ensure the approach remains as non-disruptive as possible:

- Total amount of OR time available for allocation is not altered by the addition or removal of existing blocks. As indicated earlier, this is a strategic decision (long-term) mix planning decision subject to budgetary, capacity and staffing constraints.

- Total amount of OR time allocated to various specialties is not reapportioned. This is again, a mix planning decision.

We only look to alter current master allocations. In other words, we tackle only the question of *when* time should be allocated to each surgeon/specialty, and not *how much* time is available for allocation and *how much* is allocated to each surgeon/specialty. These restrictions ensure that the proposed solutions do not increase any variable, fixed or staffing costs and possibly only require adjustments to surgeon schedules. Any changes in the OR environment tend to be difficult to implement and one of the motivations of this research was the development of relatively easy to implement solutions.

This chapter is organized in the following way: section 3.2 details some related work; sections 3.3 and 3.4 detail the problem statement and the solution methodology respectively; a numerical application of the proposed solution is presented in section 3.5 and conclusions are drawn in section 3.6.

3.2 Literature Review

The importance of reducing turnover times is evident from the amount of literature available on this subject. Infact, Dexter et al. (2003) calculated that reducing turnover times at 4 hospitals by 3-9 minutes would yield reductions of 0.8% to 1.8% in staffing costs to complete the same cases by the same services on the same days of the week in each service's allocated OR time. In units of 2001 US dollars, this would equal $52,000 to $151,000 annually. They also noted however, that this would be achievable only by reducing the OR time allocated by reducing turnover delays.

Within the healthcare domain, many researchers focus on workflow redesign to improve turnover times. Cendán and Good (2006) present a case study where the turnover times are studied and using strategic process interventions reduced from 43.7 minutes to 27.7 minutes. They achieved this by reassessing the workflow of the anesthesiologist, circulating nurse and surgical technologist. Similar reductions were attained by process redesign by another team towards the reduction of turnover time from 42.8 ± 21.1 minutes to 26.4 ± 11.2 minutes (Harders et al., 2006). Stahl et al. (2006) found that their redesign of the perioperative system improved patient flows allowing for more patients to be accomodated in one day.

Within the operations research domain, the scope of scheduling problems presented in the literature is vast. The management of resources is a critical part of OR management. A decision support system utilizing mathematical programming for scheduling resources was presented by Ozkarahan (1995). Research on OR scheduling focused on availability of beds has received considerable attention. Santibáñez et al. (2007) applied an integer programming approach to schedule surgical blocks in a hospital system to reduce resource requirements needed to care for patients after surgery, while maintaining the throughput of patients. A similar study which treated the availability of recovery rooms as the bottleneck resource in constructing an IP solution to block scheduling is presented by Jebali et al. (2006). OR staffing problems have also been studied (Dexter et al., 1999; Griffiths et al., 2005). Cardoen et al.

(2010) present a thorough review of the literature in OR scheduling divided into various categories based on the research objectives followed by individual authors. Some of these include:

- Performance measures: waiting time, throughput, utilization, leveling, makespan, patient deferrals, financial measures and preferences
- Patient characterestics: elective and non-elective patients
- Decision delineation: assignments of date, time and operating rooms where patients are scheduled, or the allocation of capacity

To the best of our knowledge, while some literature exists in reducing turnovers in ORs, none of the efforts in either the healthcare or operations research domain have adopted a block scheduling approach to reducing simultaneous turnovers. The work is similar in spirit to research performed on OR scheduling under equipment and staffing constraints. However this research is novel in its consideration of simultaneous turnovers as a source of delays which transform turnover crews into bottleneck resources. Furthermore, instead of optimizing staffing level or taking a process redesign approach, an IP-based block scheduling approach is presented to alleviate the problem at the source, in essence *acting* to the problem instead of *reacting* to it.

In terms of the tools, in addition to process redesign and mathematical modelling, simulation is a widely adopted tool for analyzing and visualizing the performance of OR suites. For instance, simulation models have been used in the study of bed occupancies (Dumas, 1984, 1985; Wright, 1987). A simulation model for predicting staff requirements was described by Duraiswamy et al. (1981). Dexter et al. (2000) used a computer simulation to study changes in OR labor costs based on the scheduling strategy employed. The advantage of simulation is the capability to analyze stochastic processes and to model more complex discrete event relationships Beliën et al. (2006). For this reason, along with its simplicity as compared to other approaches such as stochastic programming, simulation was chosen to calculate expected values of simultaneous turnovers which are then employed in solving the proposed mathematical model.

3.3 Problem Statement

To operationalize on overlaps, we define simultaneous turnovers as the sum of the length of periods of overlap of one room in an operating suite with all the other rooms of the suite conducting surgeries in parallel. A simple instance of how simultaneous turnovers are calculated is as follows: consider an OR suite comprised of a set of R rooms, where room $r_1 \in R$ is assigned to a particular specialty $s_1 \in S$. Then the simultaneous turnovers of room r_1 when assigned to specialty s_1 with all other rooms denoted by $r_2 \in R$ assigned to another particular specialty $s_2 \in S$ can be written as:

$$V_d = \sum_{r_2=1}^{R} y_{s_1 s_2 r_1 r_2} * P^b_{s_1 s_2} \quad \forall r_1, r_2 \in R, s_1, s_2 \in S. \tag{3.1}$$

where $y_{s_1 s_2 r_1 r_2}$ is a binary variable which is 1 if rooms r_1 and r_2 are assigned to specialties s_1 and s_2 respectively simultaneously and $P^b_{s_1 s_2}$ denotes the mean lengths of such overlaps (calculated using simulation). The cumulative simultaneous turnovers over an entire day of the planning horizon would similarly be the sum of simultaneous overlaps of each room with all the other rooms. The rest of the problem can be stated as follows: a set of blocks B in ORs R available for allocation in a planning horizon of D days must be assigned to a set of specialties S subject to coverage and duplicate assignment constraints, so as to minimize simultaneous turnovers. This is a binary integer problem, where the decision variable represents the mapping of blocks to specialties.

3.4 Solution Methodology

The research methodology employed is comprised of 2 steps:

1. Generate expected values for simultaneous turnovers using simulation in Anylogic.

2. Use Integer Programming model to generate block schedules which minimize the durations of overlaps occuring on each day of the planning horizon.

3.4.1 Generating Expected Overlaps

A discrete event model (DEM) implemented in Anylogic is used to generate expected overlaps. The workflow of the model is summarized in figure 3.2. Essentially, the operations of two rooms $r_1, r_2 \in R (r_1 \neq r_2)$ are simulated. Different specialties $s_1, s_2 \in S$ are assigned to the two rooms over successive runs to calculate the mean duration of simultaneous turnovers for each specialty combination and each block type $b \in B$. Further details are contained in appendix A.3.

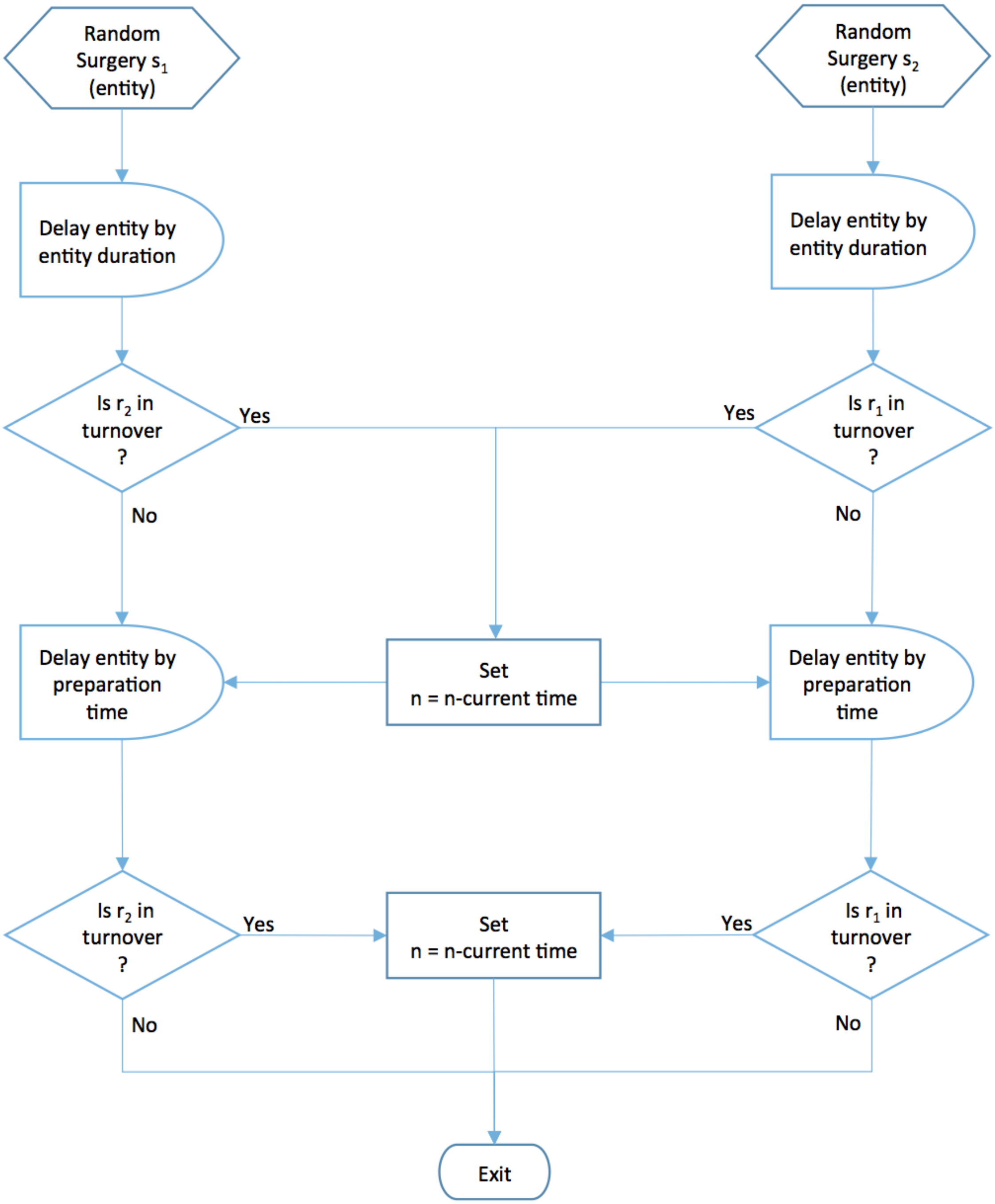

Figure 3.2: Workflow of DEM in Anylogic

Sample results are shown in table 3.1. The results can be interpreted as follows: if a block of type b in OR 1 (r_1) is assigned to the specialty General (s_1), and if a block of type b in OR 2 (r_2) is assigned to specialty Orthopedics (s_2) at the same time, then the cumulative duration of time for which r_1 and r_2 would be in turnover at the same time would be 19.454 minutes.

Table 3.1: Sample of expected overlap values based on simulation

	General	**Ortho**	**Urology**	**Plastics**
General	19.249	19.454	23.41	19.922
Ortho	19.454	21.275	24.841	24.45
Urology	23.41	24.841	29.704	26.84
Plastics	19.922	24.45	26.84	33.139

The expected values for all overlaps between all rooms, specialties and blocks are determined in this way. In the IP formulation, these values are used to define the coefficients of the objective function. It is worth mentioning that the results of the simulation are dependent on the duration of each turnover considered.

3.4.2 IP-Model

The IP model used is described below.

- *Parameters*

  1. S: number of specialties under consideration.
  2. B: number of block types under consideration.
  3. D: number of days in the planning horizon.
  4. R: number of ORs available.
  5. M: Maximum number of blocks that can be assigned to one specialty on one day.

- *Indices*

1. s: Index of specialties, $s = 1, ...S$.
2. b: Index of blocks, $b = 1, ...B$.
3. d: Index of days in planning horizon, $d = 1, ...D$.
4. r: Index of available rooms, $r = 1, ...R$.

- *Indexed Parameters*

1. ${N_b}^s$: Minimum number of blocks of type b that must be assigned to specialty s in the planning horizon.
2. $P^b_{s_1,s_2}$: Expected value of simultaneous turnovers when specialties s_1 and s_2 are assigned block b simultaneously.

- *Decision Variables*:

1. Binary variable X^s_{bdr},

$$X^s_{bdr} = \left\{ \begin{array}{ll} 1, & if\ block\ b\ on\ \ day\ d\ in\ room\ r\ is\ assigned\ to \\ & specialty\ s \\ 0, & otherwise \end{array} \right\}$$

2. Binary variable $y^b_{ds_1s_2r_1r_2}$,

$$y^b_{ds_1s_2r_1r_2} = \left\{ \begin{array}{ll} 1, & if\ on\ day\ d,\ specialties\ s_1\ and\ s_2\ are\ assigned\ block\ b \\ & in\ rooms\ r_1\ and\ r_2\ respectively,\ simultaneously \\ 0, & otherwise \end{array} \right\}$$

- *Decision Expression*: cumulative overlaps due to simultaneous turnovers on day d, calculated as:

$$V_d = \sum_{s_1=1}^{S} \sum_{s_2=1}^{S} \sum_{r_1=1}^{R} \sum_{r_2=1}^{R} y^b_{ds_1s_2r_1r_2} * P^b_{s_1,s_2} \tag{3.2}$$

$\forall\, b \in B,\ s_1, s_2 \in S, r_1, r_2 \in R\, and\, r_1 < r_2$

- *IP-Formulation*

$$\textit{Minimize} \sum_{d=1}^{D} V_d \tag{3.3}$$

Subject to

$$\sum_{s=1}^{S} X_{bdr}^{s} = 1 \quad \forall\, b \in B, d \in D, r \in R \tag{3.4}$$

$$\sum_{d=1}^{D} \sum_{r=1}^{R} X_{bdr}^{s} \geq N_b^s \quad \forall\, s \in S, b \in B \tag{3.5}$$

$$\sum_{b=1}^{B} \sum_{r=1}^{R} X_{bdr}^{s} \leq M \quad \forall\, s \in S, d \in D \tag{3.6}$$

$$X_{bdr_1}^{s_1} + X_{bdr_2}^{s_2} - 1 \leq y_{ds_1s_2r_1r_2}^{b} \tag{3.7}$$

$$\forall\, b \in B,\ s_1, s_2 \in S, r_1, r_2 \in R \,\textit{and}\, r_1 < r_2$$

The objective function (3.3) minimizes the cumulative overlap due to simultaneous turnovers over the planning horizon. Constraint 3.4 ensures every block is only assigned to one specialty while constraint 3.5 ensures adequate coverage i.e. each specialty recieves the requisite number of blocks of each type (based on the existing schedule). Constraints 3.6 limits the total number of blocks assigned to a specialty per day while 3.7 defines the relationship between the overlaps.

3.5 Numerical Instantiation

The proposed solution approach was applied to data obtained from the Veteran's hospital, Pittsburgh. The 4 busiest departments at the hospital vis a vis, General, Orthology, Urology and Plastics were considered. While the actual schedule cycles over a 5-week period, this research was limited to 4 weeks in order to improve the cyclicity of the schedule. The list of surgeries (or procedures) performed by each department over the course of one year and the scheduled and actual durations of each procedure was provided by the hospital. The current master schedule followed at the hospital was also provided. The current schedule is referred to here on as the *Expanded Schedule* and was reduced to create the *Condensed Schedule*. The two schedules are explained in greater detail in the following section.

3.5.1 The Expanded Schedule

A sample of the current schedule at the hospital for 2 rooms over one week is shown in figure 3.3 while the full schedule for 9 rooms over 4 weeks is presented in appendix A.1.

	OR 1			OR 2		
Week 1	**7:30-12:00**	**12:00-15:00**	**15:00-18:00**	**7:30-12:00**	**12:00-15:00**	**15:00-18:00**
Monday				7.5 (7:30-15:00)		
Tuesday						
Wednesday	9.5 (8:30-18:00)			6.5 (8:30-15:00)		
Thursday	7.5 (7:30-15:00)			7.5 (7:30-15:00)		
Friday	7.5 (7:30-15:00)					
Week 2						
Monday				7.5 (7:30-15:00)		
Tuesday	10.5 (7:30-18:00)			7.5 (7:30-15:00)		
Wednesday	9.5 (8:30-18:00)			6.5 (8:30-15:00)		
Thursday	7.5 (7:30-15:00)					
Friday	7.5 (7:30-15:00)					
Week 3						
Monday				7.5 (7:30-15:00)		
Tuesday						
Wednesday				6.5 (8:30-15:00)		
Thursday	7.5 (7:30-15:00)			7.5 (7:30-15:00)		
Friday	7.5 (7:30-15:00)					
Week 4						
Monday				7.5 (7:30-15:00)		
Tuesday	10.5 (7:30-18:00)					
Wednesday	9.5 (8:30-18:00)			6.5 (8:30-15:00)		
Thursday	7.5 (7:30-15:00)					
Friday						

Room Unavailable Urology Orthopedics General Plastics

Figure 3.3: Sample of current schedule part

As is evident from the schedule, the rooms are not always available. The color on the schedule indicates the specialty to which the room is currently assigned. Additionally each block carries the duration for which it is assigned to said specialty. Each day of the week is divided into 3 periods: morning or 7:30 to 12:00; afternoon or 12:00 to 15:00; and evening or 15:00 to 18:00. There are 85 blocks varying in the location, start time and duration available for allocation. Each block is currently assigned to some specialty. A summary of these blocks is given in tables 3.2 and 3.3 below, a more expanded list is available in the appendix.

Table 3.2: Types and number of blocks available for assignment

Block Type	Duration	Number of blocks available in 4 weeks
I	3	8
II	3.5	4
III	4.5	10
IV	5	10
V	6.5	7
VI	7.5	26
VII	9.5	4
VIII	10.5	16
Total		85

Table 3.3: Expanded schedule over 4 weeks

Speciality	Blocks assigned of type							
	I	II	III	IV	V	VI	VII	VIII
General	4	0	2	0	1	12	4	4
Orthopedics	0	0	4	2	4	4	0	8
Urology	4	0	0	8	0	6	0	4
Plastics	0	4	4	0	2	4	0	0

The allocations defined within this schedule are summarized in figure 3.4 for illustration purposes.

3.5.2 The Condensed Schedule

As seen in the master schedule, each day in the planning horizon is comprised of the morning, afternoon and evening period. Various blocks of varying lengths are used to cover various time intervals during the day. Blocks larger than 5 hours can be

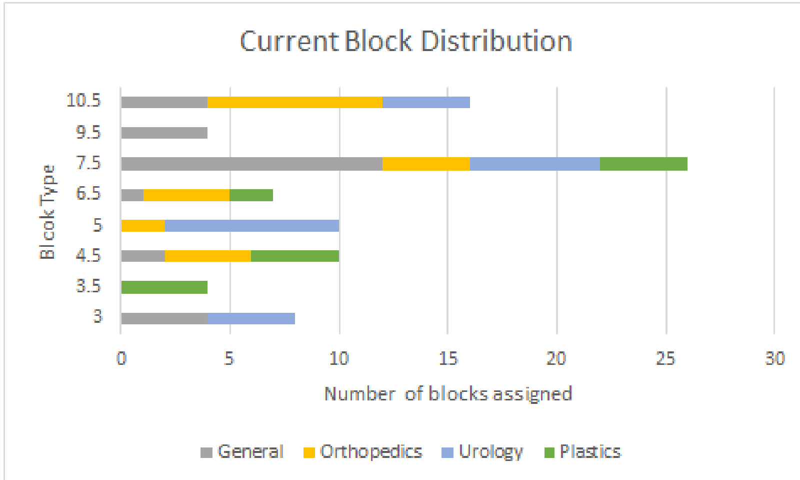

Figure 3.4: Distribution of Blocks amongst the Specialties

considered as combinations of the smaller blocks. For instance, a 9.5 hour block in the hospital starts at 8:30 and ends at 18:00. It can therefore be considered as the combination of a 3.5 hour block (8:30-12:00), a 3 hour block (12:00-15:00) and another 3 hour block (15:00-18:00). The 8 block types mentioned in the master schedule can be broken down in a similar fashion into their constituent blocks. This simplfies the process of simulation and optimization (by reducing the number of decision variables) and lends more flexibility to the optimization model in terms of block allocations made to fulfill coverage requirements. Table 3.4 details the breakdown of the type and number of each constituent block of the 4 largest blocks vis a vis 6.5, 7.5, 9.5 and 10.5 hour blocks. Using only 4 types of blocks, the *Expanded Schedule* can be reduced to the *Condensed Schedule*, given in tables 3.5 and 3.6 which are used in constraints 3.5 and 3.6.

Table 3.4: Breakdown of long blocks

Block Type	Current Block Duration	Number of constituent blocks		
		4.5	3.5	3
V	6.5	0	1	1
VI	7.5	1	1	0
VII	9.5	0	1	2
VIII	10.5	1	0	2

Table 3.5: Types and Number of Blocks available for assignment

Block Type	Duration	Number of blocks available in 4 weeks
I	3	81
II	3.5	15
III	4.5	52
IV	5	10

Table 3.6: Condensed Schedule over 4 weeks

Speciality	Blocks assigned of type			
	I	II	III	IV
General	33	5	18	0
Orthopedics	24	4	16	2
Urology	18	0	10	8
Plastics	6	6	8	0

For this experiment, only the condensed schedule was considered. This is because the number of binary variables when considering only 4 blocks is approximately 49,000. Although this is a very sparse matrix, it does require a substantial computational effort to solve to optimality. The other parameters of the numerical instance considered are:

- Number of specialties, S=4.
- Number of blocks considered, B=4.
- Number of days in the planning horizon, D=20.
- Number of ORs available, R=9.
- Maximum number of blocks than can be assigned to one specialty on one day, M=5.

3.5.3 Results

The simulation model in Anylogic was implemented to determine the expected values of overlaps between different specialties. To analyse the sensitivity of the overlap values to turnover duration, simulations were conducted for 3 different turnover times: 15 minutes, 30 minutes and 45 minutes. For instance, if the turnover crew need 15 minutes to prepare a room for surgery, what is the amount of time for which both OR 1 (assigned to General) and OR 2 (assigned to Orthopedics) are in turnovers simultaneously? What is that value if the turnover crew takes 30 minutes, or 45? Table 3.8 and figure 3.5 present the value of overlaps based on specialty combination and duration of turnover time for 4.5 hour blocks. As the amount of turnover time increases, the duration of the overlaps also increases. Similar results are seen for blocks of duration 3.5 and 3 hours, and are given in in appendix A.4.

Table 3.7: Overlap durations for 4.5 hour blocks

Block Combination	**Turnover Time (minutes)**		
	15	**30**	**45**
General-General	9.014	21.845	42.535
General-Ortho	9.364	21.188	38.274
General-Urology	10.255	24.081	42.645
General-Plastics	8.997	25.885	48.582
Ortho-Ortho	11.176	21.437	37.989
Ortho-Urology	11.376	24.011	40.007
Ortho-Plastics	10.135	25.989	46.356
Urology-Urology	12.809	28.257	48.054
Urology-Plastics	11.562	32.152	58.38
Plastics-Plastics	15.877	46.865	85.049

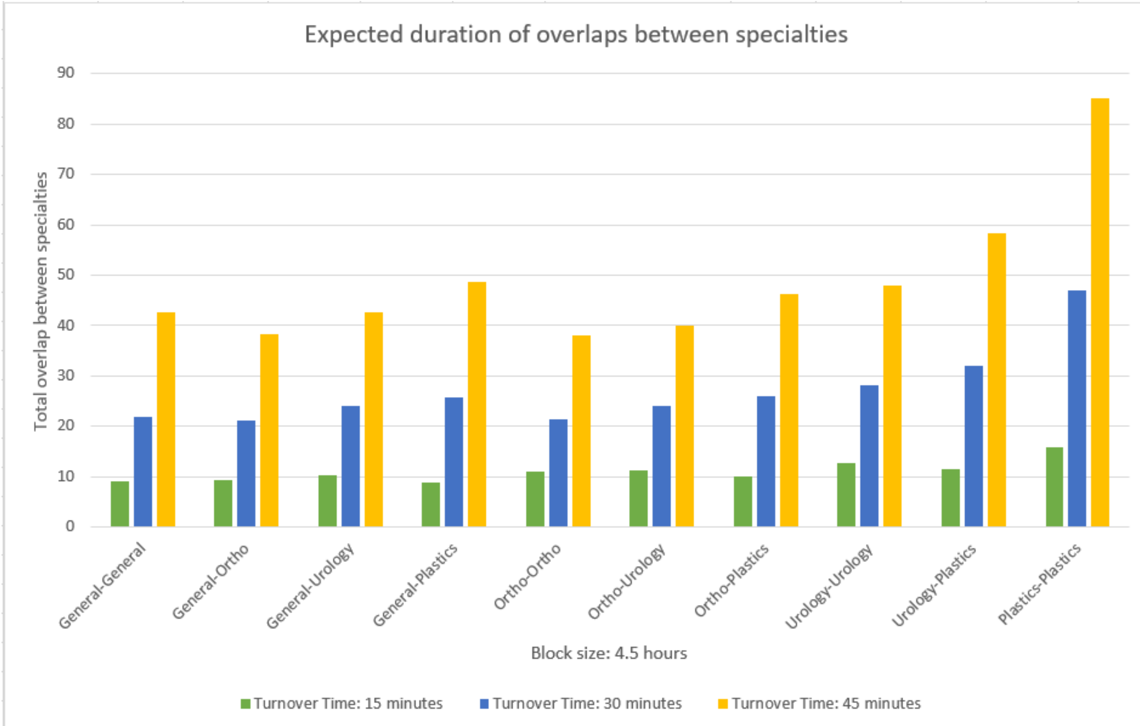

Figure 3.5: Expected overlap values for blocks of duration 4.5 hours

The optimization experiment was conducted for the three values of overtime mentioned above. The expected overlap values for each of these turnover times were were first used to calculate a baseline value of the simultaneous turnovers as per the current schedule and then implemented in the IP to build an alternative master schedule. Note that while 4 types of blocks are used for scheduling, simultaneous turnovers for only 3 are calculated because type IV (5 hr) blocks only overlap with type III (3 hr) blocks. To calculate these overlaps, we consider the type IV blocks to be equivalent to type III blocks, since overlaps occurring after 3 hours from the start can be neglected.

The results from the IP are given in table 3.8 and indicate the reductions in simultaneous turnovers possible for different turnover time scenarios. As expected, the benefit from the approach increases as turnover times increase, but is also significant at the lowest turnover time considered.

Table 3.8: Results of the Integer Program

	Turnover time (minutes)		
	15	30	45
Current (minutes)	2054.8	4981.8	9061.3
Best Integer (minutes)	1947.08	4486.31	8157.734
Improvement %	5.24%	9.95%	9.97%
Gap	26%	20%	23%
Computational Time (minutes)	20	20	10

A discussion of the results is presented in the following section.

3.6 Conclusions and Discussions

The overlap durations between different specialties increase as turnover time increases. While this result is expected, it does demonstrate an important fact. The longer the duration of turnover time at a facility, the larger is the total duration of all simultaneous turnovers. Hence the opportunity for improvement with this approach also increases as turnover time increases.

The results appear promising in reducing simultaneous turnovers. It should be further noted that the results of the numerical study are for only 4 out of the 10 specialties at the hospital and it is quite likely that by considering a larger number of specialties even greater benefits can be seen. Furthermore, the solutions from the IP are obtained with relatively large gaps from optimality (20%-26%). The large gap is because of the large solution space created by the 6-dimensional y decision variable used to quantify the overlaps. CPLEX is unable to completely fathom the solution space in a reasonable amount of time. However with the use of heuristic methods or other Monte Carlo methods, a better solution for the present study can be obtained.

The advantages of these savings can be translated directly towards reducing the strain on turnover crews and resources, increasing their utilization and keeping costs at the same level. Furthermore, delays can be reduced allowing surgeries to be performed closer to their scheduled times which would be beneficial for all stakeholders. Combined with effective surgery scheduling methods, the benefits of this research can lead to reducing overtime costs and even allowing for more surgeries to be accomodated into one work day. Future work would involve extending the numerical instance to include all specialties and all rooms and using heuristic methods to fully solve the model.

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Appendix

Appendix A

Appendix

A.1 Current Schedule for numerical instance

The schedule of the numerical instances considered in 2.5 and 3.5 are given in figure A.1 below.

	OR 1			OR 2			OR 3		
Week 1	7:30-12:00	12:00-15:00	15:00-18:00	7:30-12:00	12:00-15:00	15:00-18:00	7:30-12:00	12:00-15:00	15:00-18:00
Monday				7.5 (7:30-15:00)			4.5 (7:30-12:00)	5 (12:00-17:00)	
Tuesday									
Wednesday	9.5 (8:30-18:00)			6.5 (8:30-15:00)					
Thursday	7.5 (7:30-15:00)			7.5 (7:30-15:00)					
Friday	7.5 (7:30-15:00)								
Week 2									
Monday				7.5 (7:30-15:00)			4.5 (7:30-12:00)		
Tuesday	10.5 (7:30-18:00)			7.5 (7:30-15:00)					
Wednesday	9.5 (8:30-18:00)			6.5 (8:30-15:00)			6.5 (8:30-15:00)		
Thursday	7.5 (7:30-15:00)								
Friday	7.5 (7:30-15:00)						7.5 (7:30-15:00)		
Week 3									
Monday				7.5 (7:30-15:00)			4.5 (7:30-12:00)	5 (12:00-17:00)	
Tuesday									
Wednesday				6.5 (8:30-15:00)					
Thursday	7.5 (7:30-15:00)			7.5 (7:30-15:00)					
Friday	7.5 (7:30-15:00)								
Week 4									
Monday				7.5 (7:30-15:00)			4.5 (7:30-12:00)		
Tuesday	10.5 (7:30-18:00)								
Wednesday	9.5 (8:30-18:00)			6.5 (8:30-15:00)			6.5 (8:30-15:00)		
Thursday	7.5 (7:30-15:00)								
Friday							7.5 (7:30-15:00)		

	OR 5			OR 6			OR 7		
Week 1	7:30-12:00	12:00-15:00	15:00-18:00	7:30-12:00	12:00-15:00	15:00-18:00	7:30-12:00	12:00-15:00	15:00-18:00
Monday	7.5 (7:30-15:00)			10.5 (7:30-18:00)					
Tuesday	10.5 (7:30-18:00)								
Wednesday									
Thursday	10.5 (7:30-18:00)								
Friday				10.5 (7:30-18:00)					
Week 2									
Monday		3 (12:00-15:00)		10.5 (7:30-18:00)					
Tuesday									
Wednesday									
Thursday	10.5 (7:30-18:00)						7.5 (7:30-15:00)		
Friday		5 (12:00-17:00)		10.5 (7:30-18:00)					
Week 3									
Monday	7.5 (7:30-15:00)			10.5 (7:30-18:00)					
Tuesday	10.5 (7:30-18:00)								
Wednesday	9.5 (8:30-18:00)						6.5 (8:30-15:00)		
Thursday	10.5 (7:30-18:00)								
Friday				10.5 (7:30-18:00)					
Week 4									
Monday		3 (12:00-15:00)		10.5 (7:30-18:00)					
Tuesday									
Wednesday									
Thursday	10.5 (7:30-18:00)								
Friday	7.5 (7:30-15:00)			10.5 (7:30-18:00)					

	OR 8			OR 9			OR 10		
Week 1	7:30-12:00	12:00-15:00	15:00-18:00	7:30-12:00	12:00-15:00	15:00-18:00	7:30-12:00	12:00-15:00	15:00-18:00
Monday				4.5 (7:30-12:00)	3 (12:00-15:00)				
Tuesday									
Wednesday		5 (12:00-17:00)		3.5 (8:30-12:00)					
Thursday									
Friday		5 (12:00-17:00)						3 (12:00-15:00)	
Week 2									
Monday	7.5 (7:30-15:00)			4.5 (7:30-12:00)					
Tuesday									
Wednesday		5 (12:00-17:00)		3.5 (8:30-12:00)					
Thursday							7.5 (7:30-15:00)		
Friday							4.5 (7:30-12:00)	3 (12:00-15:00)	
Week 3									
Monday				4.5 (7:30-12:00)	3 (12:00-15:00)				
Tuesday									
Wednesday		5 (12:00-17:00)		3.5 (8:30-12:00)					
Thursday	7.5 (7:30-15:00)								
Friday		5 (12:00-17:00)						3 (12:00-15:00)	
Week 4									
Monday	7.5 (7:30-15:00)			4.5 (7:30-12:00)					
Tuesday									
Wednesday		5 (12:00-17:00)		3.5 (8:30-12:00)					
Thursday	7.5 (7:30-15:00)						7.5 (7:30-15:00)		
Friday		5 (12:00-17:00)					4.5 (7:30-12:00)	3 (12:00-15:00)	

Room Unavailable | Urology | Orthopedics | General | Plastics

Figure A.1: Current Schedule of the Numerical Instance considered

A.2 Summary of revenue results

The following tables (A.1 and A.2) list the revenues from the use of expanded and condensed schedules in generating net present values of the overall revenues.

Table A.1: Condensed Schedule Daily Revenues

Day	Condensed Schedule		
	A1	A2	A3
1	$12,130.68	$8,525.55	$12,340.87
2	$1,725.48	$1,725.48	$3,391.91
3	$4,613.01	$4,613.01	$7,506.87
4	$4,567.33	$4,567.33	$7,843.76
5	$5,187.70	$4,672.46	$7,356.39
6	$0.00	$0.00	$0.00
7	$0.00	$0.00	$0.00
8	$10,337.60	$7,819.30	$10,604.14
9	$2,980.75	$2,980.75	$4,628.17
10	$7,309.47	$6,900.74	$8,506.06
11	$8,620.47	$7,706.92	$9,062.75
12	$10,326.97	$9,282.26	$9,510.64
13	$0.00	$0.00	$0.00
14	$0.00	$0.00	$0.00
15	$12,340.87	$10,870.91	$10,185.75
16	$1,725.48	$2,314.42	$1,725.48
17	$7,181.43	$8,378.02	$6,900.74
18	$8,620.47	$9,027.29	$7,706.92
19	$4,672.46	$7,356.39	$4,856.38
20	$0.00	$0.00	$0.00
21	$0.00	$0.00	$0.00
22	$10,159.17	$10,604.14	$7,564.42
23	$1,725.48	$3,391.91	$1,725.48
24	$7,462.12	$9,041.52	$5,853.96
25	$8,620.47	$9,541.89	$6,153.92
26	$10,326.97	$11,314.09	$7,209.76
27	$0.00	$0.00	$0.00
28	$0.00	$0.00	$0.00

Table A.2: Expanded Schedule Daily Revenues

Day	Expanded Schedule		
	A1	A2	A3
1	$12,634.04	$9,325.29	$12,207.86
2	$2,113.14	$2,113.14	$3,615.24
3	$5,631.03	$5,631.03	$7,047.87
4	$5,457.60	$5,023.51	$8,724.88
5	$5,362.80	$5,362.80	$8,475.35
6	$0.00	$0.00	$0.00
7	$0.00	$0.00	$0.00
8	$10,188.96	$8,435.12	$11,010.86
9	$3,568.33	$3,568.33	$5,403.18
10	$7,917.91	$7,385.87	$8,449.95
11	$8,979.07	$8,018.04	$9,086.05
12	$11,075.98	$9,683.40	$10,202.13
13	$0.00	$0.00	$0.00
14	$0.00	$0.00	$0.00
15	$12,634.04	$11,687.08	$9,747.27
16	$2,113.14	$2,113.14	$2,113.14
17	$7,917.91	$8,449.95	$7,917.91
18	$8,979.07	$8,979.07	$7,578.30
19	$5,362.80	$7,696.11	$5,362.80
20	$0.00	$0.00	$0.00
21	$0.00	$0.00	$0.00
22	$10,188.96	$10,903.88	$8,102.36
23	$2,113.14	$3,615.24	$2,113.14
24	$8,449.95	$9,229.19	$7,280.31
25	$7,578.30	$10,619.80	$6,811.46
26	$11,075.98	$11,502.16	$8,092.09
27	$0.00	$0.00	$0.00
28	$0.00	$0.00	$0.00

A.3 Discrete Event Model in Anylogic

The discrete event model implemented in Anylogic is shown in figures A.2 and A.3 below.

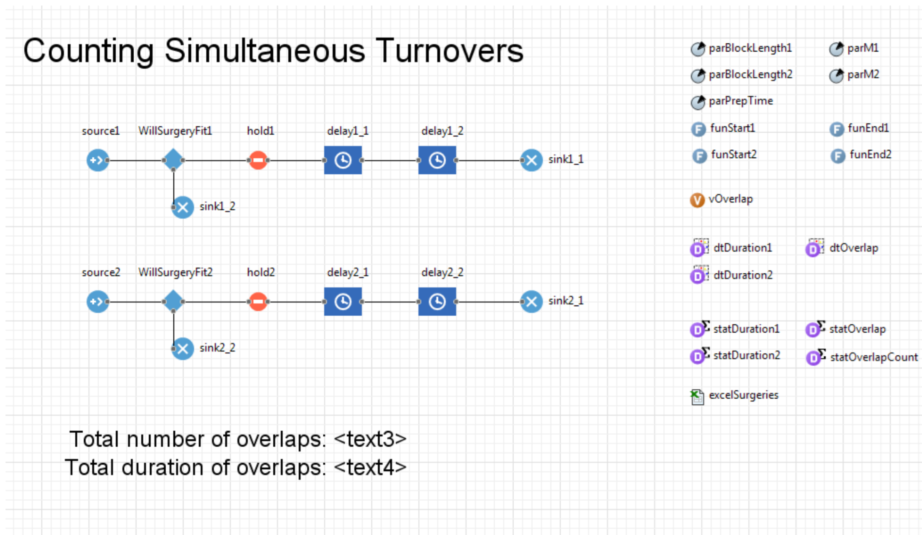

Figure A.2: Discrete event model in Anylogic

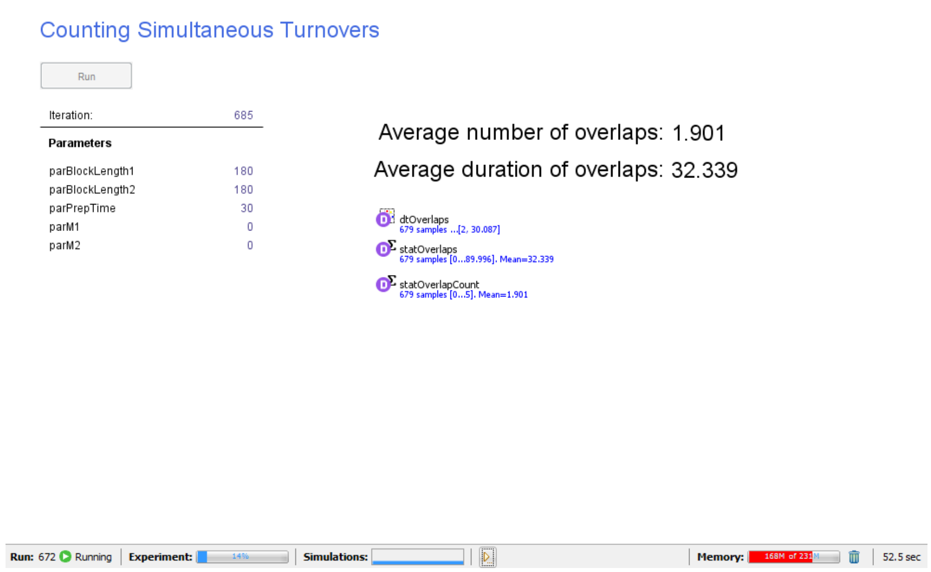

Figure A.3: Running the simulation for 10,000 replications

A.4 Summary of simulation results using Anylogic

The following tables list the detailed values of simultaneous turnovers from the simulation experiments.

Table A.3: Overlap durations for 3.5 hour blocks

Block Combination	Turnover Time (minutes)		
	15	30	45
General-General	11.43	19.652	40.666
General-Ortho	9.799	20.624	39.048
General-Urology	10.226	22.204	45.197
General-Plastics	6.958	24.247	40.853
Ortho-Ortho	10.053	22.228	40.742
Ortho-Urology	10.188	23.434	44.871
Ortho-Plastics	8.575	28.093	41.637
Urology-Urology	11.033	26.501	52.123
Urology-Plastics	9.196	30.207	47.987
Plastics-Plastics	12.999	43.33	61.589

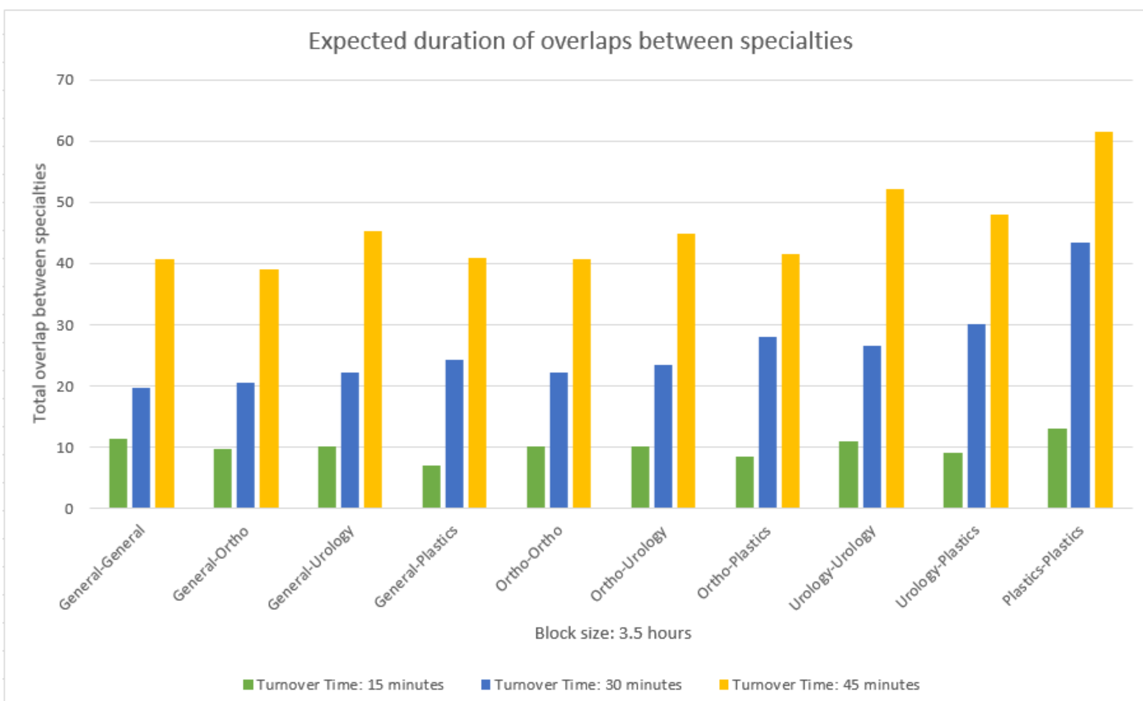

Figure A.4: Expected overlap values for blocks of duration 3.5 hours

Table A.4: Overlap durations for 3.0 hour blocks

Block Combination	Turnover Time (minutes) 15	30	45
General-General	8.867	19.249	34.743
General-Ortho	10.252	19.454	36.767
General-Urology	10.308	23.41	43.781
General-Plastics	6.907	19.922	39.384
Ortho-Ortho	12.136	21.275	41.117
Ortho-Urology	11.781	24.841	48.052
Ortho-Plastics	9.323	24.45	46.4
Urology-Urology	12.511	29.704	56.881
Urology-Plastics	8.939	26.84	61.654
Plastics-Plastics	13.218	33.139	61.426

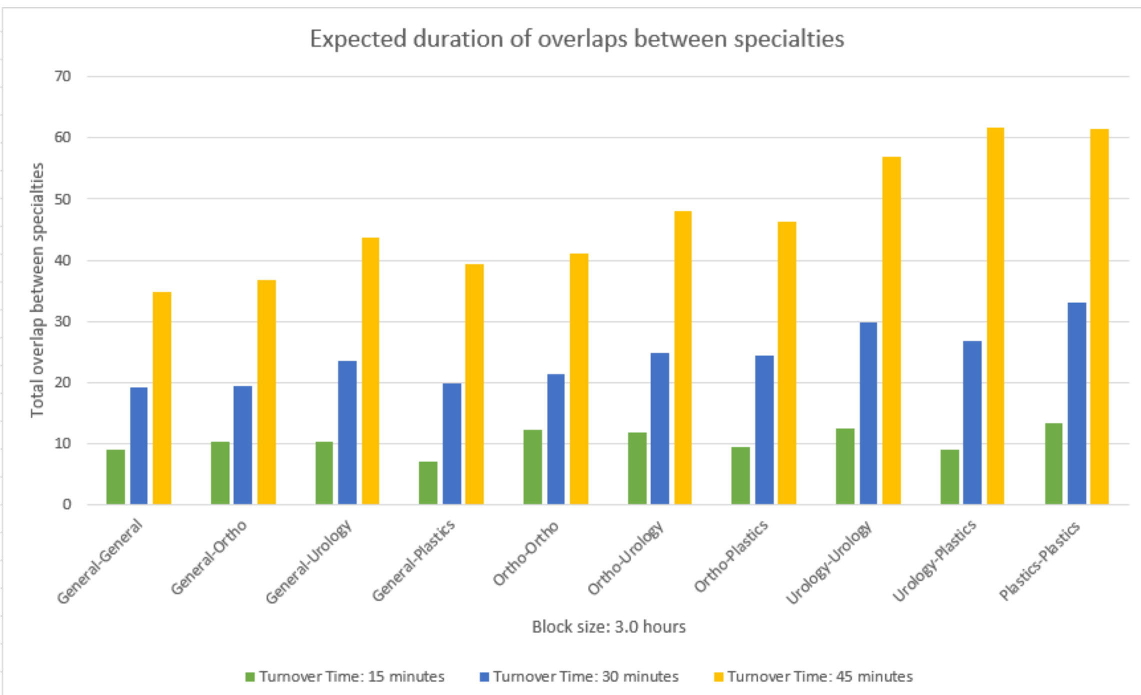

Figure A.5: Expected overlap values for blocks of duration 3.0 hours

Table A.5: Overlap durations (minutes) of type I blocks (4.5 hours) with type I blocks (4.5 hours)

Block 1	**Block 2**	**Runs**	**Mean**	**Deviation**	**Mean** Confidence	**Min**	**Max**
General	General	5000	21.845	19.586	0.543	0	89.999
General	Ortho	5000	21.188	17.6514	0.488	0	89.946
General	Urology	5000	24.081	20.073	0.556	0	89.99
General	Plastics	5000	25.885	17.923	0.497	0	89.997
Ortho	Ortho	5000	21.437	18.95	0.525	0	119.999
Ortho	Urology	5000	24.011	20.044	0.556	0	90
Ortho	Plastics	5000	25.989	21.891	0.607	0	119.949
Urology	Urology	5000	28.257	22.367	0.62	0	90
Urology	Plastics	5000	32.152	21.51	0.597	0	104.994
Plastics	Plastics	5000	46.865	23.645	0.655	0	119.99

Table A.6: Overlap count of type I blocks (4.5 hours) with type I blocks (4.5 hours)

Block 1	**Block 2**	**Runs**	**Mean**	**Min**	**Max**	**Count**
General	General	5000	1.327	0	4	6637
General	Ortho	5000	1.326	0	4	6631
General	Urology	5000	1.472	0	4	7360
General	Plastics	5000	1.699	0	5	8497
Ortho	Ortho	5000	1.361	0	7	6804
Ortho	Urology	5000	1.535	0	5	7673
Ortho	Plastics	5000	1.707	0	7	8536
Urology	Urology	5000	1.734	0	5	8670
Urology	Plastics	5000	2.054	0	6	10270
Plastics	Plastics	5000	2.893	0	7	14464

Table A.7: Overlap durations (minutes) of type II blocks (3.5 hours) with type II blocks (3.5 hours)

Block 1	Block 2	Runs	Mean	Deviation	Mean Confidence	Min	Max
General	General	5000	19.652	18.175	0.504	0	60
General	Ortho	5000	20.624	16.4	0.455	0	60
General	Urology	5000	22.204	17.611	0.488	0	60
General	Plastics	5000	24.247	15.569	0.432	0	89.99
Ortho	Ortho	5000	22.228	19.074	0.529	0	89.99
Ortho	Urology	5000	23.434	17.83	0.494	0	89.992
Ortho	Plastics	5000	28.093	20.629	0.572	0	90
Urology	Urology	5000	26.501	18.393	0.51	0	89.995
Urology	Plastics	5000	30.207	18.059	0.501	0	90
Plastics	Plastics	5000	43.33	22.153	0.614	0	90

Table A.8: Overlap count of type II blocks (3.5 hours) with type II blocks (3.5 hours)

Block 1	Block 2	Runs	Mean	Min	Max	Count
General	General	5000	1.177	0	3	5887
General	Ortho	5000	1.28	0	3	6400
General	Urology	5000	1.336	0	3	6679
General	Plastics	5000	1.605	0	4	8023
Ortho	Ortho	5000	1.394	0	5	6972
Ortho	Urology	5000	1.458	0	5	7289
Ortho	Plastics	5000	1.785	0	5	8923
Urology	Urology	5000	1.585	0	5	7926
Urology	Plastics	5000	1.937	0	5	9683
Plastics	Plastics	5000	2.579	0	5	12984

Table A.9: Overlap durations (minutes) of type II blocks (3.0 hours) with type II blocks (3.0 hours)

Block 1	Block 2	Runs	Mean	Deviation	Mean Confidence	Min	Max
General	General	5000	19.249	15.687	0.435	0	60
General	Ortho	5000	19.454	14.927	0.414	0	59.99
General	Urology	5000	23.41	15.594	0.432	0	60
General	Plastics	5000	19.922	14.551	0.403	0	60
Ortho	Ortho	5000	21.275	16.992	0.471	0	89.998
Ortho	Urology	5000	24.841	15.943	0.443	0	89.989
Ortho	Plastics	5000	24.45	17.252	0.478	0	89.997
Urology	Urology	5000	29.704	15.585	0.432	0	60
Urology	Plastics	5000	26.84	15.469	0.429	0	89.993
Plastics	Plastics	5000	33.139	17.897	0.496	0	90

Table A.10: Overlap count of type II blocks (3.0 hours) with type II blocks (3.0 hours)

Block 1	Block 2	Runs	Mean	Min	Max	Count
General	General	5000	1.051	0	3	5255
General	Ortho	5000	1.114	0	3	5568
General	Urology	5000	1.266	0	3	6329
General	Plastics	5000	1.261	0	3	6305
Ortho	Ortho	5000	1.274	0	5	6369
Ortho	Urology	5000	1.433	0	5	7167
Ortho	Plastics	5000	1.519	0	5	7593
Urology	Urology	5000	1.598	0	3	7990
Urology	Plastics	5000	1.648	0	4	8241
Plastics	Plastics	5000	1.972	0	5	9862

Vita

Mohit Shukla moved to the University of Tennessee-Knoxville after completing an undergraduate degree in Biotechnology and working as an IT Consultant for 4 years. His project and research work at UT has been in the healthcare domain including an instructional app on fetal heart rate monitoring and a conference paper on nurse rostering based on preference considerations. In his spare time, he enjoys badminton and all things Batman related.