Application of Lean Methods and Multi-objective Optimization to Improve Surgical Patients Flow at Winnipeg Children's Hospital

By

Nasim Norouzi Esfahani

A thesis submitted to the

Faculty of Graduate Studies

in partial fulfilment of the requirements for the degree of

Master of Science

Department of Mechanical and Manufacturing Engineering

University of Manitoba

Winnipeg, Manitoba, Canada

Abstract

Surgical patient flow improvement program in Winnipeg children's hospital (WCH), has been defined in response to the hospital challenges such as long waiting times, delays and cancellations in surgical flow. Preliminary studies on the surgical flow revealed that definition and implementation of successful process improvement projects (PIPs) along with application of an efficient master surgical schedule (MSS) are efficient solutions to the critical problems in WCH. An efficient MSS will optimize the hospital resource allocation, increase the number of procedures, and decrease the variability in patient flow. However successful implementation of an optimized MSS requires efficient processes that provide surgical services to patient flow. The aim of this research is to improve the surgical patient flow in WCH.

In the first phase of this work, a process improvement program including three major PIPs, is defined and implemented in WCH in order to improve the efficiency of the processes providing surgical service for patients. In the second phase, two new multi-objective mathematical models are presented to develop efficient MSSs for operating room department (OR) in WCH. Both models generate weekly OR MSS schedules that improve the surgical patient flow by increasing the number of procedures, reducing artificial variability in the surgical processes, optimizing the allocation of surgical recourses based on demand and smoothing post-operative bed occupancy. Furthermore, the second model predicts and reserves OR capacity for emergency cases within the weekly MSS to facilitate theses patients’ access to surgical services, reduce delays, cancellations and unwanted variability in the surgical flow caused by emergency cases. Both models are solved using lexicographic goal programming approach and the results, obtained by the models, show considerable improvement in all defined objectives compared to the actual collected data from hospital.

Acknowledgement

First and foremost, I would like to express my gratitude to my thesis advisor, Dr. Tarek Y. ElMekkawy. This research work was not possible without his guidance and help. I would also like to thank Dr. Gerarda Cronin, Dr. Jack McPherson, Leslie Galloway, and Karin Dixon for their invaluable support during the surgical flow improvement project.

I am indebted to the children's hospital quality team, managers, surgeon, nurses and staff, who patiently provided the opportunity for me to gain the required knowledge during the course of this project. Without their help, it was not possible to achieve this invaluable insight into the patient flow and healthcare system.

Last but not least, I would like to thank my parents. Without their invaluable and endless support, it wouldn't be possible for me to be where I am today.

List of Abbreviations

CHA	Canada Health Act
DM	Decision Maker
ER	Emergency Department
FCFS	First Come First Served
MOO	Multi Objective Optimization
MSS	Master Surgical Schedule
OR	Operating Room
PACU	Post-anesthesia Care Unit
PDCA	Plan Do Check Act
PICU	Pediatric Intensive Care Unit
PIP	Process Improvement Project
P.Med.	Pediatric Medicine
SOO	Single Objective Optimization
TDSA	Time Difference between the scheduled and the Actual
WCH	Winnipeg Children’s Hospital

Contents

List of Tables

List of Figures

Chapter 1: Introduction

1.1 Motivations

Long waiting times, delays, and cancellations are common occurrences in the patient flow process in hospitals, to the extent that patients and providers have come to anticipate them as an inevitable part of their care. Patient flow in a hospital is the movement of patients between teams and departments to receive required healthcare services. Inefficient patient flow and variability in the number of patients contribute largely to the problems of long waiting times, delays, and cancellations, as well as wasting hospital resources [Hall, 2006, McManus, 2003].

Amongst all the hospital resources, operating rooms (ORs) are one of the most expensive resources in every hospital, providing a very important and critical service to the patients [Kharrajal, 2006]. Due to the integral services provided by ORs, inefficient patient flow within these departments is one of the most challenging issues that hospital executives face.

Since long waiting times, delays, and cancellations are the direct results of inefficient patient flow, the minimization of these inefficiencies is only possible by improving the patient flow. Among different techniques to achieve this goal, process improvement programs and scheduling optimization are the most promising.

A process improvement program is a systematic approach to help an organization optimize its underlying processes to reduce cost, increase productivity, improve customer satisfaction, grow revenue, and enhance overall competitiveness [Weiyong, 2006]. During a process improvement program, process improvement projects (PIPs) are defined with smaller scope to improve the processes of the organization. Successful implementation of process improvement program leads to smoothness of the patient flow in the surgical department strongly.

On the other hand, patient flow scheduling aims to optimize the utilization of healthcare system resources such as physicians, nurses and facility recourses and synchronize their activities. As a result, patient flow will be optimized without adding more resources to the system. Increasing OR capacity by adding more resources is an expensive task, which emphasizes the importance of efficient utilization of OR resources. For this reason, optimizing the OR scheduling system is considered as one of the most effective ways to improve patient flow and reduce the total cost.

OR scheduling can take place in three main phases [Cardoen, 2007]. In the first stage the OR staffed hours are defined into blocks of time. In the second stage the defined OR time blocks are allocated to surgical groups (groups of surgeons providing the same surgical service, e.g. orthopedic, dental or plastic surgery) in a specific time cycle called master surgical schedule (MSS). An efficient MSS can enhance the surgical patient flow directly through allocation of OR time blocks to surgical groups based on the demand. An accurate OR block schedule can increase efficiency in the

OR resource allocation and also reduce waiting times of surgeries. Finally, in the third stage, surgery cases are scheduled into the MSS and the daily OR schedule is produced. All surgical patient flow scheduling phases attempt to optimize the surgical resource utilization through careful allocation of the existing capacities according to the required demand.

An overview of the literature shows that the lack of practicality is an issue in most of the previous improvement programs and scheduling systems as they often do not consider the required infrastructure within the hospitals. Therefore, many of these systems have never been implemented. The process improvement program, through defining and executing appropriate PIPs, will provide the supportive infrastructure for implementation of an efficient scheduling system.

Both of these topics are the subject of investigation in this research and presented in the different chapters of this thesis. First, the process improvement program in Winnipeg children's hospital (WCH) and its different PIPs will be introduced. Second, the OR scheduling optimization will be discussed and some mathematical models will be introduced.

1.2 Thesis Objectives

The main objective of this thesis is to improve the flow of patients through the surgical processes at the WCH. To achieve this goal, this research is focused on the process improvement program and scheduling optimization of surgical patient flow as the two main solutions for improving the patients flow.

In the first section of the thesis, a process improvement program including three major PIPs is described. These PIPs are defined and implemented in WCH in order to improve the efficiency of the processes providing surgical service for patients. These three PIPs are post-operative OR clean-up process improvement, surgical booking time improvement using historical data analysis and process improvement in WCH departments using lean approach; will be introduced and their definition, implementation and results will be discussed.

The second section focuses on scheduling optimization technique applied to the ORs in WCH. The scheduling optimization is done using multi-objective mathematical models to optimize the master surgical schedule (MSS) efficiency. Two new multi-objective mathematical models are introduced which generate weekly OR MSSs that optimize the surgical patient flow.

The first mathematical model optimizes several performance measures at the same time. The first performance measure is the weekly number of performed surgical procedures. It also optimizes the surgical recourses utilization and OR blocks allocation into the surgical groups according to the defined OR share targets. These targets are set based on the demands; therefore, this model results in a better management of the waiting lists. It also minimizes the variation in the number of patients between any two days of the schedule. Variation in the patient flow may lead to lack of bed and resources in hospital units resulting in excessive waiting times, delays, surgery overtime in surgical flow, patient dissatisfaction, and finally threats to the quality of patient's care. Minimizing this measure will reduce the stress experienced by the surgeons and nurses and also smoothes the post-operative bed occupancy.

The second mathematical model optimizes the above measure while it considers capacity for emergency cases as well as the elective cases. As a result, it will reduce variation caused by the emergency cases in addition to the other objectives that the first system considers. Defining MSS, which considers capacity for emergency cases is not applied in previous works. Yet it is important in practice as it can decrease the variation caused by these patients and as a result reduce potential delays, cancelations and overtimes due to the emergency cases.

1.3 Thesis Outline

This thesis includes five chapters. Following this introductory chapter, Chapter 2 covers the literature review related to of this research starting with the healthcare system attributes, basic definitions, current issues and problems, followed by some fundamental definitions of the OR scheduling and finally the operations research solutions to the healthcare problems. A brief description of the multi-objective mathematical modeling is also presented.

The surgical flow process improvement projects (PIPs) are described in Chapter 3. This chapter explains three PIPs for improving surgical flow and supportive processes. Chapter 4 covers a detailed description of the two OR block scheduling systems and the developed multi-objective mathematical models. These models have been defined and applied to the case of Winnipeg children's hospital, using actual data for the past three years and the results have been compared with the actual hospital data. Finally, Chapter 5 presents the conclusions and future work suggestions.

Chapter 2: Literature Review

In this chapter, the healthcare system features and various Canadian healthcare problems are introduced. Next, literatures on the OR scheduling, mathematical modeling and multi-objective optimization are described briefly. Lastly, a comparison between the literature and the proposed mathematical models presented in this thesis is explained.

2.1 Introduction

Healthcare services in Canada are available through a publicly funded system. Various levels of government pay for Canadians' healthcare through provincial and federal taxes and insurance premiums [Hall, 2006]. Canadians have the opportunity to participate in health and dental insurance plans either offered through their employers or obtained independently [OECD, 2004]. The government assures the quality of care through the Canada Health Act (CHA). CHA outlines conditions and regulations under which the healthcare system must operate. Through the CHA, healthcare services are provided to all Canadians on the basis of need rather than on the individual’s ability to pay [Hall, 2006].

Healthcare services, like most other services, differ from production goods in five aspects [Jacobs, 2009]. First, services are intangible and cannot be measured easily. Second, services are provided through interaction with the costumer, unlike a product.

Third, services are inherently heterogeneous. In other words, they vary from day to day as a function of the characteristics of the customer or the service provider. An emergency department (ER) in a hospital is a good example of this as the number and type of patients arriving in the ER varies from day to day. The fourth difference is that the services are perishable. This means that unlike goods, services are both provided and experienced at the same time and cannot be stored. The fifth difference is that services are defined and evaluated as a package of features including supporting facility (e.g. lay out or medical supporting equipments) facilitating goods (e.g. medicine in a hospital) and explicit services (e.g. training of staff or consistency of service performance).

In an ideal healthcare system, the flow of patients within the system is smooth and uniform with maximum throughput based on the available resources. Patient flow in a healthcare system is defined as the movement of patients between teams, departments or organizations to receive various healthcare services required. Hospitals are mainly dealing with three categories of patients flows: outpatient flow, inpatient flow, and emergency patient flow [Hall, 2006]. Outpatient flow consists of patients who come into the system to receive the required service and then leave the healthcare facility. This flow of patients can be controlled through scheduling and setting appointments. The healthcare resources, including physicians, surgeons, nurses, beds and equipment can be planned and assigned to the patients according to their individual needs in advance. Inpatient flow involves patients who are already in the system waiting to receive required services. Hospitals deal with inpatient flow when a patient is waiting for surgery or special care while within the system (e.g. staying in wards). Emergency patient flow is the most complicated flow in terms of scheduling and resource allocation because the number of patients and type of required services and resources are unknown and unpredictable.

A major problem of the Canadian healthcare system is long waiting lists for surgeries. Canadian hospital executives and managers reported that waiting times for elective surgery are growing longer in recent years [The Commonwealth Fund, 2004]. Long waiting times for elective surgery can harm patients or lead to unnecessary suffering [Ray et al., 2001].

Canadian hospitals also experience delays in surgical patient flow, which can be rooted in inefficient processes for providing services to the patient flow. These delays can lead to cancellations on the day of surgery. Delays and cancellations lead to waste in terms of time and inefficient use of costly resources and contribute to growing waiting lists.

Variation in surgical patient flow also creates problems in hospitals such as extended waiting times, overcrowding, lack of resources in hospital units, departments, post-anaesthesia care units, intensive care units and delay in surgeries. These problems cause enormous stress on everyone in the system, including the patient and their family, and decrease the quality of healthcare. Generally, two types of variability can be defined in the surgical flow system: natural variability and artificial variability

[Litvak, 2005]. Natural variability is a result of the need for emergency or unscheduled surgeries that are necessary and unpredictable. This type of variability is inevitable in healthcare services. Artificial variability in elective surgical flow is caused by inefficient surgical scheduling, which is the source of peaks and valleys in demand within surgical units. When peaks occur in the elective surgical schedule, there is an increased demand for staff, equipment and space within the surgical unit, while expensive resources will be wasted and remain idle during the valleys.

Optimal utilization of OR resources can be a key solution to all these problems. However, in order to optimize the OR resource utilization, a strong foundation built on efficient patient flow and efficient OR scheduling is required [Augusto, 2006]. OR scheduling optimization, the subject of a great deal of research [Cardoen, 2010], aims to increase patient flow and reduce variation in surgical flow through eliminating artificial variability.

Winnipeg children's hospital, like many other Canadian hospitals, has also recognized that variability in surgical flow, long waitings, delays and cancellations are the main problems in the elective surgical flow. In response to all of the problems discussed, this thesis focuses on improvement projects on the surgical supporting processes, and optimization of OR scheduling, as the two key fundamental requirements in WCH.

This chapter encompasses the literature review on the patient flow and scheduling in the healthcare system, operation research management and multi-objective optimization. A comparison between literature and the proposed models is also presented at the end of this chapter.

2.2 Patient Flow Scheduling

The aim of patient flow scheduling is to optimize the utilization of healthcare system resources (e.g. physicians, surgeons, nurses, personnel and facility). As a result, patient flow is maximized without increasing system costs.

For scheduling the outpatient flow, timetables are defined through setting appointments. The length of stay and type of physicians, nurses, treatment and equipments required need to be identified and considered for scheduling. Ho (1992) performed a comprehensive study on the techniques for outpatient scheduling. In this research he considered various rules for scheduling outpatients and investigated their ability to minimize cost.

For scheduling inpatient flow, resources need to be determined according to patient needs and availability of resources. Beliën (2008) developed scheduling systems for improving the inpatient flow within hospitals. Scheduling the emergency rooms is more complicated due to the uncertainties in the time of arrival and type of requirements for the patients. Simulations of patient flow have been applied for scheduling the emergency departments. Hung (2007), Rossetti (1999) and Kumar (1989) have used simulation models for scheduling the resources in emergency departments.

Surgical patient flow includes three basic categories: emergency, inpatient and day surgeries. Several departments may be involved in surgical patient flow which can be categorized in three groups of pre-operative, operative room and post-operative departments.

This thesis specifically looks at the surgical process improvement and scheduling for elective surgeries. Therefore, in the next section, different approaches and phases of OR scheduling will be described in more details.

2.2.1 Operating Room Scheduling

Operating room (OR) is one of the most expensive resources in a healthcare system; therefore optimized utilization of OR resources is highly important for hospital management [Kharrajal, 2006]. OR scheduling as mentioned in Section 2.3 is one of the most important foundations for optimized utilization of surgical resources. OR scheduling is complex and requires many steps due to the large number of resources and constraints involved. The sequence and priority of the scheduling steps will be defined according to the scheduling system and method that a facility chooses for the OR scheduling. Two practical systems have been used for elective OR scheduling: Any Workday and Fixed Hours [Dexter, 2003, Ozkarahan, 1995].

Any Workday system is mainly used by private hospitals. This system is flexible for the surgeons in the amount of OR time and number of surgeries they can book, even if overtime is needed. The surgeons and patients decide on the date the surgery will be performed. The disadvantage of this system is that the OR staff times can not be scheduled accurately, especially when there is more than one surgeon booking surgeries in an operating room.

Fixed Hours system is more appropriate for the government funded hospitals as they mostly have a fixed annual budget. In this system the management first defines the OR time that can be staffed according to the available annual budget. The staffed OR time is called as the available OR time. Surgeons can only schedule cases if the total surgery times does not exceed the OR available time. The disadvantage of this system is that the OR can be easily underutilized. OR scheduling is important and more complicated when the hospital applies this system. As a government funded hospital, Winnipeg children's hospital is also using the fixed hour system.

Two main scheduling methods are defined in the literature for booking elective cases into the OR schedule in any of the scheduling systems defined in Section 2-2-1: non-block scheduling (FCFS) and block scheduling [Ozkarahan, 1995].

In the non-block scheduling or first come first served (FCFS) method, a scheduling center receives request of cases by surgeons. According to the hospital scheduling system policy, scheduling center may choose one of the following alternatives. In a fixed hour scheduling system, cases can be scheduled due to the OR available time limitations. Therefore the cases will be scheduled on FCFS basis until estimated procedures time reaches the OR time capacity. In any workday system, the cases may be scheduled on an FCFS basis until the number of procedures reaches a specified maximum number [Charnetski, 1984, Rising, 1973, Cox, 1985].

This method has many disadvantages. One of them is that the OR time can be over booked, which leads to high cancellation rate. This method is not flexible in rescheduling the cancelled surgeries and the cancellations will mostly lead to unused OR time. This method also has a large variation in OR utilization rate [Ozkarahan, 1995]. In this method the specialties with more elective requests can fill all the OR time and the specialties with more urgent or emergent requests may not be able to book the required OR time. Block scheduling method has addressed this problem [Magerlein, 1978].

The OR block scheduling method includes three main stages [Cardoen, 2007]. In the first stage the OR hours are defined into blocks of time. Time blocks can be one hour, two hours or even eight hours (a full working day). The OR available staff are allocated to these time blocks. The available staff hours for OR are determined by administrators according to the hospital budget. The staffed OR blocks indicate the available OR time.

In the second stage the available OR time blocks are allocated into surgical groups in a specific time cycle. A surgical group indicates one surgeon or a group of surgeons, providing same service, for example plastic, orthopaedic or dental surgery [Belien, 2005]. These allocated staffed OR blocks of time into the surgery groups define the master surgical schedule (MSS). The MSS is a time table that shows the OR available time assigned to surgical groups during a period of time. This period may vary from a week to a month. In other words, a master surgical schedule (MSS) specifies the OR planning as a list of recurring surgical procedure types that must be performed on each day during a cycle of time. Table 2-1 depicts an example for a master surgical schedule with a cycle time of a week. S1 to S5 are indicating surgery groups. Blake et al. (2002) and Belien (2005) worked on developing MSS.

Table 2-1: An example of a master surgical schedule (MSS) with a cycle time of one week

	OR1	OR2	OR3	OR4
Monday	S1	S1	S2	S3
Tuesday	S2	S3	S2	S5
Wednesday	S2	S4	Not available	S1
Thursday	S1	S2	S3	S4
Friday	S2	S4	S3	S5

In the third stage, surgery cases are scheduled into the MSS and the daily OR schedule is produced. The daily OR schedule specifies the patient, the surgery start and end time, and the surgeon and OR team who are performing the operation. Guinet and Chaabane (2003) and Weiss (1990) performed research on daily OR scheduling.

This method has many advantages. As the time blocks are guaranteed for each surgical group in the MSS, the competition between surgeons for the OR time is reduced to the minimum possible extent. The OR booking does not have to be done in advance. Therefore it can be ensured that an operation is performed on a certain day and then book OR times, consequently, cancellations are considerably reduced. Block scheduling rules permit a surgery to be booked only if it can be completed within the available block time, therefore this method decreases over-booking and decrease variations in OR utilization. Finally being well defined, this method achieves a better overall utilization.

2.3 Mathematical Modeling of OR Scheduling

Organizations experienced a growth in complexity and specialization after the world's industrial revolution. With the increase in complexity and specialization, it became more difficult for the organizations to allocate the available resources to the various activities they should perform in the most effective way for the organization as a whole. Mathematical modeling looks for solutions to these kinds of problems in organizations and has been applied extensively in areas such as manufacturing, transportation, telecommunications, financial planning, military, public services and the healthcare [Hillier, 2008].

Developing a mathematical model encompasses five overlapping phases. The first phase is to define the problem of interest and gather relevant data; second phase is formulating a mathematical model to represent the problem. The third phase derives solutions to the problem by solving the model through developing computer based procedures. In the fourth phase the model will be verified and tested to see if the solutions provided by the model are valid, and the last phase is to consider management requirements and system preparations for improving and solving the model and finally implementing the solutions into the system.

Augusto (2008), Blake et al (2002), Beliën (2006), Cardoen (2007) and Coello (2007) have applied mathematical modeling for OR scheduling. Amongst them Blake et al (2002), Beliën (2006) developed mathematical models to optimize OR MSSs, while others defined mathematical models to optimize OR daily schedules. However healthcare organizations are complex due to the large number of variables and constraints and mathematical modeling provides powerful techniques for OR scheduling. Sometimes developing an efficient OR schedule may require more than one objective to be optimized at the same time. Multi-objective mathematical models are powerful for solving problems when they have multiple objectives. However, because of the complexity of the multi-objective models, there are not a lot of multi-objective mathematical models defined and used in OR scheduling.

This thesis proposes two multi-objective mathematical models for defining master surgical schedules for the OR departments, which have been validated and appraised by applying to the Winnipeg children's hospital (WCH). Therefore a brief literature review on multi-objective optimization is described in next section.

2.4 Multi-Objectives Optimization

A multi-objective optimization (MOO) is defined by more than one objective, decision variables and constraints. Decision variables can be continuous, binary, integer or a mixture of them. The feasible region for solutions will be defined by equality and inequality constraints and the variable bounds. In MOO problems, the objectives are often conflicting. Generally in such problems there will be many optimal solutions in such a way that one solution is better than the others in at least one objective. In the other words, one objective improves while at least one other objective deteriorates when moving from one optimal solution to another. The solutions of a MOO problem are known as the Edgeworth-Pareto optimal or Pareto-optimal solutions [Ehrgott, 2005].

2.4.1 Multi-Objective Optimization Methods

Many different methods are available for solving MOO problems; however, most of them involve converting the MOO problem into one or a series of single objective optimization (SOO) problems [Evans, 1984]. Each of these SOO problems consists of an aggregate function of the objectives in the original MOO. There are also different ways to define an aggregate function, and therefore many MOO solving methods exist based on the way selected to convert the MOO to SOO. The aggregating approach is easy to understand, although the resulting SOO problem may not be easy to solve.

Available MOO methods can be classified in different ways. Miettinen (2008), Diwekar (2003), and Lieberman (1991) classified MOO methods into *generating* methods and *preference-based* methods based on the rule of the decision maker (DM), and if the method generates one Pareto-optimal solution or more. Beside this classification evolutionary algorithms can also be applied to solve multi-objective mathematical models, which will be described at the end of this section.

2.4.1.1 Generating Methods

A generating method will generate one or more Pareto-optimal solutions without any inputs from the DM. The obtained solutions then will be presented to the DM for selection. Generating methods are also divided into three sub-groups: *no-preference* methods, *a-posteriori* methods using the aggregation approach and *a-posteriori* methods using the multi-objective approach [Evans (1984), Marler (2004)].

In no-preference methods there is no need to define priority in the defined objectives. A particular no-preference method can achieve only one Pareto-optimal solution, and in order to generate more than one Pareto-optimal solution, more than one no-preference methods are needed to be solved. The disadvantage of these methods is that they do not consider the DM's opinion either before, during or after solving the problem. These methods are appropriate when the DM cannot concretely define what he or she prefers. Global criterion and multi-objective proximal bundle methods are under the no- preference methods category [Miettinen, 1999].

In a-posterior methods the DM will be involved after solving the problem and finding the Pareto-optimal solutions. A-posterior methods can be divided into two sub-groups, as they employ different approaches for solving the MOO problems; *a-posteriori* method using the aggregation approach and *a-posteriori* method using the multi-objective approach [Miettinen, 2008].

A-posterior method using aggregation approach, converts an MOO problem into a SOO problem. This method uses ε-constraint and weighting techniques for defining the aggregate functions. The problem then can be solved by a suitable method to find one Pareto-optimal solution. To find the other Pareto-optimal solutions, a series of such SOO problems are needed to be solved. ε-constraint methods are mostly effective and simple for problems with a few objectives, yet sometimes it can be difficult to select suitable values of ε. Weighting methods are not able to find Pareto-optimal solutions when the feasible region is non-convex [Marler, 2004]. In ε-constraint and weighting methods, solution of the resulting SOO problem may not be applicable in the original problem environment.

A-posteriori method using the multi-objective approach includes population-based methods such as non-dominated sorting genetic algorithm and multi-objective differential evolution as well as multi-objective simulated annealing. These methods start with ranking trial solutions based on objective values and then find many Pareto-optimal solutions. All a-posteriori methods provide many Pareto-optimal solutions.

The DM can review and select the most appropriate one for implementation [Evans, 1984].

2.4.1.2 Preference-Based Methods

Preference-based methods involve the DM to define his priorities at some stages before or during solving the MOO problem. Preference-based methods can be divided into *a-priori* methods and *interactive* methods sub-groups. In a-priori methods, preferences of the DM are included in the initial formulation. Value-function methods and lexicographic goal programming are examples of a-priori methods [Marler, 2004].

Value-function method includes the original objectives and preferences of the DM for optimization in formulating a value-function and then solves the resulting SOO problem. Weighting method can be applied for formulating a value-function in this method. It may be difficult to specify the value-function before having knowledge on the objective values

In a goal programming lexicographic approach, the objectives are arranged according to their importance for DM. These objectives or goals must be solved sequentially. In this procedure, a new problem is formulated and solved for each objective function, beginning with the highest priority. Once a solution for the highest priority formulation is achieved, the value of the objective is added to the model as a constraint, and the second-priority becomes the new objective. A new solution is achieved for each new objective sequentially until all the priorities are solved or it becomes clear that a better solution cannot be reached [Tan, 2008].

The advantage of the goal programming method is that the DM prioritizes the objectives when the problem is defined; this approach is more efficient for complex problems when the objectives are contradictory. This approach is suitable when the problem nature is more preference based to be weighted, or the problem is naturally a multi-objective one and also is hard to give weights.

Interactive methods require interaction with the DM during the solution of the MOO problem [Shin, 1991]. After an iteration of these methods, the DM reviews the obtained Pareto-optimal solution(s) and decides on compromises desired in each of the objectives. These preferences of the DM are then incorporated in formulating and solving the optimization problem in the next iteration. At the end of the iterations, the interactive methods provide one or several Pareto-optimal solutions. These methods are more efficient for the problems with many objectives since the DM is involved during the solution. Implementation of these methods requires the DM's time for interaction, which may not always be practicable.

Some of the MOO methods can also be placed in two groups at the same time due to the way the model solvers find it suitable to interact with the DM. For example, weighting method from *a-posteriori* methods can also been used as value-function methods in the *a-priori* methods and the ε-constraint method from the *a-posteriori* methods and goal programming from *a-priori* methods have also been used for developing interactive methods [Miettinen, 1999].

2.4.1.3 Evolutionary Algorithms

Evolutionary Algorithm (EA) uses some principles inspired by biological concepts to find solutions to an optimization problem [Coello, 2007]. The EA first generates initial solution candidates randomly, called the parent population. Each possible solution from the population is called an individual. Then the selection process removes the low quality individuals from the population and keeps the high quality individuals for reproduction. In this way the average quality within the population will be increased. The quality of an individual is defined based on the objective functions and constraints, which is presented by a scalar value called *fitness value*. After the selection process, mutation process takes place to generate new population within the search space. The mutation process generates a certain number of children by recombining a certain number of parents. This process has been also referred as recombination or cross over.

The EA iterates the loop of the evaluation, selection, and mutation processes. Each loop is called a generation. EA will continue the iterations until a defined condition is reached. Conditions may be existence of an individual with sufficient quality in the population or stagnation in the population. At the end, the optimal solution found by the EA will be the best individual(s) in the final population or found during the entire evolution process. Depending on the stopping condition, these methods are more likely to find an acceptable good solution rather than the optimized solution. Furthermore, it is sometimes difficult to define the algorithm parameters in a way to make sure that the EA is searching within the feasible solution space [Jones et al. 2002].

Genetic algorithms, ant Colony optimization, tabu search and simulated annealing are examples of EA optimization methods. The DM will often be involved after finding the optimal solutions by the EA for selecting the best one, according to his/her preferences. Therefore, these methods can also be classified under the posteriori methods using the multi-objective approach.

2.5 Comparison between the Literature and the Proposed Models

The second stage of OR scheduling, MSS, has been less focused by researchers [Testi, 2007]. Mathematical models have been used for developing MSS in some previous reports. For example, Blake and Donald defined a model to distribute the available OR blocks between five surgery groups according to the pre-determined share for each group [Blake, 2001]. In another study at Mount Sinai hospital, a mathematical model was used in response to the limited OR blocks that are needed to be assigned to five surgical groups [Blake, 2002]. The objective was to minimize the shortfalls between the defined shares and the assigned OR time for the surgical groups in the master schedule. However in both studies some simplifications were used such as considering only five surgery groups or decreasing the number of constraints related to equipments or surgeons.

In other research clustering of surgery types is considered to be important for developing a MSS [Oostrum, 2008]. They developed a method for constructing of surgery types to be used in master surgical scheduling. They defined the clustering method based on the average frequency of performing each surgery type. They classified the more frequent procedures into the surgery groups and the remaining less frequent surgery types into dummy surgery types. Yet, this approach has its own limitations, for example different types of surgery procedures may vary in the process times; therefore, the dummy surgery types will lead to higher level of uncertainty in the resource consumptions of patients [Oostrum, 2008].

In other research two approaches for developing MSS have been compared [Kharrajal, 2006]. In the first approach, the OR blocks of time have been broken down to the extent that could be assigned to individual surgeons, while in the second strategy, the OR blocks have been assigned to surgical groups. Presenting tests and evaluations, they concluded that the second approach is more efficient and will lead to better results mainly because the second strategy will provide more flexibility inside the surgeon groups for scheduling their operations [Kharrajal, 2006]. This efficient strategy has also been used as an assumption for the proposed models in this thesis. For instance surgical groups are defined and the OR blocks are assigned to this groups rather than individual surgeons.

In research performed by Oostrum et. al., they used a method for developing MSS with the goal to level the workload of subsequent departments in the hospital. They assumed the length of surgery process for each surgeon as a multinomial distribution function [Oostrum, 2008]. However, in developing MSS based on the surgery group strategy, it is more efficient to estimate the surgery time for surgical groups instead of individual surgeons.

To the best of the author's knowledge, all the previous research have been focused on one main goal. The models in this thesis consider more than one goal at the same time. These goals are to maximize the number of procedures, minimize the under allocation of OR blocks into the surgical groups based on the defined targets for surgery groups, and minimize the variation in the total number of procedures on a daily basis, which will lead to a more level post operative bed occupancy in post-anesthesia care unit (PACU), day surgery, pediatric intensive care unit (PICU) and the hospital wards. Balancing the post operative resource consumption results in the reduction of fluctuations in the demands for beds in all of the post-operative departments caused by surgical procedures. A decrease in the demand fluctuations will lead to reduction in the potential resource shortages and as a result minimizes the amount of cancellations and delays caused by post operative bed shortages in surgical procedures. The proposed models also implement a better synchronization between the schedule and the waiting lists through defining bounds for the assigned OR time to surgery groups, which is not considered in past research.

Furthermore, in most of the previous work there is a gap between the theoretical analysis and practical needs of the system mostly because of the lack of validated actual data, which is the key to define a successful MSS schedule. The proposed models try to decrease this gap through adjustment of both the objectives and the assumptions. The objectives have been set directly in response to the needs of Winnipeg children's hospital management system and after studying and understanding the current problems and the model assumptions have been defined based on the actual data driven from these studies performed in the last three years to generate an optimal MSS.

Chapter 3: Surgical Flow Improvement in Winnipeg Children's Hospital

This chapter starts with a brief introduction to the process improvement programs in Section 3.1. The surgical patient flow improvement program and the elective surgical patient flow at WCH are introduced in Sections 3.2 and 3.3, respectively. Lastly, three process improvement projects implemented during the course of the surgical patient flow improvement initiative are explained in details in Sections 3.4, 3.5 and 3.6.

3.1 Introduction

Process improvement programs are one of the central research topics in operations management. A process improvement program is a systematic approach to help an organization optimizes its underlying processes to reduce cost, increase productivity, improve customer satisfaction, grow revenue, and enhance overall competitiveness.

During the course of a process improvement program, improvement teams often define many process improvement projects (PIPs) to study and improve the internal processes of an organization. Improvement teams choose and apply an appropriate approach to each PIP in an effort to improve the processes based on the organizational features. However, applying PIPs in an organization can sometimes be greatly difficult for two reasons [Weiyong, 2006]. First, many approaches such as lean are experience-based, and no widely accepted standard definition exists for these projects. Second, it is difficult to compare the efficiency of different approaches directly, and share the learning across different programs, as each organization has its own unique features.

However, there are tools, techniques and approaches that can be used to study, define and implement successful PIPs [McLaughlin, 2004]. To achieve sustainable improvement in an organization Plan Do Check Act (PDCA) concept proposes four phases that should be continuously implemented in organizations [McLaughlin, 2004]. In Plan phase, the organizational processes are studied and documented, to achieve an accurate understanding of the processes. Then data on the current processes are collected and analyzed to identify the processes bottlenecks, constraints and improvable areas. In this phase, the quality improvement team is involved mostly with the data analysis and decision making to define improvement objectives. In the Do phase, the new processes are implemented on a small scale. The Check phase is mainly the feedback phase, where the new processes are measured and compared with the old process. In the Act phase, the quality team determines whether to apply changes that lead to improvement and make decisions concerning the scope. When a pass through these four steps does not result in improvement, the PDCA cycle should be refined until there is a plan that results in improvement.

In Section 3.2, surgical patient flow improvement program at WCH is introduced and the surgical patient flow is explained. This chapter is continued by introducing three

PIPs that have been defined and implemented in WCH during the course of the surgical patient flow improvement initiative.

3.2 Surgical Patient Flow Improvement Program

The Winnipeg children’s hospital (WCH) at the Health Sciences Center (HSC) initiated a process improvement program by collaborating with the Faculty of Engineering at the University of Manitoba. Their main goal was to improve surgical patient flow across the WCH. This project was defined along with two nationwide projects, the “National wait time initiative project” and the “National paediatric surgical wait time project” in response to the Winnipeg children’s hospital challenges and need for improvement in surgical patient flow by Dr. Gerarda Cronin and Dr. Tarek ElMekkawy. The Child Health Quality Team from WCH along with two graduate students from the Mechanical Engineering Department of the University of Manitoba were involved in this project for over two years.

To achieve an accurate understanding of the process providing the required services for elective surgical patients in Winnipeg children’s hospital (WCH), different operation improvement tools were utilized in the surgical flow improvement project. Patient flow in the various departments involved in surgical flow were studied and documented using process maps and flow charts. In the following sections, patient flow for elective surgeries throughout the various departments are described and depicted in process maps. Three PIPs that were performed during the surgical process improvement program in WCH are reviewed.

3.3 Elective Surgical Patient Flow in WCH

Elective surgical processes are similar in different hospitals. In WCH, the elective surgical process begins with the request for the surgery, usually from a family physician, that is sent to the surgeon's office. At the surgeon's office, secretaries review the requests and contact the patient's family to coordinate an appointment for the patient to visit the surgeon. The patient arrives at the clinic on the scheduled appointment day to be seen by the surgeon. The surgeon makes a decision concerning the necessity of a surgery. If a decision is made to proceed with the surgery, a booking request form is completed and the patient's name is entered onto the waiting list for the surgery.

The surgeon's office will contact the patient's family to confirm the date of surgery. After the family indicates that the date of surgery is acceptable, the booking request form is sent to the Operating Room (OR) central slating office, where the OR schedules are developed. The surgical date is finalized by the OR central slating clerk and the surgeon's office is informed. A copy of the booking information will accompany the patient's file and be sent to the Pre-Admit Clinic.

The Pre-Admit Clinic (PAC) reviews the patient's file and contacts the patient's family to invite the patient and the caregiver to an optional visit to the PAC. During the visit, they are introduced to the OR process and given instructions on preparing for the surgery.

On the day of surgery, the patients and their family should arrive at the clinic an hour before the time of surgery. The author's observations indicated that delays of the first scheduled patients in the morning lead to further delays that cause delays throughout the day.

The process begins with patient arrival at the admission desk. The receptionist at the admission desk enters the patient information into the system. Then the patient's family is directed to day surgery. At day surgery, the patient and their family are instructed to wait for a nurse who will take some measurements and vital signs and ask questions related to their preparedness for the surgery to ensure that all requirements have been met. The patient is then asked to change into the appropriate surgical outfit.

The patient is then directed to the OR waiting room where they will wait until the assigned operating room is cleaned and equipped and is ready for use. The surgical procedure begins when the assigned OR becomes available and the OR team, including nurses, anaesthesiologist and surgeon are in place. In the case that a PICU (pediatric intensive-care unit) bed is needed, staff make sure that one is available for the patient after the surgery, before proceeding with the surgery. Once the room is ready and a monitored bed confirmed (if necessary), the patient is taken to the OR by a nurse.

After each surgery, the OR is cleaned and setup to prepare for the next surgery. In order for the next surgical procedure to start, the following conditions must be met:

- OR is clean and ready
- Patient arrival in the OR
- Surgical team arrival in the OR
- In the case that the patient requires a post-operative monitored bed in PICU, this must be confirmed that a bed is available in the PICU following surgery.

After completion of the surgical procedure, the patient's recovery process begins. The patient is transported to the PACU for the recovery procedure. In PACU, the patient is intensively monitored while they recover. Once the patient leaves the OR and is transferred to the PACU, the OR is prepared for the next patient.

When the patient wakes up following surgery, they may take any one of the following four paths. Some patients may be transferred to the day surgery rest room. These patients are released by the end of the day and receive care instructions for home. Other patients may be transferred into PICU, day surgery, or to the children's ward. Figure 3-3 illustrates the elective surgical patient flow at the WCH.

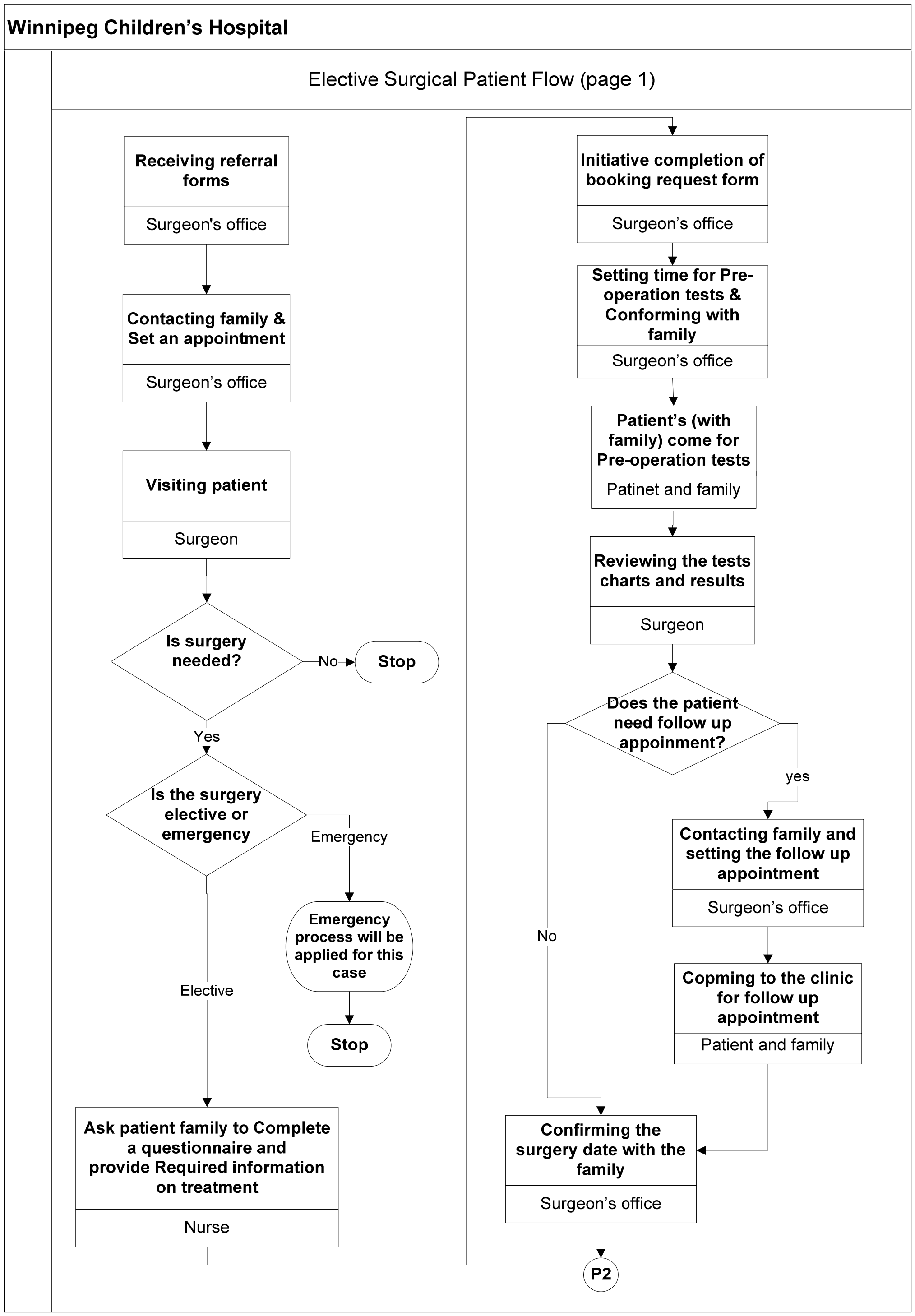


Figure 3-1: The elective surgical patient flow in WCH (page 1)

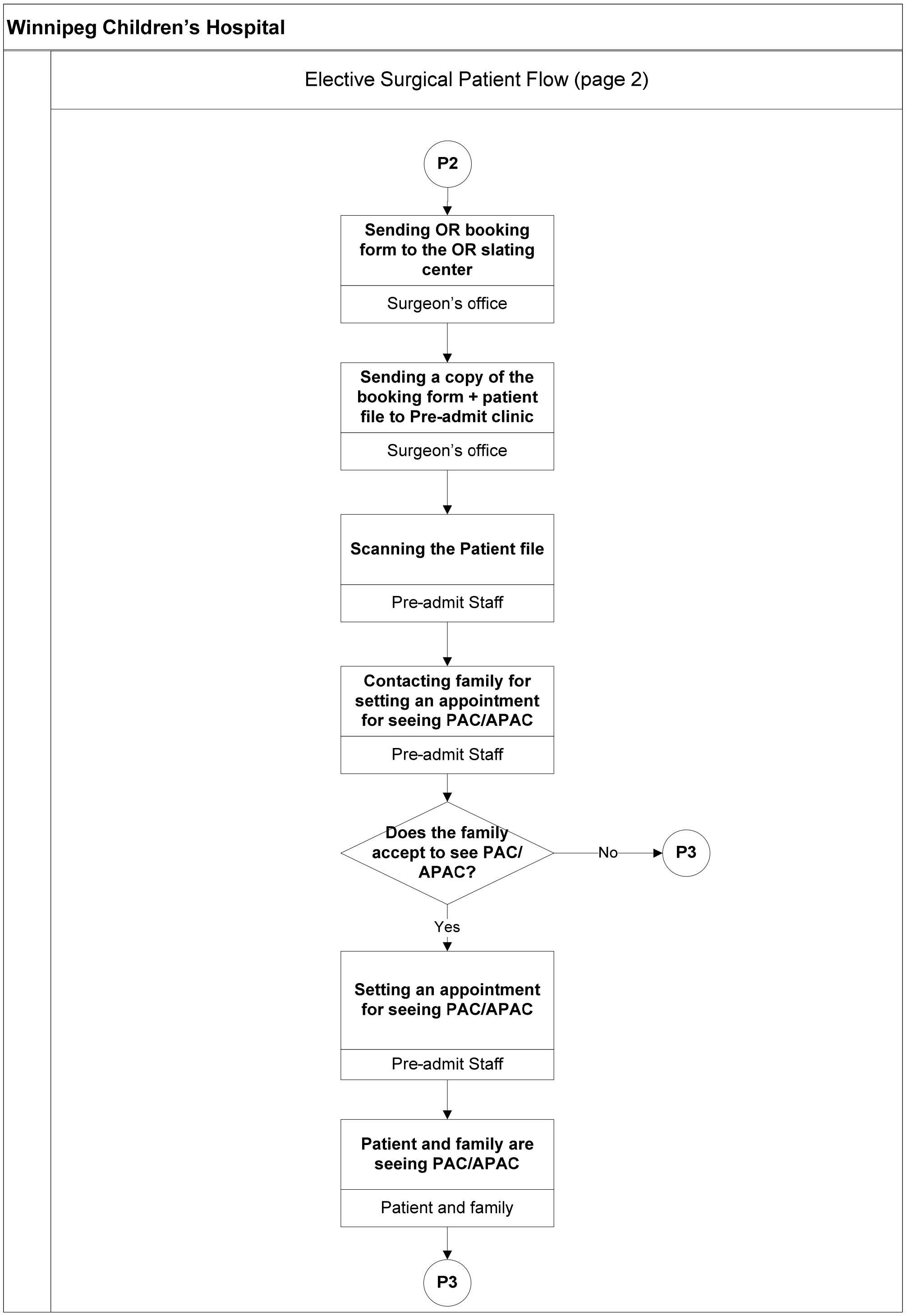


Figure 3-1: The elective surgical patient flow in WCH (page 2)

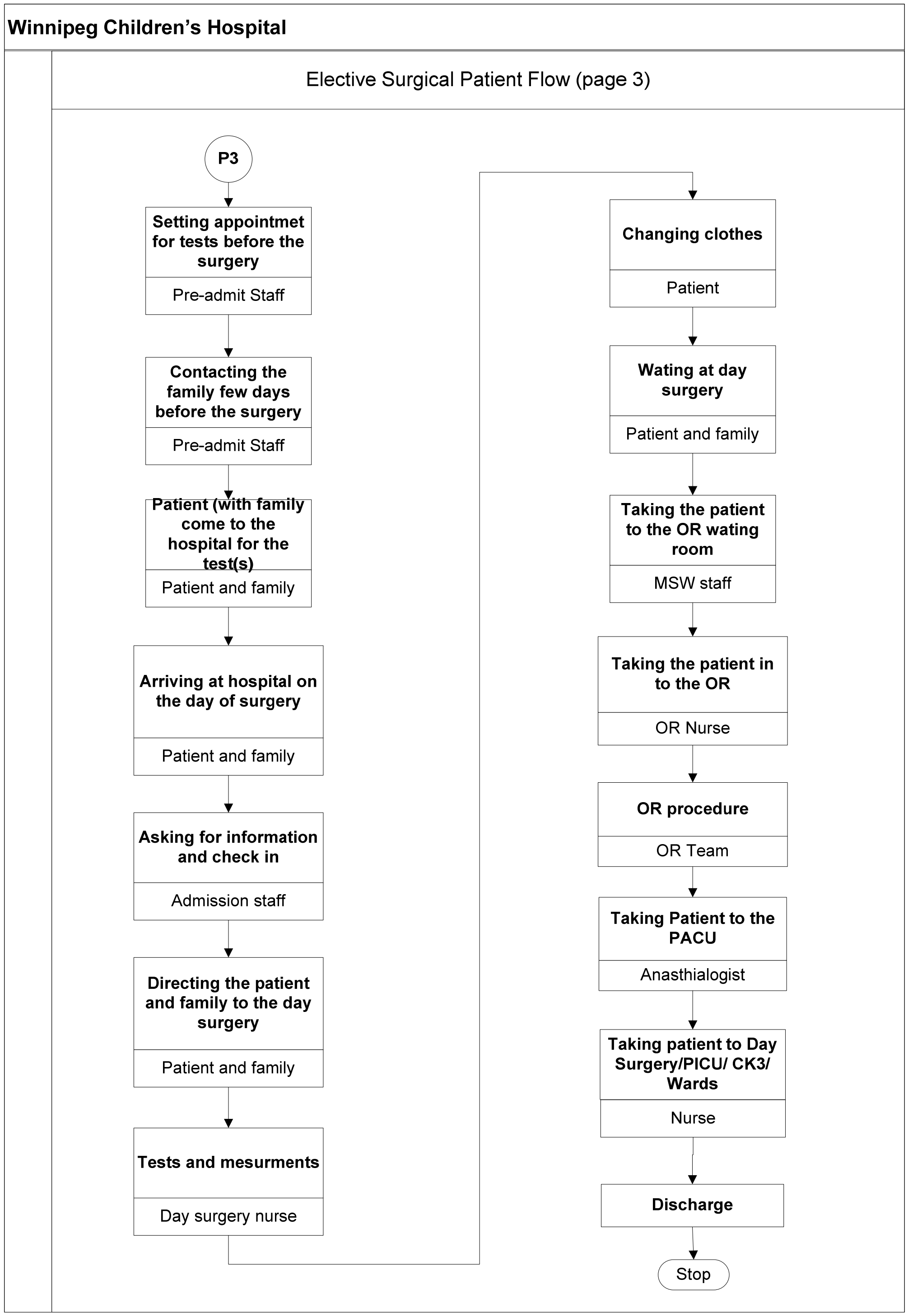


Figure 3-1: The elective surgical patient flow in WHC (page 3)

As mentioned earlier, surgical patients who are having an elective surgery may visit the pre-admit clinic before the day of surgery, and on the day of surgery will go directly to day surgery. The patient flow in these departments will be presented in the next sections.

3.3.1 Pre-Admit Clinic

The purpose of the pre-admit clinic (PAC) is to ensure that patients are prepared for their surgery. The PAC is an outpatient clinic and facilitates patients flow on the day of surgery. Visiting this clinic is still voluntary in WCH and is booked for patients approximately one week before their operation.

A copy of the patient's booking request is sent to the PAC/APAC (anaesthesia pre-admission clinic) along with the patient's file. The pre-admit nurse then screens the patient file and schedules an appointment for the patient to have a PAC/APAC visit. The pre-admit nurse reviews the patient's chart to ensure that the medical history and physical examination have been done.

The visit usually begins with a nursing assessment of the patient's health prior to the operation, and general anaesthetic if required. The nurse will interview the patient's family to gather information about the patient's health condition and complete a form during the visit. The nurse provides information about the operation or procedure, the process the patient will go through on the day of surgery, and anything relevant to the patient's case that the family may need to know. The PAC/APAC nurse will make sure to schedule any required tests before the surgery day such as blood tests, or x-rays. Figure 3-1 summarizes the patient flow for visiting the pre-admit clinic in WCH.

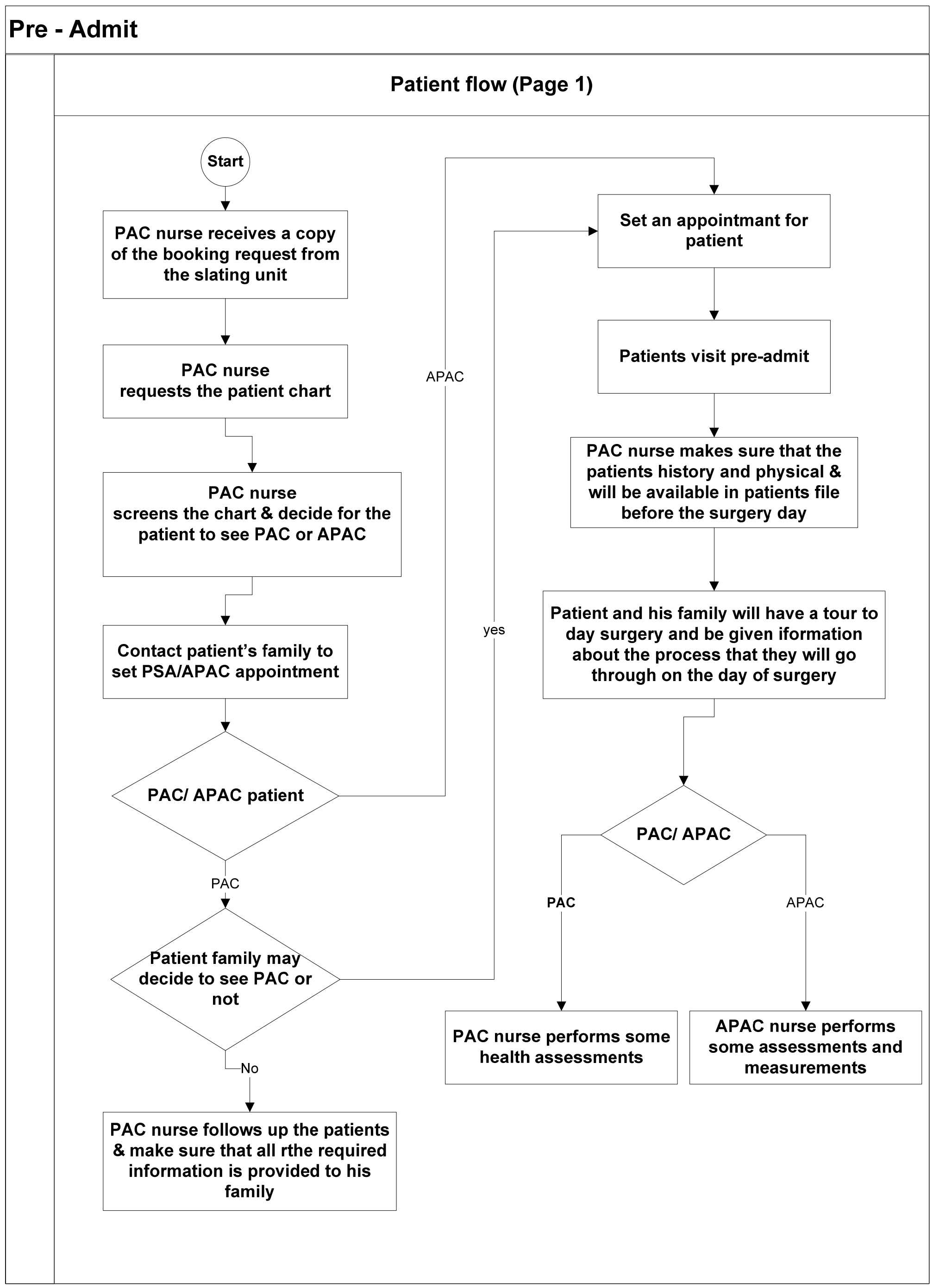


Figure 3-2: Patient flow for the pre-admit clinic in WCH

3.3.2 Day Surgery Unit

The day surgery unit in WCH provides the pre-operative preparation and post-operative care for the same day patients who are having an elective surgery. These patients will stay in the day surgery unit for 2-3 hours after having recovered in PACU and will be discharged for home on the same day as their surgery. Same day patients receive before and after surgery care in the day surgery unit.

PAC/APAC sends all the patients' files that are scheduled for the next day to day surgery every afternoon. Day surgery also receives the next day OR schedule every afternoon. At day surgery, the patients' files are checked to make sure that all the patients' files are available according to the next day OR schedule. These files are expected to include the patients' history, consent and blood test. In some cases, these documents may not be included due to the following conditions:

- Sometimes it is expected that the history will be brought by the patient's parents on the day of surgery.
- Some surgeon's prefer to receive the consent for surgery from the patient's parents on the surgery day.

However, patients are expected to arrive on the day of surgery at least an hour before surgery start time. The patient's family receives three sheets from admission and brings them to the day surgery, including a pink sheet if it is a day surgery case or a white one if it is a same day admission case, consent for receiving hospital care and a communicable disease screen sheet as well as an addressograph. These will be added to the patient's file in day surgery. On the patient's arrival, the patient's file is checked and stamped. If the patient's file does not include all the required documents, the following steps are followed:

- Check with the patient's parents for the missing document(s).
- Check with the PAC/ APAC to inquire if the document has been faxed late on the previous day.
- Check with the surgeon.
- Some surgeons cancel the surgery at this stage.
- Contact the patient's physician and ask them to fax it again.
- Ask a resident to complete history and physical tests.
- If there is not any resident available, the documents may be completed by the surgeon, or the surgeon may call the clinic or emergency for completing history and physical tests. However, surgeons may not follow all the actions in the last step as it is time consuming and will delay the surgery. As a result the surgery will be cancelled at this stage in these cases.

The patient is assigned a nurse at day surgery. The nurse takes the patient to the examining rooms, performs pre-operative assessments and completes the required forms. The nurse also provides needed information to the patient's family such as how long the surgery will take and where they can wait and rest. If any problem such as a fever is observed, it will be reported to the anaesthesiologist and the surgeon. They will decide which action is appropriate. For example, if the patient has ingested food prior to the surgery, the anaesthesiologist may cancel the surgery or postpone the surgery to the last surgery in the OR schedule.

After these assessments, the patients and their families will be directed to the day surgery waiting room to wait for a porter from the OR to take them to the OR. After the surgical procedure, the patient is taken to the PACU. After waking up at PACU, the day surgery patients are taken to day surgery where a bed and a chair are allocated to the patient and his or her parents. The patient will stay here for a while to drink. The patient's family will receive after operation care instructions. When it is comfortable and safe for the patient to leave, he or she is discharged. Figure 3-3 shows the patient flow in the day surgery unit in WCH.

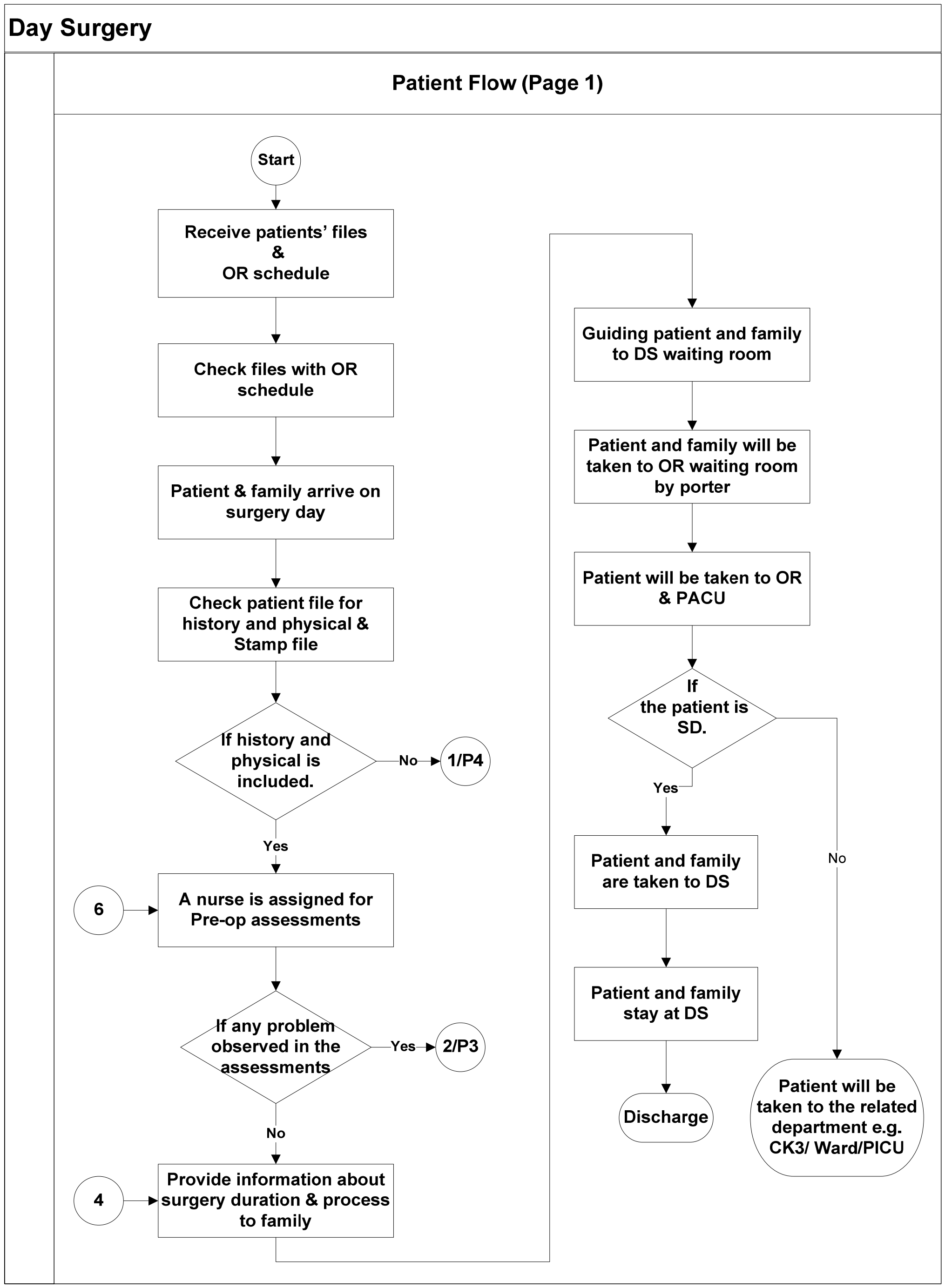


Figure 3-3: Patient flow at the day surgery unit in WCH (page 1)

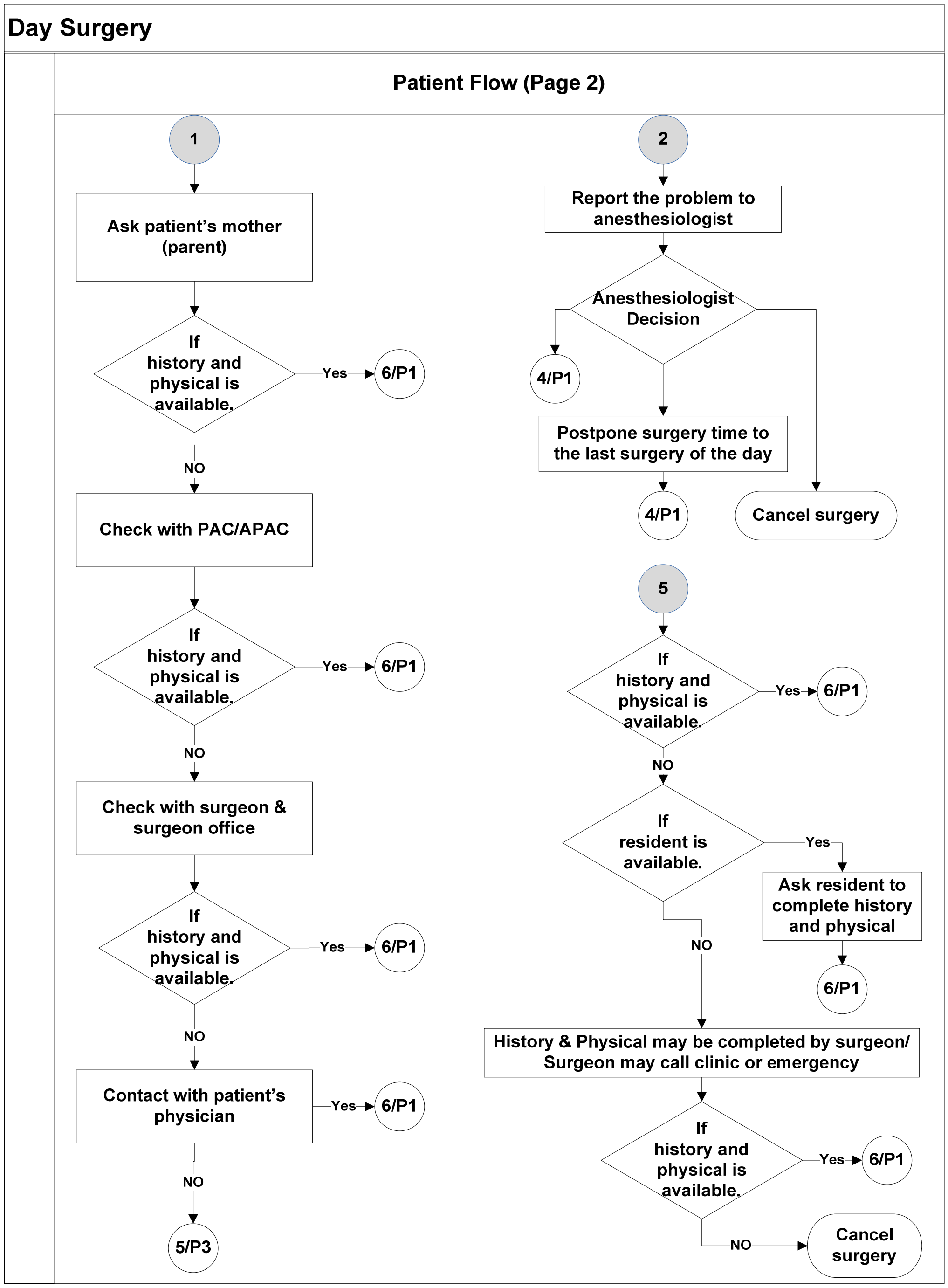


Figure 3-3: Patient flow at the day surgery unit in WCH (page 2)

3.4 OR Cleanup Processes Improvement Project

3.4.1 Project Definition

One of the necessary processes in the surgical flow process is cleaning and preparing the OR. The time consumed for this process directly adds to the surgical time process. This project was defined as the first PIP at WCH, to improve the post-operative OR clean-up process. The main objective was to standardize the OR cleanup process to make it run smoother, more efficient and faster. Other objectives were to provide education for the MSW (multi skill worker) staff and to decrease any variability in the process. Achieving these objectives would lead to a decrease in process time and narrow any variation in process time. As a member of the quality team working in the surgical flow improvement project, the author studied the OR clean-up process, documented the tasks in the process and collected data on the process times.

The post-operative clean-up process consists of a number of tasks performed by the MSW staff. These tasks include:

- Cleaning the anaesthetic machine
- Throw used bed sheets into dirty linen bags
- Throw the used anaesthetic machine attachments (tubes, foam supports,…) into garbage receptacle
- Empty dirty and waste bags

- Take “dirty” cart outside the OR
- Wipe operating bed, carts, tables, equipment, and lights
- Mop the OR floor
- Insert new garbage bags
- Put clean sheets on operating bed
- Move dedicated equipment back to storage
- Take dirty cart to elevator for removal

The cleaning process of the anaesthetic machine by itself includes a number of tasks can be performed by the anaesthetic MSW or any other MSW staff. These tasks include:

- Throw out used tubes
- Put dirty pan and instruments on cart
- Clean arm wrap
- Wipe cables
- Attach new tubes
- Cover the machine tray with a cloth
- Replace used supplies (tubes, pan, syringes, mask, sensors)
- Attach new arm band and sensors (based on size of next patient)
- Refill supplies in anaesthesia machine drawers
- Refill supplies in anaesthesia side cart and IV cart

3.4.2 Task Analysis and Classification

Observations of the MSW staff activities during the OR clean-up process revealed that these tasks could be categorized into six groups respecting three attributes:

- Similarity
- Possibility to be performed by one person during the clean-up process
- Respecting the necessary precedence (order) relationships

The similar tasks were grouped within a task-group (TG) but only if it could be performed by one person during the clean-up process and also have similar priority in the order in which they should be performed. The six task-groups are defined below:

- **Task- Group 1**

  - ✓ Throw out used tubes
  - ✓ Put dirty pan and instruments on cart
  - ✓ Clean arm wrap
  - ✓ Wipe cables
  - ✓ Attach new tubes
  - ✓ Cover the machine tray with a cloth
  - ✓ Replace used supplies (tubes, pan, syringes, mask, sensors)
  - ✓ Attach new arm band and sensors (based on size of next patient)
  - ✓ Refill supplies in anaesthesia machine drawers

- ✓ Refill supplies in anaesthesia side cart and IV cart

- **Task- Group 2**

  - ✓ Strip bed of used sheets and throw into dirty bags
  - ✓ Throw used attachments (tubes, foam supports,…) into garbage
  - ✓ Empty dirty and waste bags
  - ✓ Take “dirty” cart out from OR

- **Task- Group 3**

  - ✓ Mop the OR floor

- **Task- Group 4**

  - ✓ Wipe operating bed, carts, tables, equipment, and lights
  - ✓ Move dedicated equipment back to storage

- **Task- Group 5**

  - ✓ Take dirty cart to elevator for removal
  - ✓ Insert new garbage bags

- **Task- Group 6**

  - ✓ Put clean sheets on operating bed

According to applicable quality standards, mopping the floor can start only if the dirty cart has been removed from the room. The anaesthetic cart can be transferred to the OR only when the floor has been cleaned. If one can arrange the task-groups in a way that the anaesthetic cart can be brought into the OR, time would be saved as the anaesthetic MSW can cut down on a number of trips to the anaesthetic cart outside the OR and anaesthesia side cart or IV cart for refill supplies. Task-group 3 should take place only if task-group 2 has been completed. This will speed up the performance of last activity in task-group 1 if task-group 3 is completed before the last activity in task-group 1 starts.

3.4.3 Data Gathering and Analysis

OR clean-up process task times have been recorded through observations over a ten day period. More than thirty samples were recorded to assure the validity of the data. MSW staff did not have the above definition of task-groups in performing their tasks, so the author collected most of the task times individually and calculated the approximate task-group times based on the individual values. Task times were calculated based on statistical averages. This can reduce the time wastes between different tasks.

3.4.4 Improvement Plan

As described in Section 3-3-2, the tasks were classified into six task-groups (TGs). In categorizing the tasks, standards and required sequences were considered in addition to the common sense achieved by observations on the performed tasks during the OR clean-up process. One of the advantages of categorizing tasks into groups is that it helps the MSW staff. As a result, if the MSW staff performs their tasks according to the task-group classification, the process can be performed smoother and faster.

Activity charts were used for demonstrating activities of each individual MSW staff during the clean-up process in the OR. Tables 3-1, 3-2, 3-3 and 3-4 are examples of these activity charts. Table 3-1 depicts an example of how the clean-up process was performed in old process during a non-busy time of the day when all of the MSW staff were available. In Table 3-1, the columns demonstrate the time in minutes and each row depicts one of the available MSW staff performing tasks during the clean-up process. The utilization was defined as the percentage of the actual active time of a MSW staff to the assigned time.

Table 3-1: Old clean-up process performed by four MSW staff (P1-P4)

<table>
<tr><th></th><th colspan="2">1</th><th colspan="2">2</th><th colspan="2">3</th><th colspan="2">4</th><th colspan="2">5</th><th colspan="2">6</th><th colspan="2">7</th><th colspan="2">8</th><th colspan="2">9</th><th colspan="2">10</th><th colspan="2">11</th><th colspan="2">12</th><th>Utilization</th></tr>
<tr><td>P1</td><td colspan="18">TG1</td><td></td><td></td><td></td><td></td><td></td><td></td><td>75%</td></tr>
<tr><td>P2</td><td colspan="5">TG2</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>21%</td></tr>
<tr><td>P3</td><td></td><td></td><td></td><td></td><td></td><td colspan="4">TG3</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="4">TG6</td><td>34%</td></tr>
<tr><td>P4</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="7">TG4</td><td></td><td></td><td></td><td></td><td colspan="2">TG5</td><td></td><td></td><td></td><td></td><td>42%</td></tr>
</table>

Table 3-2 shows an example of how the tasks were performed during a busy time when there were only two staff available. During the busy times, a maximum of two MSW staff could be assigned to each OR.

Table 3-2: Old clean-up process performed by two MSW staff (P1-P2)

<table>
<tr><th></th><th colspan="2">1</th><th colspan="2">2</th><th colspan="2">3</th><th colspan="2">4</th><th colspan="2">5</th><th colspan="2">6</th><th colspan="2">7</th><th colspan="2">8</th><th colspan="2">9</th><th colspan="2">10</th><th colspan="2">11</th><th colspan="2">12</th><th colspan="2">13</th><th colspan="2">14</th><th>Utilization</th></tr>
<tr><td>P1</td><td colspan="18">TG1</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>64%</td></tr>
<tr><td>P2</td><td colspan="5">TG2</td><td colspan="5">TG3</td><td></td><td></td><td colspan="7">TG4</td><td></td><td colspan="4">TG5</td><td></td><td></td><td colspan="2">TG6</td><td>82%</td></tr>
</table>

In a proposed scenario (scenario 1), in order to improve the utilization and reduce the total clean-up time, if the anaesthetic staff can perform another task-group after completing the anaesthetic task-group (task-group 1), there would be a 21% improvement by approximately 3 minutes decrease in total clean-up time (See Table 3-3). Furthermore, the staff utilization would be increased using this scenario.

Table 3-3: Scenario 1, when clean-up process is performed by two MSW staff (P1-P2)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	Utilization
P1	**TG1**									**TG6**					**100%**
P2	**TG2**		**TG3**				**TG4**				**TG5**				**86%**

By reviewing Table 3-1 it can be understood that the bottleneck of the OR clean-up process is the anaesthetic staff task (task-group 1). One possible way to solve this problem was to divide those tasks into different groups in order to be performed by two staff members, when more than two MSW staff were available in the room. For example, they can be divided into two groups, TG1-A and TG1-B.

TG1-A group includes all the tasks regarding anaesthetic machine and TG1-B group includes tasks regarding refilling supplies in side cart and IV cart. Table 3-4 depicts a new scenario considering the last task classification with three staff available. In this scenario (scenario 2) the total time for the OR clean-up process will be reduced to 7.5 minutes while the utilization of two staff persons will be increased to 100% and the third one to 73%. According to the present number of MSW staff, it is not possible to perform all the clean-up processes with three staff members. Yet, mostly two MSW staff persons would be available to perform new scenario 1.

Table 3-4: Scenario 2, when clean-up process is performed by three MSW staff (P1-P3)

	1	2	3	4	5	6	7	8	Utilization
P1	TG1-SA						TG6		100%
P2	TG2		TG3			TG2-SB			100%
P3	TG4			TG5			TG6		73%

Information and discussion sessions were held inviting the infection specialist who educated the cleanup staff by explaining the standards of the clean up process. In discussion sessions, the task-group classification and the new scenarios have also been discussed with the MSW staff. This project could successfully lead to the knowledge increase in staff about the process, redesigning the OR clean-up process, documentation of a standardized process for cleaning up the OR (developing a manual on the OR clean-up process for MSW staff). These achievements led to the increased quality of the process and decrease in the average cleanup time. Knowledge of the clean-up process gained during this project was employed in defining the mathematical model for the OR patient flow system and data was used as input data for the model.

3.5 Implementation of a Booking Time Guideline to Improve OR Patient Flow

3.5.1 Project Definition

The Winnipeg Children's Hospital, like many other hospitals across Canada, faces delays and cancellations in surgical flow. This results in increased costs and decreased resources utilization which in turn leads to long waiting lists for elective surgeries. Using inaccurate surgery times for surgical scheduling can expose costs of under utilizations or overtimes that increases workload and stress on staff of the OR and other. Therefore, it is very important to schedule surgeries as precise as possible by adjusting the surgical booking times with the actual time needed according to the procedure types. The objective of this PIP was to decrease the time difference between the scheduled surgical time and the actual elapsed surgical time. The surgery process encompasses four main sub-processes: OR setup, anaesthesia, surgery and OR clean-up as shown in Figure 3-4.

Figure 3-4: Schematic diagram of the surgical sub-processes at WCH

Anesthesia pre-op and aesthesia post-op process times in this study have been defined as the time required for pre-operative and post-operative anesthesia within the surgery process respectively. This is shown in Figure 3-5. The summation of Anaesthesia pre-op and Anaesthesia post-op time is calculated as following:

$$\text{(Anaesthesia stop time – Anaesthesia start time) – Surgery time} \quad (3\text{-}1)$$

Figure 3-5: Anaesthesia sub-process in more detail

3.5.2 Surgical Booking Time Guideline and Objectives

At WCH, surgeons and their office staff book OR procedures based on estimated times which may be inaccurate, leading to delays, overtime, waste and finally frustration. To accurately schedule a case it is crucial to account for all sub processes within the surgical process, so that the actual time spent in the OR is properly accounted for in the schedule. The surgical booking guideline is the proposed OR time assigned to each type of surgical procedures and is defined based on the historical actual surgical elapsed times. The main objective of defining a booking guideline is to decrease the time difference between scheduled and actual surgical time (TDSA).

$$\text{TDSA} = \text{Schedule Elapsed Time} - \text{Actual Elapsed Time} \qquad (3\text{-}2)$$

This will reduce the over/under-booking and give a more realistic estimation of the cost and if followed accurately, an optimized booking guideline can decrease surgical delays and cancellations.

3.5.3 Developing Booking Time Guideline

To develop the booking guideline, the total surgical elapsed time and the time required for four sub-processes (OR setup, anaesthesia, surgery and clean-up) were recorded for the nine most common specialties at the WCH. The surgical process data for the past two years and more than 6200 surgical cases were analyzed. Data analysis gives an estimate of the actual required time for each surgical sub-process in the nine most common surgical specialties. Actual elapsed time was calculated:

$$(\text{Anaesthesia stop time} - \text{Setup start time}) + \text{Clean-up time} \qquad (3\text{-}3)$$

Information derived from the data analysis was discussed within the surgical quality team involved in the surgical patient flow improvement project. Eventually the booking guideline was developed for the nine common specialties based on the median total elapsed time for each procedure. Table 3-5 demonstrates an example of the developed booking guideline for nine common procedures in WCH.

Table 3-5: An example of the surgical booking guideline

Procedure (note that surgeries with multiple procedures are excluded)	Count	Range of Scheduled Times by Surgeon	50th Percentile					Recommendation based on 50th Percentile (Median)
			Scheduled time	Actual Elapsed	Surgery Elapsed	Anaes Pre &Post Op	Range of Median Total Elapsed Times per Surgeon	
Adenoidectomy	24	60 - 90	60	60	14	22	52 - 71 min	60 min
Circumcision	16	60 - 210	98	106	38	41	81 - 93 min	75 or 90 min
Dental Restorations & Dental Treatment as Required	103	60 - 240	90	107	57	25	105 - 111 min	105 min
Inguinal Hernia Repair	27	45 - 315	90	105	39	35	88 - 117 min	90 min
Orchiopexy	8	90 - 165	113	120	53	40	114 -154 min	120 min
Strabismus Repair	19	75 - 135	75	87	28	27	76 -106 min	75 or 90 min
Tonsillectomy	30	60 - 75	60	72	23	23	57 - 76 min	60 min
Tonsillectomy/ Adenoidectomy	70	60 - 90	60	71	25	22	61 - 91 min	75 min
T-Tube Insertion	96	30 – 240	30	42	7	11	36 - 58 min	30 & 45 min (for every other Case Booked)

3.5.4 Implementation of the Booking Time Guideline

The data analysis and the booking guideline was shared and discussed with surgeons. The approved guideline was distributed to the surgeons' offices and education was provided for their office staff. Discussion sessions were held to increase the surgeons and their staff awareness about the actual time that the surgical process takes in the most common specialties. To facilitate the use of booking guideline by the surgeons for scheduling, a scheduling tool was developed in Excel. The scheduling tool assists the surgeons in avoiding errors or miscalculations in the case time estimations by providing a pool of samples of all the surgeons' historical cases. The samples pool is available in an Excel worksheet as shown in figure 3-6, which is linked to the historical case times and description for elective cases of the past three years. As figure 3-7 shows the historical statistics are given for a number of procedures. The scheduling tool also has the option to demonstrate the statistical distributions of the common procedures using charts. Figure 3-8 depicts an example of this option.

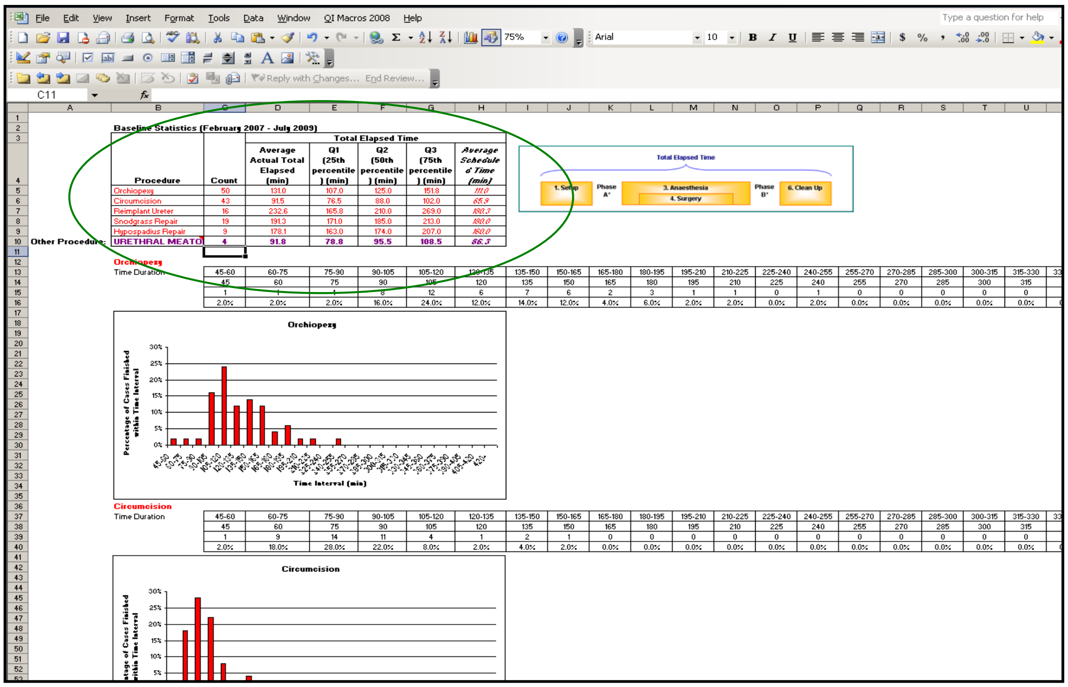


Figure 3-6: A snapshot of the Excel worksheet showing pool of samples linked to the historical case times and descriptions for elective cases of the past three years.

				Total Elapsed Time				
2	Baseline Statistics (February 2007 - July 2009)							
4		Procedure	Count	Average Actual Total Elapsed (min)	Q1 (25th percentile) (min)	Q2 (50th percentile) (min)	Q3 (75th percentile) (min)	*Average Scheduled Time (min)*
5		Orchiopexy	50	131.0	107.0	125.0	151.8	*111.0*
6		Circumcision	43	91.5	76.5	88.0	102.0	*65.9*
7		Reimplant Ureter	16	232.6	165.8	210.0	269.0	*180.3*
8		Snodgrass Repair	19	191.3	171.0	185.0	213.0	*180.0*
9		Hypospadius Repair	9	178.1	163.0	174.0	207.0	*160.0*
10	Other Procedure:	**HYDROCELECTOMY**	**9**	**111.2**	**98.0**	**105.0**	**123.0**	***101.7***

Figure 3-7: Historical statistics for a number of procedures.

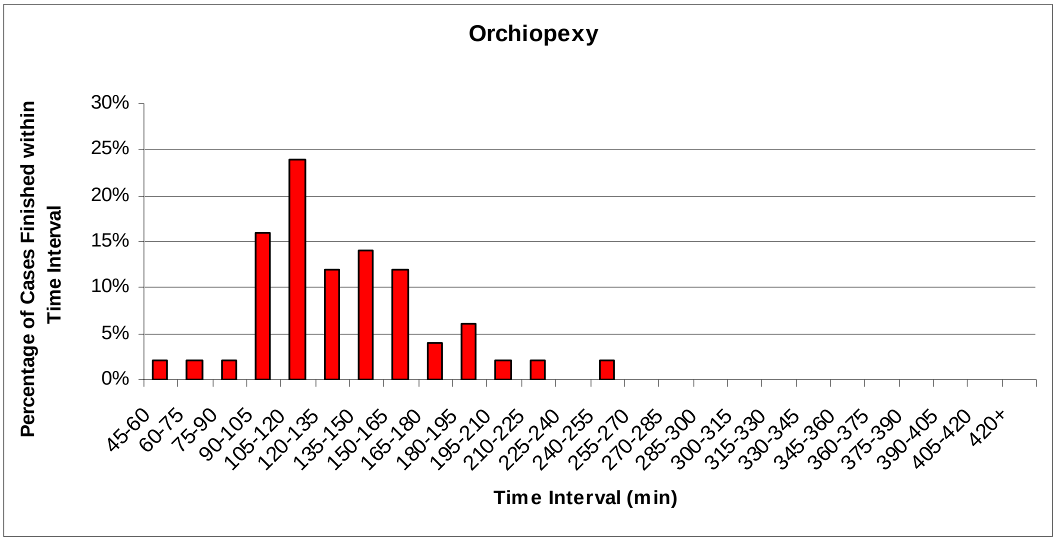
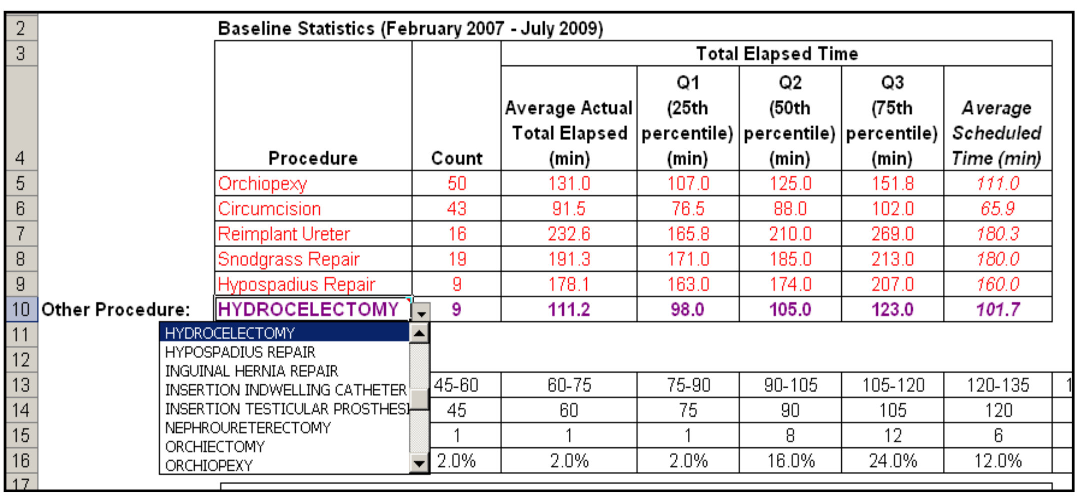


Figure 3-8: Statistical distributions for a procedure shown in the scheduling tool.

The user has the option to retrieve the statistical and historical distribution on any type of procedure, using a drop-down of all the single procedures. Figure 3-9 shows an example of the drop-down menu.



Baseline Statistics (February 2007 - July 2009)

	Procedure	Count	Total Elapsed Time: Average Actual Total Elapsed (min)	Q1 (25th percentile) (min)	Q2 (50th percentile) (min)	Q3 (75th percentile) (min)	Average Scheduled Time (min)
	Orchiopexy	50	131.0	107.0	125.0	151.8	111.0
	Circumcision	43	91.5	76.5	88.0	102.0	65.9
	Reimplant Ureter	16	232.6	165.8	210.0	269.0	180.3
	Snodgrass Repair	19	191.3	171.0	185.0	213.0	180.0
	Hypospadius Repair	9	178.1	163.0	174.0	207.0	160.0
Other Procedure:	HYDROCELECTOMY	9	111.2	98.0	105.0	123.0	101.7

45-60	60-75	75-90	90-105	105-120	120-135
45	60	75	90	105	120
1	1	1	8	12	6
2.0%	2.0%	2.0%	16.0%	24.0%	12.0%

Figure 3-9: Drop-down menu in the scheduling tool.

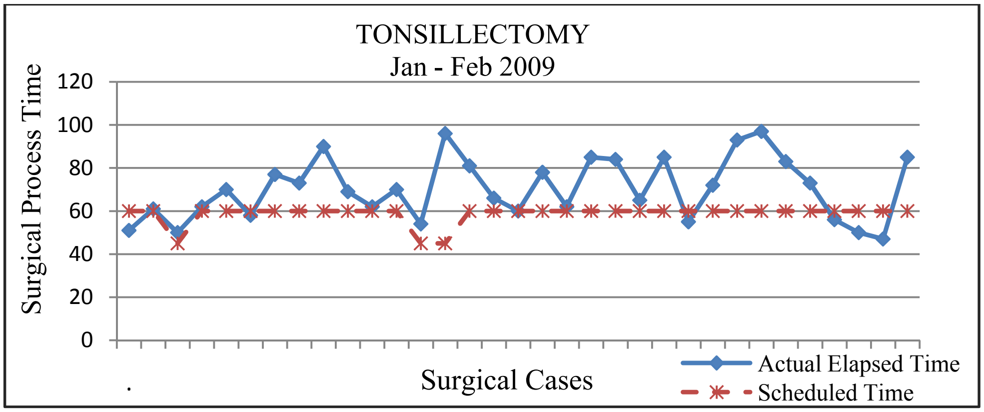
Analysis of the collected surgical data, before implementation of booking time guideline, shows that the baseline total elapsed time exceeded estimated time in 68% of cases. After implementation of the booking guideline, there has been a 42% decrease in time discrepancy per case for the seven surgical procedures with lowest variability in surgical elapsed time.

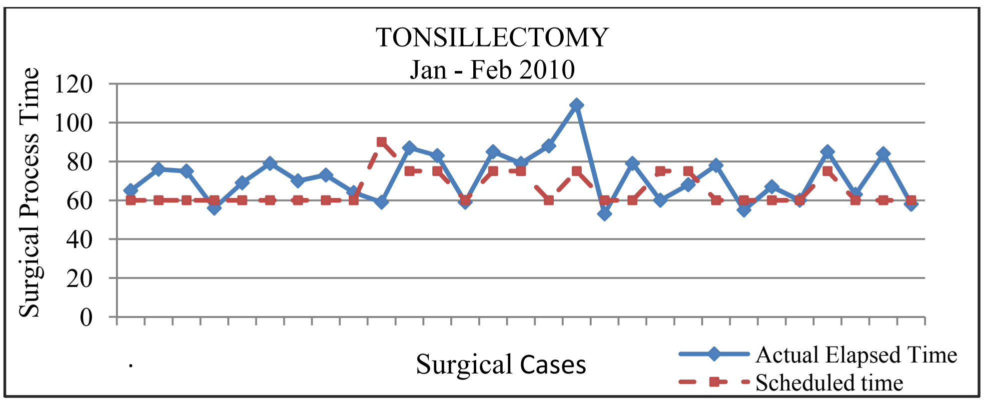
Comparison of data from January-February 2009 and January-February 2010 shows a statistically significant increase in the time requested by surgeons for tonsillectomy, tonsillectomy/adenoidectomy and T-tube insertion. The difference between estimated and actual total surgical elapsed time decreased significantly. The comparisons between the baseline (Jan – Feb 2009) and data after the implementation of the booking guideline approach (Jan 2010 – Aug 2010) is presented in Table 3-3. Data has been gathered and analyzed after two months of implementation for providing the first feedback. As the analysis revealed improvement, training and implementation have continued. More data was collected and analyzed after eight months. The comparisons between the baseline (Jan – Feb 2009) and data after the implementation of the booking guideline approach (Jan 2010 – Aug 2010) is presented in Table 3-6.

Table 3-6: Comparisons between the baseline, implementation and ongoing implementation of the booking guideline approach

Procedure	TDSA			Improvement
	Jan-Feb 2009	Jan-Feb 2010	March-Aug 2010	
Adenoidectomy	7	5	3	23%
Circumcision	23	4	10	81%
Inguinal Hernia Repair	24	17	1	29%
Orchiopexy	23	13	5	45%
Tonsillectomy	12	7	4	42%
Tonsillectomy/ Adenoidectomy	9	7	1	21%
T-Tube Insertion	10	5	4	56%

Preliminary results suggest that surgeons' awareness of the actual time required for common surgical procedures encourages them to request more realistic time on the OR schedule. This may reduce delays and waste in the OR time. Surgical procedures with low variability in surgical process elapsed time are good candidates for a booking guideline. Ongoing data analysis has shown that the TDSA factor has been significantly decreased in seven specialties. This can lead to a considerable improvement in surgical scheduling. Figures 3-10, 3-11 and 3-12 depict the data analysis before the implementation of the booking guideline, two months after implementation (phase 1) and 8 months after implementation (phase 2) for three different specialties.





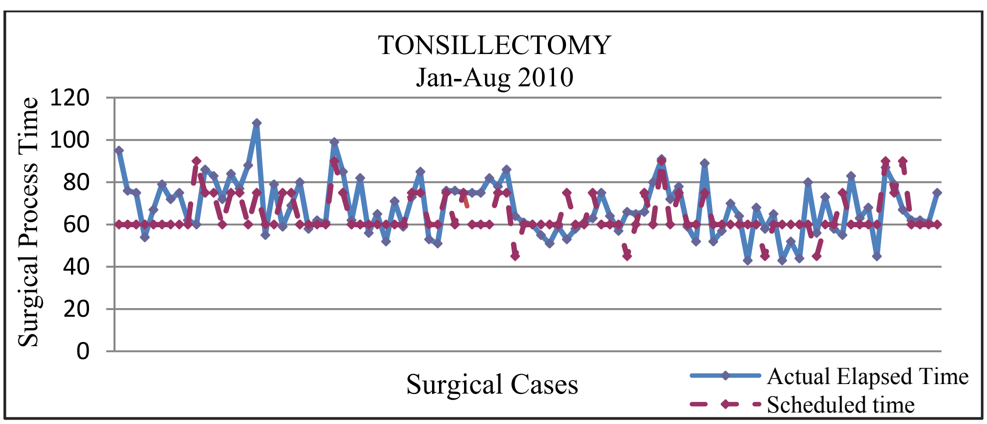
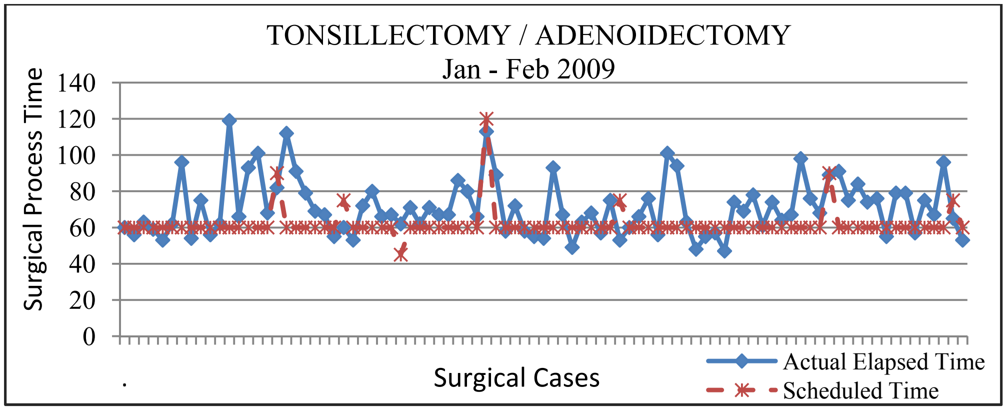
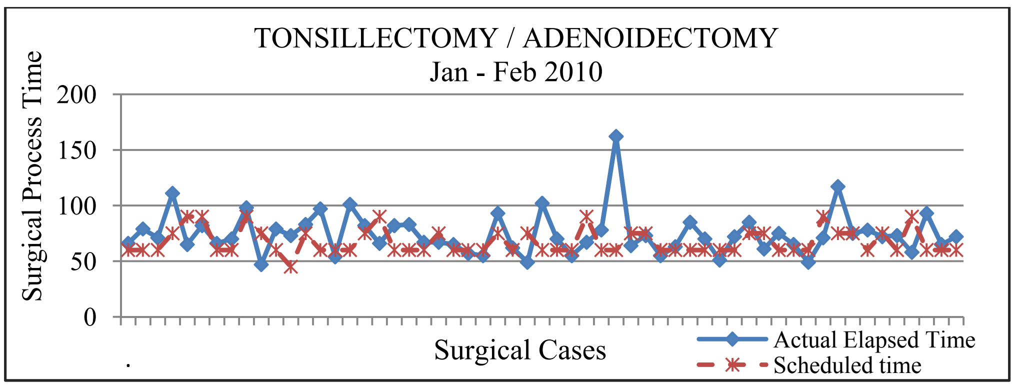


Figure 3-10: Data analysis before the implementation of the booking guideline, two months after implementation (phase 1) and 8 months after implementation (phase 2) for Tonsillectomy.





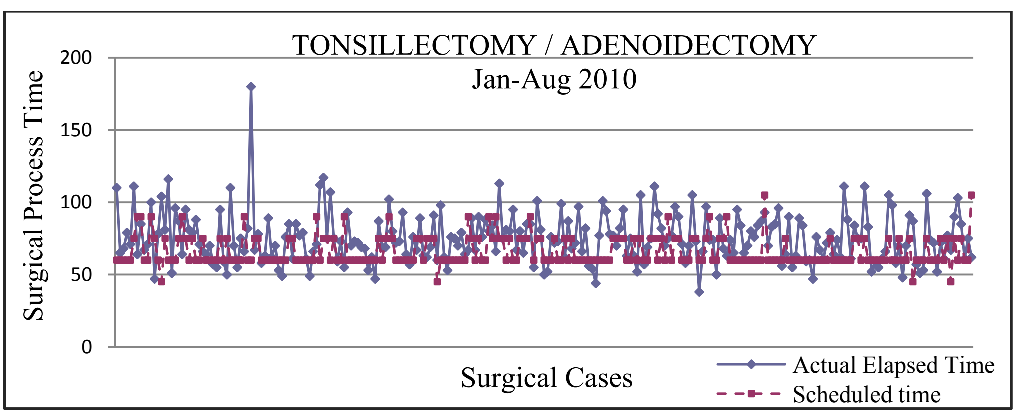
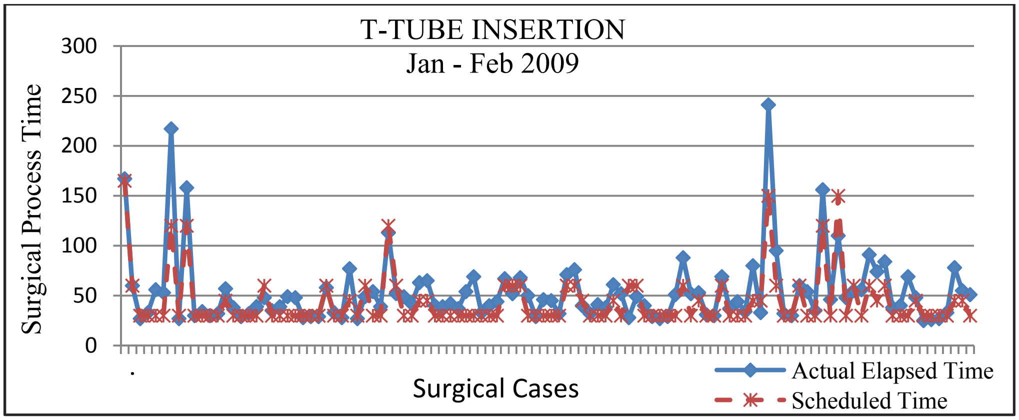
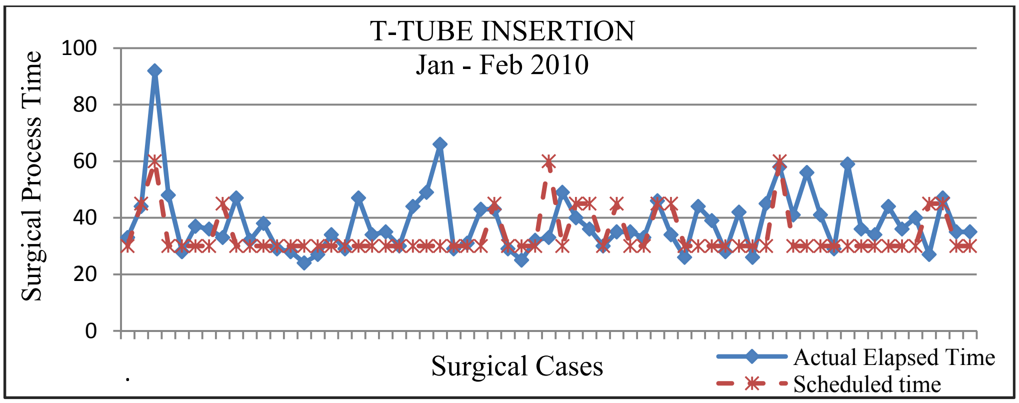


Figure 3-11: Data analysis before the implementation of the booking guideline, two months after implementation and 8 months after implementation for Tonsillectomy/Adenoidectomy.





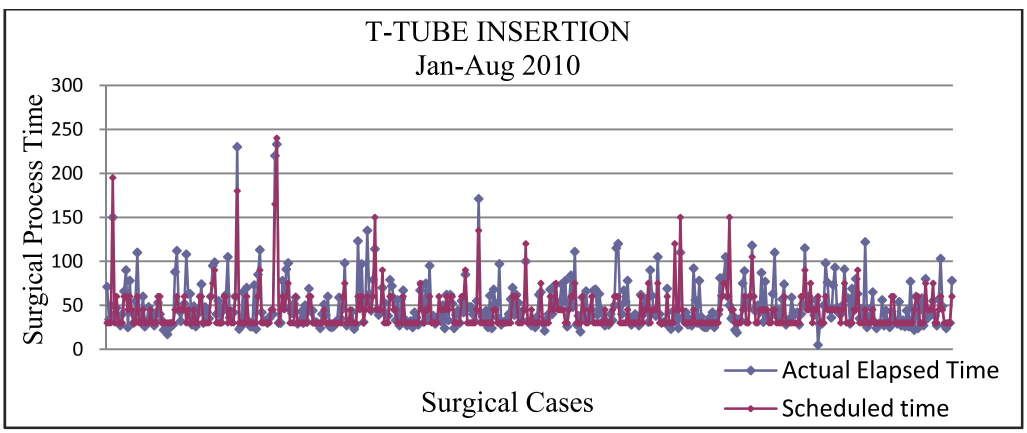


Figure 3-12: Data analysis before the implementation of the booking guideline, two months after implementation and 8 months after implementation for T-tube insertion.

As the other important outcome, the booking time guideline project gave us an insight to the surgical flow as well as more accurate data for developing master surgical schedules defined in next chapter. This knowledge was employed in definition of the mathematical models for the OR patient flow system and the collected data was directly used as input for the model. Details of the models definition input and output data are presented in chapter 4.

3.6 Lean Thinking Approach

3.6.1 Project Definition

In order to improve the surgical patient flow and reduce waste in the related services in WCH, lean training sessions were held in the OR, PACU, pre-admit clinic and day surgery departments. Although the lean thinking approach was first developed in manufacturing sectors, in recent years there has been an increasing interest in the application of lean concepts in the service and health care sectors. Lean thinking approaches in healthcare attempts to eliminate any kind of waste in the process. There are seven types of activities considered as wastes in lean approach including overproduction, waiting, transportation, over-processing, motion, defects and inventory.

3.6.2 Lean Implementation

The lean thinking approach was used to define another PIP (the third PIP) in WCH to improve the surgical patient flow and reduce waste in the related services and resources in the hospital. In order to improve surgical patient flow and reduce waste in the related services and resources in WCH, lean training sessions were held in the OR, PACU, pre-admit clinic and day surgery departments. After the lean concept was explained to each department staff, brainstorming sessions were held to identify the waste areas in each department. In the next step, staff and the quality team continued discussions to bring up further suggestions for elimination of the identified waste. Plans were developed for implementing the agreed upon suggestions. In summary, the following tasks were carried out in order to successfully implement lean thinking approach in WCH:

- Step 1: studied and documented the surgical patient flow process in each department to specify the value added and non-value added activities according to the customer desire.
- Step 2: held lean training sessions for the staff in each department.
- Step 3: held brainstorming sessions between the quality team and staff to identify non-value added activities or waste and discuss possible suggestions to eliminate the identified wastes (by staff and quality team). Seven common wastes are considered as: Over processing, Motion,

Transportation, Waiting, Inventory, Defects. Table 3-7 demonstrates definition and examples for each of these waste types in halthcare.

Table 3-7: Type of wastes and examples in healthcare [Bush, 2007].

Wastes	Definition	Healthcare
Overproduction	Producing what is unnecessary, when it is unnecessary, or in an unnecessary amount.	Providing copies of reports to people who have not asked for it or will not actually read them, Pills given early to suit staff schedules Testing ahead of time to suit lab schedule
Transportation	Movement of product that does not add value to customer	Moving samples Moving patients for testing or treatment
Movement	Movement of patient, physician, nurse, or staff, that does not add value for customer	Searching for patients Searching for charts, files, or information Gathering supplies or equipments Handling paperwork
Waiting	Idle time created when patient, physician, nurse, staff, information, or equipment is not ready	Bed assignment delay Delay in admission to Emergency Dept. Delays in testing, treatment, or discharge Delay in patient lab test results
Processing	Effort that adds no value from the customer's viewpoint	Retesting Excessive paperwork Unnecessary procedures Multiple bed moves
Inventory	More equipments, medicine, or products on hand than the customer needs right now	Bed assignments Pharmacy stock Lab supplies
Defects / Rework	Work that is less than the level the customer or the next process requires, which leads to rework by co-workers	Missing, incomplete or incorrect information Medication error Misfiling documents Wrong or incomplete procedure

- Step 4: collection of data from the current processes to assess the current patient flow including the identified wastes.

- Step 5: define improvement projects based on the collected data and suggestions for eliminating the wastes.
- Step 6: prioritized the defined improvement projects based on their importance and possible improvement (by staff).
- Step 7: implemented the projects.
- Step 8: collected data to assess the improvement after project implementation and provided feedback.

3.6.3 Improvement Projects

The collected data was documented and studied for each of the processes that support surgical patient flow in the different departments, specifying the value added and non-value added activities. Improvement projects were defined based on data for each department at WCH. The following improvement plans were defined for the surgeons' offices, OR department, PACU, day surgery and the pre-admit clinic:

- Development of an electronic booking request form
- Improving internal communication processes within the OR
- Improving communication for transporting patients from the ED/wards to the OR
- Developing a standardized reporting system in the OR
- Developing a new documentation scoring tool for PACU sign-out
- Improving transfers from PACU to the ward/day surgery

- Developing of a standard reporting system in PACU
- Defining a standard process for the report process from the OR to PACU
- Defining a standard order sheets for PACU
- Improving communication with the OR
- improving transporting patients from the day surgery to the OR
- Installed OR scheduler on the computer in day surgery
- Defining new discharge criteria for the Day Surgery and CK3 patient
- Developed a database for the role in day surgery
- Developing a database for pre-admit clinic
- An addressograph is being used to decrease the amount of hand writing required when preparing the OR packages
- Defined standardized information for patients regarding fasting guidelines

In defining and implementing the improvement plans, lean mechanisms were considered to eliminate waste. Two of these improvement plans, implementing an error proofing system, and, lean pull system mechanisms, are described in this section.

Error proofing systems are designed in a way to eliminate errors. Errors occur because of the interaction of people within a system. We can reduce errors by redesigning the system to make it less likely for people to make errors when interacting with the system.

The implementation of an effective error proofing system enables the facility to guarantee good quality by preventing operator error.

The original booking request form was often missing information that is required by the other departments. This issue created a lot of rework or non-value added activities to collect the required information in time of need for the other departments' staff. An electronic booking request form was developed that prevents missing information by drawing the operator attention to complete the obligatory fields. Unless the required information was inputted, the secretary could not proceed with completing the form. In this way it eliminated the error of missing required data at the time of data entry and reduced further rework. Defining and documenting of a standardized reporting system or guidelines for patients' families also reduced errors that can occur by people interacting with the system.

In a "push" system, information is just "pushed" toward the customer, when it is possible for the customer to demand the needed information according to his requirements. While in a pull system, the consumer requests the product and pulls it through the delivery channel. In other words, a push system produces products and puts them in inventory without considering the demand or demand patterns of the customer, while in a lean pull system the system is characterized by quick responses to customer demand, and smooth product flow. The day surgery unit was working based on a push system. They used to prepare the patients for transportation into the OR. The patient was then asked to wait in a waiting room. The OR used to call the day surgery when it was time for a patient to be transferred to the OR. The OR department had to arrange the transfer. Improving patient transportation to the OR process was redesigned in day surgery. In the new process when the patient is ready to be transferred to the OR, day surgery will inform the OR department. Then the OR department can arrange for transport of the patient to the OR within an appropriate time. As a result the potential delay in surgeries caused during the patient transfer into the OR would be deceased.

Implementation of these PIPs defined base on the lean approach could reduce the patients' average length of stay (LOS) in day surgery from from 118 minutes to 109 minutes and in PACU from 52 minutes to 50 minutes. Considering the total number of patients which is more than 100 per week, these minor improvements will add up to make a considerable time (and cost) saving for the hospital. Furthermore the rework due to the incomplete patients' file (missing physical history assessment forms), and rework regarding to telephone calls and information transfer between OR and day surgery. As a result, the lean approach projects improved surgical flow as the number of steps and the amount of time and information transfer needed to serve the customer continually decreases, which, in turn, reduces patients wait time and LOS. Analysis of data gathered through customer satisfaction surveys was used to measure customer satisfaction, from the patients' families. Data also revealed that families felt that the quality of care was increased.

3.7 Summary

The surgical patient flow improvement program at WCH was described in this chapter. During this program, improvement teams defined many process improvement projects (PIPs) to study and improve the processes supporting the surgical flow at WCH. The patient flow in different departments was discussed and three main PIPs which were defined and implemented in different departments were explained.

OR clean-up improvement project, as the first PIP, successfully reduced the average OR clean-up time and enhanced the quality of this procedure. The second PIP, described in this chapter, was a booking time guideline system to improve the OR patient flow. Implementation of the booking guideline system considerably decreased the surgical TDSA. Lean thinking approach, as the third PIP discussed in this chapter, was used to define and implement several improvement projects in different departments providing services to surgical patient flow. The main goal of this PIPs was to find and eliminate the major wastes in surgical resources in day surgery, OR and PACU units and they successfully managed to achieve these goals. In the next chapter, multi-objective mathematical models for optimization of OR MSS will be presented.

Chapter 4: Multi-Objective Mathematical Models for Optimizing the Master Surgical Schedule

This chapter describes two multi-objective mathematical models proposed for optimizing master surgical schedule (MSS). The chapter is organized as follows. The first model descriptions, assumptions, notations, equations, implementation and solution are described in section 4.1. Next, the second model description is presented in section 4.2. Lastly, section 4.3 looks over the results of both models.

4.1 Optimizing OR Master Surgical Schedule Encompassing Elective Surgeries

4.1.1 Problem Description

The first model is proposed for developing master surgical schedule (MSS) encompassing elective surgeries. Emergency surgeries are not considered within this MSS due to the complexities associated within the nature of the emergency department. Emergency cases are involved with large variability in the number and duration of surgeries. Furthermore, emergency cases mostly need some pre-operative preparations to be done during the morning time. As a result, most hospitals develop MSS considering only the elective surgeries, assuming that emergency cases can be performed during the afternoon overtime or weekends. This model is developed based on block scheduling system. MSS is considering the multiple objectives of maximizing the number of performed surgeries during the schedule period, minimizing the difference between each surgical group's target times and its actual assigned OR time, and finally minimizing day-to-day variation of number of surgeries. All operative and post operative resource constraints must be respected. Considering the priorities of objectives, the problem is mathematically modelled and solved using lexicographic goal programming. The model has been implemented and validated using actual data from Winnipeg children's hospital, which was collected during the process improvement project described in Chapter 3.

In Winnipeg children's hospital, five staffed OR rooms are available during the weekdays. Elective surgeries are grouped within eleven surgical groups (SGs). Theses surgical groups are general surgery, ENT (ear, nose and throat), urology, neurosurgery, spine, ophthalmology, Pmed (paediatric medicine), oral surgery, plastic surgery, dentistry and orthopaedics. However, only ten SGs are scheduled in MSS for each week at WCH, as Pmed and oral surgery are expected to be given an OR block every other week if the block is a whole day block.

As it is shown in figure 4-1, an elective surgery process has three phases: intake, surgery and recovery. The second phase or surgery procedure in OR department includes the OR setup, anaesthesia, surgery and the OR clean up. Therefore surgery procedure duration includes, all these procedure times.

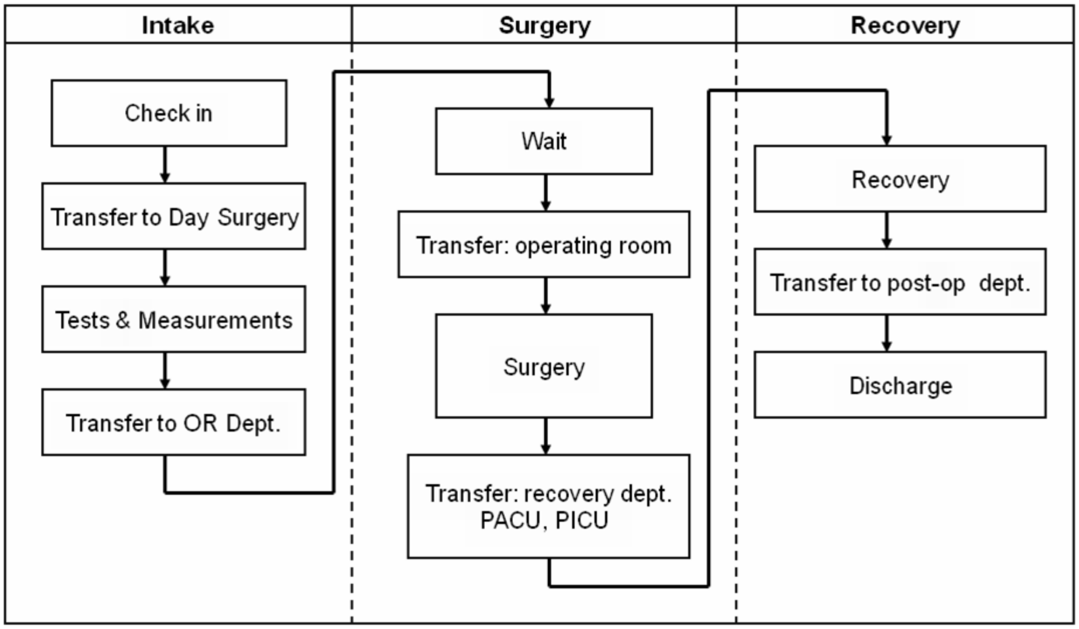


Figure 4-1: Elective surgery process in Winnipeg children's hospital

4.1.2 Model's Assumptions

In this model, each OR block of time is defined by an operating room and a day of the week. It is highly preferred to assign each OR block of time to one surgical group per day. Surgical groups are defined as a surgeon or a group of surgeons who are performing the surgeries within the same specialty. An OR block of time can be allocated to a surgical group (SG) only if at least a surgeon within that SG will be available on that day. Each surgeon can schedule cases into only one OR block at most during a day. For example, to schedule two OR blocks for one surgical group on one day, it is required that at least two surgeons from that surgical group be available on that day.

Surgeons can assign cases into an OR block time only if the surgery process can be completed within the OR block time. A surgery process includes: OR set up, anaesthesia, surgery and OR clean up. Therefore surgery process time encompasses the OR set up and clean up times, the pre-operative and post operative aesthesia process times and the surgery time which have been estimated based on three years of collected actual data from the Winnipeg children's hospital. An OR block time can be allocated to a SG only if required specialized set of equipment is available for that surgical group operations on that day. Emergencies are not considered within the MSS schedule proposed by this model. MSS period has been assumed to be five days which covers the working days of a week.

All the ORs are the same therefore the mathematical model does not assign ORs to the SGs. The model specifies the number of OR blocks should be assigned to each surgery group for all days of the schedule. The management assign the ORs to the SGs based on their preferences.

4.1.3 Model's Objectives

This model has three objectives defined in three priority levels. Priority level one attempts to maximize the weekly throughput (the number of patients that can be scheduled during a week). Priority level two attempts to minimize the difference between the scheduled OR time for each surgical group and its target times. The targets are set for surgical groups by management based on the request for surgeries in each surgical groups derived from waiting lists. Priority level three tends to minimize the day-to-day variability in the number of surgeries. As a result, the OR resource waste will decrease and the workload in the departments providing different services to the surgical flow will be balanced.

4.1.4 Model's Input Data

Table 4-1 summarizes the different input data needed for this model. The input data has been classified based on the different resource groups including SG, OR, surgeons and post-operative resources.

As all the parameters for the Pmed and oral surgery are the same, it would be possible to replace these surgical groups with each other every other week. Therefore one surgical group has been considered for both Pmed and oral surgery. Ten surgical groups have been used as input to the model. Theses surgical groups are indicated as S1 for general surgery, S2 for ENT, S3 for dentistry, S4 for neurosurgery, S5 for ophthalmology, S6 for Pmed & oral surgery, S7 for orthopaedics, S8 for plastic surgery, S9 for spine, S10 urology. All required data and different input values have been provided from the WCH based on their actual available resources.

Table 4-1: Input data required for master surgical schedule model#1

Source	Data used in the model
Surgical groups	✓ The surgical groups (Services) needed to be scheduled in the MSS. ✓ Estimated procedure duration for each surgical group (service) (including set-up, anaesthesia, surgery, and clean up). ✓ Number of required operative equipments for each SG. ✓ Minimum number of blocks required to be assigned to a SG during a week. ✓ Maximum number of blocks that can be assigned to a SG during a week. ✓ Target number of blocks for each SG.
OR	✓ Number of available OR (blocks) on each day of the schedule. ✓ Available OR (blocks) time on each day of the schedule for each OR.
Surgeons	✓ The number of surgeons available in each surgery group, on each day.
Post-op resources	✓ Maximum capacity of the post operative resources (day surgery, PACU, Wards, PICU, etc.) on a daily bases.

4.1.5 Model's Mathematical Description

Indices:

i *Days of the schedule cycle*

s *Surgical group*

Parameters:

Dur_s *Average duration of procedures in SG s;*

Av_OR_i *Number of available OR on day i;*

$Av\_OR\_Hr_i$ *Available number of OR hours on day i;*

$Av\_Post\_op_i$ *Capacity of post operative resources available on day i;*

$Av\_Equ\_SG_{is}$ *Available number of the special equipment sets for SG s on day i,*

$Av\_Sur\_SG_{is}$ *Available number of the surgeons for performing surgery in SG s on day i,*

$Time\_OR\_SG_s$ *Total OR time allocated to the SG s during the schedule period (one week),*

Min_OR_s *Lower bound for OR time or the minimum number of the OR blocks to be assigned to SG s during the schedule period (one week),*

Max_OR_s *Upper bound for OR time or the maximum number of the OR blocks to be assigned for SG during the schedule period (one week),*

$T\_OR\_HR_s$ *Target OR time defined for SG s during the schedule period (one week),*

Variables:

SUM_U_T *Total amount of OR time under allocated to all surgical groups according to the defined targets (under-supply), in hours,*

Num_P Number of scheduled procedures within the schedule period (one week),

OR_SG_{is} Number of OR blocks allocated to the SG s on day i,

$Num\_p\_Day_i$ Number of scheduled procedures on day i,

$Num\_p\_Day\_SG_{is}$ Number of scheduled procedures of SG s on day i,

Max_Dev Largest deviation in the number of cases that are scheduled on any two days of week,

$UN\_T^-{}_s$ Amount of OR time under allocated to SG s according to the defined target (under-supply), in hours,

$OV\_T^+{}_s$ Amount of OR time over allocated to SG s according to the defined target, in hours,

dev^+ The amount of positive deviation in the number of cases scheduled on any two days of week,

dev^- The amount of negative deviation in the number of cases scheduled on any two days of week,

4.1.5.1 Objective Functions

The three functions that represent the three objectives of the model are given below:

The objective function (4-1) attempts to maximize the weekly number of performed surgical procedures within the obtained MSS cycle (weekly throughput).

$$\text{Maximize } \mathrm{Num\_p} \tag{4-1}$$

The objective function (4-2) minimizes the total under allocation of OR time to the surgical groups compared to the defined target values (under-supply).

$$\text{Minimize } \mathrm{SUM\_U\_T} \tag{4-2}$$

Objective (4-3) minimizes the largest deviation between total numbers of surgeries that can be scheduled on any two days of the schedule.

$$\text{Minimize } \mathrm{Max\_Dev} \tag{4-3}$$

4.1.5.2 Constraints

The following constraints are defined based on the actual available resources and conditions imposed by WCH management:

$$\sum_i \mathrm{OR\_SG}_{is} \leq \mathrm{Max\_OR}_s \qquad \text{for all s,} \tag{4-4}$$

$$\sum_i OR\_SG_{is} \geq Min\_OR_s \qquad \text{for all s,} \tag{4-5}$$

Equations (4-4) and (4-5) ensure that the assigned number of OR blocks to each SG within a week, should be within the lower and the upper bounds defined by the management.

$$OR\_SG_{is} \leq Av\_Sur\_SG_{is} \qquad \text{for all i \& } s, \tag{4-6}$$

Constraint (4-6) permits the OR blocks to be assigned to an SG if there is enough surgeons available on day i.

$$OR\_SG_{is} \leq Av\_Equ\_SG_{is} \qquad \text{for all i \& } s, \tag{4-7}$$

Equation (4-7) ensures that OR blocks can be assigned to an SG if there is enough available equipments on day i.

$$\sum_s OR\_SG_{is} \leq Av\_OR_i \qquad \text{for all i,} \tag{4-8}$$

Equation (4-8) limits the number of OR blocks that can be assigned to SGs to be less than or equal to the available OR blocks on day i.

$$Num\_p\_Day_i \leq Av\_Post\_op_i \qquad \text{for all i,} \tag{4-9}$$

Equation (4-9) bounds the number of procedures on each day i to be less than or equal to the capacity of post operative resources on day i.

$$\sum_s (\mathrm{Num\_p\_Day\_SG}_{is} \,.\, \mathrm{Dur}_s) \leq \sum_s (\mathrm{OR\_SG}_{is} \,.\, \mathrm{Av\_OR\_Hr}_i) \quad \text{for all i,} \tag{4-10}$$

Equation (4-10) estimates the number of procedures on each day for SGs, based on the assumption that procedures can only be assigned to a block of OR time if there is enough time available to perform the complete surgical procedure.

$$\mathrm{Num\_p\_Day}_i = \sum_s \mathrm{Num\_p\_Day\_SG}_{is} \tag{4-11}$$

Equation (4-11) calculates the total number of procedures on day i.

$$\mathrm{Num\_p} = \sum_i \sum_s \mathrm{Num\_p\_Day\_SG}_{is} \tag{4-12}$$

Equation (4-12) estimates the total number of procedures in a week.

$$dev^{-} - dev^{+} - \geq \mathrm{Num\_p\_Day}_j - \mathrm{Num\_p\_Day}_k \qquad \text{for all j \& } k \in [1..\mathrm{i}] \text{ \& } j \neq k \tag{4-13}$$

$$\mathrm{Max}_{\mathrm{Dev}} \geq dev^{+} + dev^{-} \tag{4-14}$$

Equations (4-13) & (4-14) calculate the deviation between total numbers of surgeries on any two days of the schedule.

$$\mathrm{Time\_OR\_SG_s} = \sum_i (\mathrm{OR\_SG_{is}} \ . \ \mathrm{Av\_OR\_Hr_i}) \quad (4\text{-}15)$$

$$\mathrm{T\_OR\_HR_s} = \mathrm{Time\_OR\_SG_s} + \mathrm{OV\_T^+}_s - \mathrm{UN\_T^-}_s \quad (4\text{-}16)$$

Equation (4-15) calculates the OR time allocated to SG number s, and equation (4-16) estimates the under and over allocation of OR time into each surgical group.

$$\mathrm{SUM\_U\_T} = \sum_s \mathrm{UN_T}^-{}_s \quad (4\text{-}17)$$

Finally, equation (4-17) calculates the total under allocation in the OR time for all surgical groups according to the defined target times (under-supply).

4.1.6 Model Implementation and Results

Lexicographic goal programming approach has been used to solve this mathematical model. In this approach, objectives are defined into different priority levels according to the WCH management to improve the surgical patients' flow. In other words, the first objective function is more important for management according to the practical needs for improvement in the WCH surgical flow.

According to the lexicographic approach, presented in chapter 2, the model is solved first with a single objective which is the first priority goal defined by the management. The obtained solution is then added to the model as an equality constraint and the problem is solved again for the second priority level as the objective function. This procedure is repeated once more for the third priority level. Using this approach, the final obtained solution will not violate any of the goals and satisfy all the objectives.

The model has been executed in Lingo software from Lindo® using the hospital actual data (see appendix A). The solutions were manually validated to confirm that all constraints and assumptions are satisfied. The solutions were compared with actual hospital data to verify the model efficiency. Table 4-2 shows a solution using the actual data from WCH.

Table 4-2: A master surgical schedule obtained from model#1 based on actual data

	OR1	OR2	OR3	OR4	OR5
Monday 7:30 – 15:30	**S1**	**S2**	**S5**	**S8**	**S9**
Tuesday 7:30 – 15:30	**S1**	**S2**	**S4**	**S5**	**S6**
Wednesday 8:30 – 15:30	**S1**	**S2**	**S3**	**S5**	**S10**
Thursday 7:30 – 15:30	**S1**	**S2**	**S3**	**S8**	**S10**
Friday 7:30 – 15:30	**S1**	**S2**	**S3**	**S7**	**S8**

Table 4-3 presents the computational results for the mathematical model. The solver was able to find the global optimum for all objectives in three priority levels.

Table 4-3: Computational results from the first model

Objective Number	Objective Function	Number of Variables	Number of Constraints	CPU Time (sec)	Objective value
1	Num_P	138	185	1021	135
2	Sum_U_T	138	186	201	2
3	Max_Dev	138	187	652	2

Figure 4-2 compares the proposed model results with the actual hospital data for average number of surgeries. Comparison with hospital actual data for four consecutive weeks shows a 35% increase in the average number of procedures performed per week. According to the actual data, the average number of performed procedures per week is 100 patients while the model proposes an average of 135 procedures.

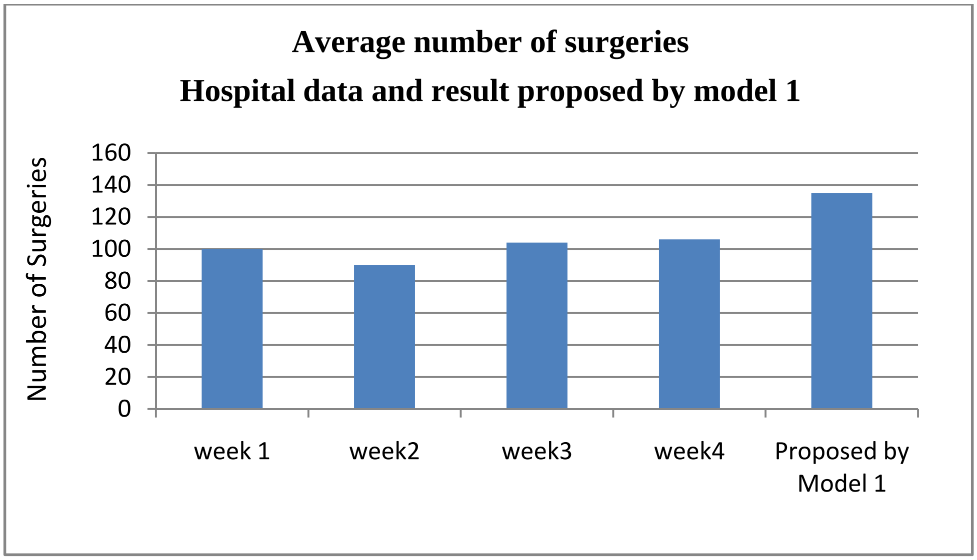


Figure 4-2: Direct comparison between the solution proposed by model #1 and the actual data for the total number of surgeries, calculated for four weeks.

The second objective value indicates that the proposed schedule accuracy in achieving the OR target time is ~99%. The accuracy is calculated as:

$$\text{Accuracy} = \left[1 - \frac{\text{Sum of under supply in all surgery groups based on the specified targets}}{\text{Available OR time during the scheduling period}}\right] * 100$$

which can be expressed as:

$$\%\ \text{Accuracy} = \left[1 - \frac{[\sum_s \text{UN}_{T}{}^{-}{}_{s}]}{\text{Total AvailableOR Time}}\right] * 100 \qquad (4\text{-}18)$$

The results of the proposed model also show a 76.4% decrease in the largest deviation in the number of patients between different days of a week compared to the actual data. The average of largest deviations in the demand for the post-operative beds in the hospital is 8.5 patients while the model proposes the largest deviation of 2 patients for the same parameter.

Figure 4-3 compares the proposed model results with the actual hospital data for largest deviation in the number of patients between any two days of the schedule.

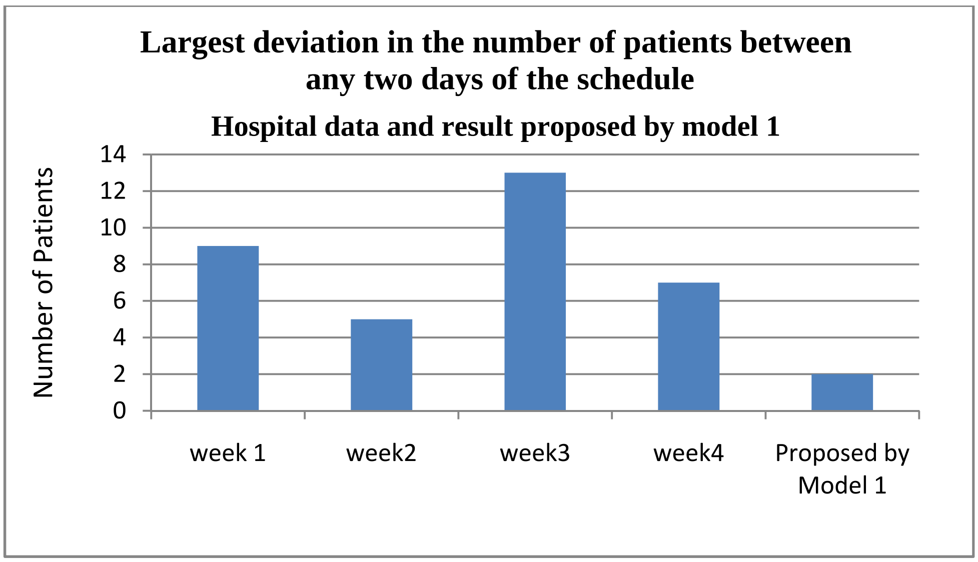


Figure 4-3: Comparison between the solutions proposed by model # 1 and the hospital actual data for largest deviation in the number of patients between any two days of the schedule calculated for four weeks.

In the following chapter, the second version of the mathematical model which considers the emergency cases, will be discussed.

4.2 Optimizing OR Master Surgical Schedule (MSS) Encompassing Elective and Emergency Surgeries

This section describes the second model proposed for optimizing master surgical schedule (MSS). In the first model, emergency operations were not considered due to the complexities associated with the nature of the emergency department. On the other hand, WCH experience shows that if a predicted portion of OR time is set aside in the MSS for the emergency cases, the hospital can provide better access to the surgical services for emergency patients. Furthermore, the surgical flow will become smoother and the bumps in the surgical flow caused by the unpredicted emergency cases will be reduced which, in turn, will reduce the delays and cancellations in the surgical flow. Therefore, WCH management decided to assign a number of OR blocks to the orthopaedic emergencies, which has the most frequent demand between emergency cases. This requires the consideration of some new constraints that are described in this chapter. It is important to know that the emergency blocks will be considered in the MSS system in addition to the emergency surgeries which are running in case of serious emergencies (e.g. accidents, etc) during and after the OR working hours or on the weekends.

The other advantage of considering emergency time blocks (mainly for the orthopaedic emergency operations) in the OR schedule is reducing the stress levels of physicians, surgeons, nurses and other staff in the OR and emergency department. It is highly preferred to allocate OR blocks of time in MSS to the emergencies during the afternoon at WCH, as emergency cases may require some time in the morning to be ready for the operations. Therefore, it is needed to define half-day OR blocks by breaking full-day blocks of time into two half-day blocks. The second model, the same as the first mode, is developed based on block scheduling method. The MSS is developed using a multiple objective mathematical model similar to the first model which is also solved using lexicographic goal programming. This model has also been validated using the data collected from Winnipeg children's hospital.

4.2.1 Assumptions and Input Data

Emergencies are included within the second model through assigning a number of half-day blocks of OR time in the MSS schedule. Therefore, the MSS with be composed of two types of OR block: full-day blocks and half-day blocks. For defining a full-day block, an OR is going to be allocated to a SG for the whole day. For example, OR1 is assigned to SG1 on Monday from 7:30 to 15:30. While for defining half-day bocks, an OR can be assigned to a SG for half of a day. For example, OR5 is assigned to SG6 on Monday from 7:30 to 11:30. It is highly preferred to allocate OR blocks to the emergency cases during the afternoon. All the other assumptions for the second model are the same as the assumptions for the first model explained in section 4-1-2. Including the Orthopaedics emergencies, model #2 encompasses eleven surgery groups (SG): General Surgery (S1), ENT (S2), Dentistry (S3), Neurosurgery (S4), ophthalmology (S5), Pmed and oral surgery (S6) orthopaedics (S7), plastic surgery (S8), spine (S9), urology (S10), Orthopaedic emergency (S11).

Table 4-4 summarizes the input data that the second model requires in addition to the input data from the first model described in Table 4-2.

Table 4-4: Input data required for MSS model#2 in addition to input data from MSS model #1

Source	Data used in the second model
Surgery groups	✓ Minimum number of half-day blocks required to be assigned to a SG during a week. ✓ Maximum number of half-day blocks the can be assigned to a SG during a week. ✓ Target number of blocks for each SG. ✓ Number of available operative equipments, during half-day blocks, for each SG.
OR	✓ Number of available Full-day OR blocks ✓ Number of Available Half-day OR blocks ✓ Hours of available OR on each day of the schedule for Full-day block. ✓ Hours of available OR on each day of the schedule for half-day block.
Surgeons	✓ The number of surgeons available, during half-day blocks, for each service, on each day.

4.2.2 Model Description

4.2.2.1 Parameters and Decision Variables

The same decision variables, parameters and notation as used in the first model, have been applied to define the second model's boundaries and constraints. However this model has some more variables and parameters which are defined in this section.

Parameters:

$Av\_OR\_Hr\_H_i$ *Number of hours that OR is available on day i during half-day blocks;*

$Av\_OR\_H_i$ *Number of available half day OR blocks on day i;*

$Av\_Equ\_SG\_H_{is}$ *Available number of the special equipment sets for half-day blocks, for SG s on day i,*

$Min\_OR\_H_s$ *Minimum number of the half day OR blocks to be assigned to SG s during the schedule period (a week),*

$Max\_OR\_H_s$ *Maximum number of the half day OR blocks to be assigned for SG s during the schedule period (a week),*

Variables:

$Num\_p\_Day\_SG\_H_{is}$ *Number of procedures can be scheduled in half-day OR blocks for SG s on day i,*

$OR\_SG\_H_{is}$ *Number of half-day OR blocks allocated to the SG s on day i,*

4.2.2.2 Objective Functions

Second model has the same objective functions as the model 1.

4.2.2.3 Constraints

The second model has the following constraints in addition to all the constraints defined in the first model:

$$\sum_i \mathrm{OR\_SG\_H}_{is} \leq \mathrm{Max\_OR\_H}_s \qquad \text{for all s,} \tag{4-19}$$

$$\sum_i \mathrm{OR\_SG\_H}_{is} \geq \mathrm{Min\_OR\_H}_s \qquad \text{for all s,} \tag{4-20}$$

Equations (4-19) and (4-20) ensure that the assigned number half-day OR blocks to each SG within a week, should be within the specified lower and upper bounds.

$$\mathrm{OR\_SG}_{is} + \mathrm{OR\_SG\_H}_{is} \leq \mathrm{Av\_Sur\_SG\_H}_{is} \qquad \text{for all i \& } s, \tag{4-21}$$

Equation (4-21) makes sure that the OR half-day blocks of time can be assigned to a SG if there are enough surgeons available on any day of the schedule. This equation 4-6 should be replaced by this equation in the second model.

$$\mathrm{OR\_SG\_H}_{is} \leq \mathrm{Av\_Equ\_SG}_{is} \qquad \text{for all i \& } s, \tag{4-22}$$

Equation (4-22) guarantees that an OR block of time can be assigned to a SG if required equipments are available for the SG during the block time, on any day of the schedule.

$$\sum_s \mathrm{OR\_SG\_H}_{is} \leq \mathrm{Av\_OR\_H}_i \qquad \text{for all i,} \tag{4-23}$$

Equations (4-23) expresses that the number of OR half-day blocks that can be assigned to SG number s should be less or equal to the available OR half-day blocks on any day of the schedule.

$$\sum_s(\text{Num\_p\_Day\_SG\_H}_{is} \,.\, \text{Dur}_s) \leq \sum_s(\text{OR\_SG\_H}_{is} \,.\, \text{Av\_OR\_Hr\_H}_i) \quad \text{for all i,} \qquad (4\text{-}24)$$

Equations (4-24), estimates the number of procedures scheduled during half-day blocks on each day for each SG s to the type of OR block, based on the assumption that procedures can only be assigned to a block of OR time if there is enough time.

$$\text{Num\_p\_Day}_i = \sum_s[\text{Num\_p\_Day\_SG}_{is} + \text{Num\_p\_Day\_SG\_H}_{is}] \qquad (4\text{-}25)$$

Equation (4-25) calculates the total number of procedures for each day of the schedule. This equation 4-11 should be replaced with this equation in the second model.

$$\text{Num\_p} = \sum_i \sum_s[\text{Num\_p\_Day\_SG}_{is} + \text{Num\_p\_Day\_SG\_H}_{is}] \qquad (4\text{-}26)$$

Equation (4-26) calculates the total number of procedures for the schedule period (one week). Equation (4-12) should be replaced by equation (4-26) in the second model.

$$\text{Time\_OR\_SG}_s = \sum_i[(\text{OR\_SG}_{is} \,.\, \text{Av\_OR\_Hr}_i) + (\text{OR\_SG\_H}_{is} \,.\, \text{Av\_OR\_Hr\_H}_i)] \qquad (4\text{-}27)$$

Equation (4-27) calculates the OR time allocated to SG i, considering both full-day blocks and half-day blocks. Equation (4-15) should be replaced by equation (4-27) in the second model.

4.2.3 Model Implementation and Results

The second mathematical model is also solved using lexicographic goal programming approach. The same steps were taken as explained in section 4-1-6. This model has also been executed in Lingo software from Lindo® using the hospital actual data. The solutions were manually validated and the solutions were compared with actual hospital data to verify the model efficiency. Table 4-5 shows a solution using the actual data from WCH.

Table 4-5: A master surgical schedule developed by model#2 based on actual hospital data

	Time	OR1	OR2	OR3	OR4	OR5
Mon	7:30 – 11:30	S1	S2	S5	S9	S7
	11:30 – 15:30					S11
Tue	7:30 – 11:30	S1	S2	S6	S10	S7
	11:30 – 15:30					S11
Wed	8:30 – 12	S1	S2	S4	S5	S5
	12 – 15:30					S11
Thu	7:30 – 11:30	S1	S2	S3	S8	S4
	11:30 – 15:30					S11
Fri	7:30 – 11:30	S1	S2	S3	S8	S3
	11:30 – 15:30					S11

Table 4-6 presents the computational results for the mathematical model 1, solutions. The solver was able to find the global optimum for all objectives in three priority levels.

Table 4-6: Computational results of mathematical model #2

Objective Number	Objective Function	Number of Variables	Number of Constraints	CPU Time (sec)	Objective value
1	Num_P	283	358	10677	131
2	Sum_U_T	283	359	7446	4
3	Max_Dev	283	360	1080	1

Comparison with hospital actual data for four consecutive weeks shows a 31% increase in the average number of procedures performed per week proposed model #2. The average number of performed procedures per week in the hospital is 100 patients while the model proposes an average of 131 procedures. Figure 4-4 compares the proposed model results with the actual hospital data.

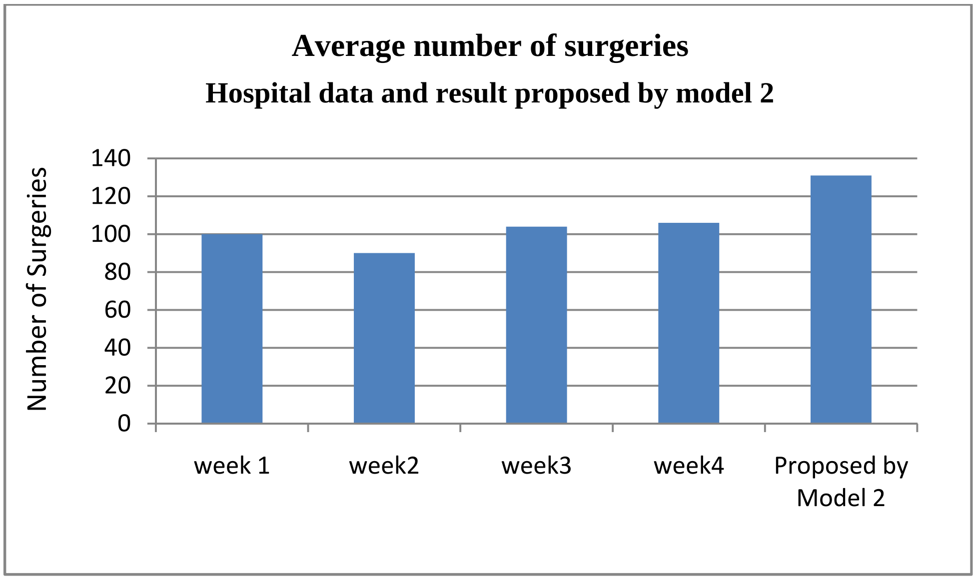


Figure 4-4: Direct comparison between the solution proposed by model # 2 and the actual data for the total number of surgeries, calculated for four weeks.

Objective 2 optimal value shows that the proposed schedule accuracy is 98%. Accuracy is calculated using equation 4-18. The proposed model results also show a 88.2% decrease in the largest deviation in the number of patients between different days of a week comparing to the hospital actual data as the average of largest deviations in the demand for the post-operative beds in the hospital is 8.5 patients while the model proposes the largest deviation of 3 for the same parameter. Figure 4-5 compares the proposed model results with the actual hospital data.

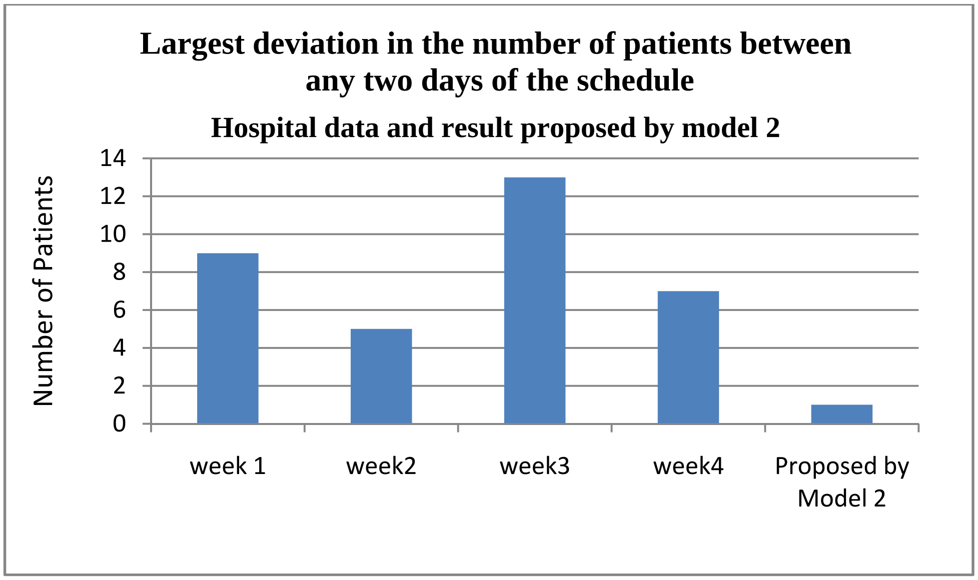


Figure 4-5: Comparison between the solutions proposed by model # 2 and the hospital actual data for largest deviation in the number of patients between any two days of the schedule calculated for four weeks.

4.3 Models Analysis, Results and Discussions

4.3.1 Investigating the Effect of Priority Exchange

In multi-objective optimization problems, the objectives are often conflicting. In such cases, there will be many optimal solutions in such a way that, one solution is better than the others in at least in one objective. In other words, one objective improves while at least another objective becomes worse when moving from one optimal solution to another.

In lexicographic approach it is possible to find more optimal solutions by exchanging the priority of the solutions. To find out how the objectives are compromised, models are solved with all possible combination of the priorities. Providing these solutions to the hospital managers, as decision makers, can give them more insight into how the objectives are compromising and they can choose the best solution for their organization. The optimal solutions for different objective orders in model 1 are presented in tables 4-7. “P” stands for the number of scheduled procedures in one week, “T” stands for total hours of under-supply of operating rooms to surgery groups according to the specifies targets and “D” stands for the largest deviation in the number of scheduled procedures during one week.

Table 4-7: Optimal solutions by exchanging the priority of the objectives in model#1

Model 1	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Priority 1	P: 135	P: 135	T: 2	T: 2	D: 0	D: 0
Priority 2	T: 2	D: 2	P: 135	D: 0	T: 2	P: 130
Priority 3	D: 2	T: 2	D: 2	P: 130	P: 130	T: 2

According to the results taken from the first model, no change was observed in the amount of under-supply parameter (T) in the operating rooms. However, the other two parameters (i.e. the total number of scheduled procedures, P, and the largest deviation in the number of scheduled procedures, D) were changed as the objective order was changed. It is interesting as it suggests that with the current surgical resources there would is an inevitable amount of under-supply based on the specified targets for the surgical groups. This amount of under-supply seems to be the minimized amount and independent to the other two objectives, according to the system constraints and specifications.

On the other hand, the total number of scheduled procedures and also the amount of deviation changed in response to the change in the order of objectives. Maximizing the number of scheduled cases comes with a price which is a variation in the number of patients per day (D). Depending on the hospital conditions, for example in response to a staffing issue, the management might prefer to decrease the deviation to zero instead of having the maximum number of scheduled cases.

Table 4-8 summarizes the optimal solutions for different objective orders in model 2. As opposed to the first model results, here all the objectives have shown a change as a result of change in the priority of objectives. Four different scenarios were observed and the management has the ability to control each parameter by just changing the order of objectives.

It was also interesting that in both models, deviation and under-supply parameters act independently, i.e. their value does not change by changing the priority of these two objectives. It could be concluded that for the studied cases, a smaller deviation in the number of scheduled cases per day does not necessarily lead to more under-supply (test1 & test 6).

Table 4-8: Optimal solutions by exchanging the priority of the objectives in model#2

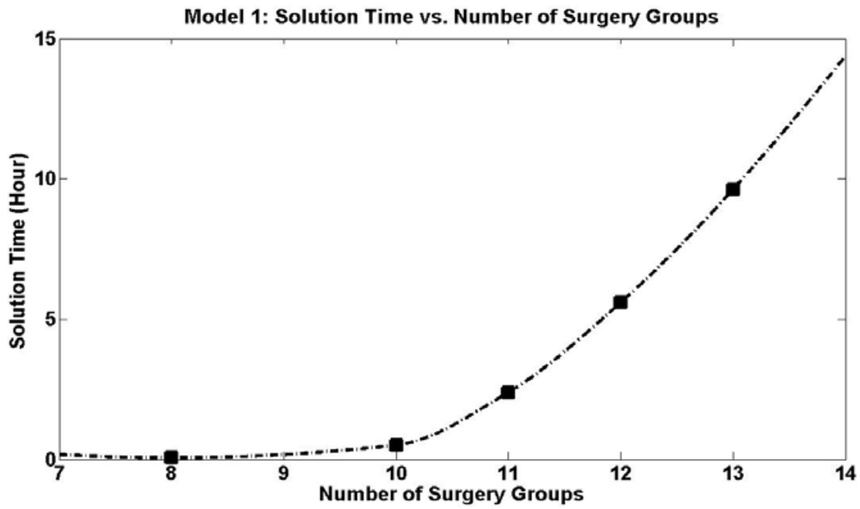
Model 2	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6
Priority 1	P: 131	P: 131	T: 2	T: 2	D: 0	D: 0
Priority 2	T: 4	D: 1	P: 128	D: 0	T: 2	P: 125
Priority 3	D: 1	T: 4	D: 3	P:120	P: 120	T: 4

However, maximizing the total number of scheduled cases as the second priority leads to two different scenarios, a decrease in the under-supply parameter with the price of an increase in the deviation (test 3) or a decrease in the deviation with the price of an increase in the under-supply. The right choice could be made by management according to the hospital condition and needs. Overall, these basic results suggest that changing the order of the priorities could provide the management with a pool of different scenarios and increase the flexibility of the system in response to the immediate, unpredictable needs of the hospital environment.

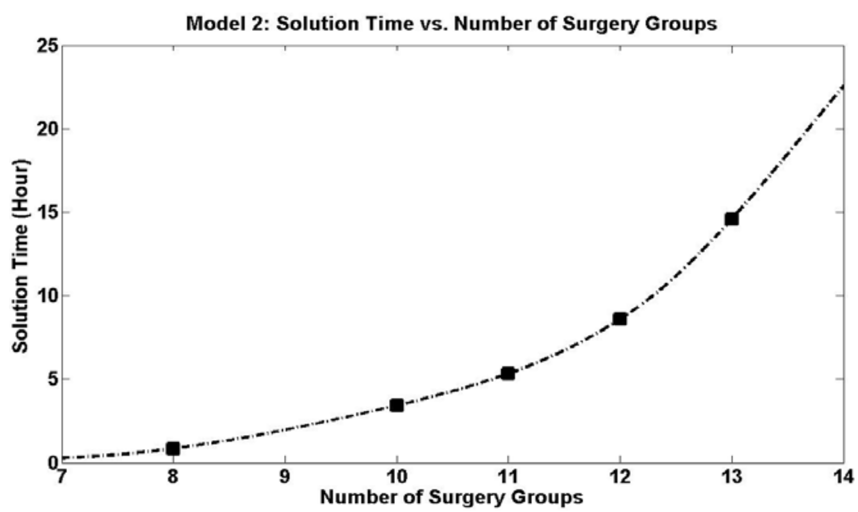
4.3.2 The Effect of Changing the Total Number of Surgery Groups

To appraise the extent to which the developed models are likely to be applicable to other facilities, an operational schedule, produced for WCH, was used with the number of SGs changed from 8 to 13.

The input data was checked to ensure feasible solutions could be identified in all the runs. Feasible solutions were found for all cases in less than an hour. The solution time was recorded for different number of surgery groups, when only 5 ORs are available. The solution time for achieving global optimum vs. number of surgery groups for model 1 and 2, are shown in figure 4-6(a) and 4-6(b) respectively.



(a)



(b)

Figure 4-6: Time to find the global optimum vs. number of SGs to be scheduled within five ORs for (a) model 1 and (b) model 2.

As expected, the solution time increases with an increase in the number of surgery groups. Using MATLAB®, the solution time for higher number of surgery groups could also be approximated.

Considering the CPU times shown in figures 4-6 and 4-7, these models could be reasonably applied to cases with as high as 14 surgery groups. Time comparisons between two models clearly shows the effect of added complexity by considering the emergency cases and adding half-day OR blocks to the second model. In this test, the model's performance decreases when the number of SGs is more than 14 while there are still five ORs available.

However, a search in the practical cases reported in the literature [Black, 2001, Black 2002, Kharrajal , 2006] verifies that, in all the real cases, the number of surgery groups stays well below these maximum numbers. This confirms that the simulation or CPU time is not an issue and it is possible to confidently apply our proposed model to all of these practical, real-life examples with a range of different surgery group numbers.

4.3.3 Comparison with Previous Results in Literature

The proposed models in this work, are both, multi-objective models, offering a flexible and easy to understand structure. Looking at different aspects, from definition and structure of the models to the complexity level of the solved cases at WCH, the proposed models surpass the reported works in the literature to this date.

The nature of the cases, in terms of the number of surgery groups, is more complicated than what is currently reported in literature. Bake and Donald (2001), assigned eight operating rooms to five surgery groups, less than what is dealt with in our cases.

Bake et al (2001) have considered only one type of block (full-day blocks), and the accuracy in allocating the OR time to the surgical groups according to the defined targets was considered as the only objective. In their research, the model accuracy was tested by varying the number of ORs. It was shown that the accuracy increases as the number of ORs increase. For the scenario in which five ORs were assigned to five surgery groups, they reported 97% - 98% accuracy. The proposed model #1 in this thesis shows 99% accuracy in assigning five ORs to ten surgery groups, which is essentially a higher accuracy given the same number of resources with a higher demand.

In another study reported for the case of Mount Sinai hospital, Blake et. al. (2002), defined a model to generate MSS for 8 ORs to be assigned to 6 surgery groups. The number of ORs and surgery groups still structures a simpler problem according to what is defined in this research. Kharrajal et. al. (2006) also report cases with 4 surgery groups sharing 4 rooms, which leads to less complexity in their defined model comparing to what is developed in this thesis.

Another important advantage of the proposed models over the previously reported works is consideration of emergency demand patterns and allocation of OR time blocks to them, This, in turn, leads to a decrease in the amount of cancellations and OR overtime while achieving all the defined objectives.

However, Kharrajal et. al. (2006) report approximately four hours of CPU time required for their solution, much higher than what was achieved in our models, yet an accurate and complete comparison between the models' performance in terms of their solution time was not possible as it requires the exact specification of the computer hardware used as well as the exact run time for each model. Such detailed information are not provided in most of the reports. It should also be considered that, in addition to the model structure, the input data-sets, which are not revealed as to the ethics in healthcare system may not permit, could also affect the solution time.

4.4 Summary

In this chapter, two novel scheduling systems, based on multi-objective mathematical modeling, were proposed to optimize the OR master surgical schedule (MSS). Two mathematical models were developed to optimize OR resource allocation.The first model was used to schedules elective surgeries, while the second model reserved some OR time blocks for the emergency surgeries.

Three objectives in three priority levels were defined. As the first priority, the number of surgeries were maximized. The difference between the OR scheduled time and the target times and also the day-to-day variability in the surgeries number were minimized as the second and third priority levels respectively. The models were solved using lexicographic goal programming approach and the results show considerable improvement compared to WCH current data. Furthermore, the effect of priority exchange was also investigated for both models, providing a better insight to the relationship between different objectives. Model solution times were also evaluated confirming the applicability of the models for cases with as high as 14 different surgery groups. Comparison between the proposed models and previous works reported in literature, ascertains their better performance in handling complexity and also higher accuracy.

Chapter 5: Conclusions and Future Work

Improvement of surgical patient flow at WCH was the main objective of this thesis. To achieve this goal, this research focused on the process improvement program and scheduling optimization of surgical patient flow as the two main approaches for improving the patients flow. This chapter is summarizes the main accomplished projects, results and some future research that can be built up upon this work.

5.1 Research Results

5.1.1 Process Improvement Program

Surgical patient flow improvement program was defined with partnership of the Faculty of Engineering at the University of Manitoba and WCH to improve surgical patient flow. During the course of this program, it was shown that hospital can solve its operational issues and substantially improve the patient flow through application of process improvement projects (PIPs). Successful application of PIPs is greatly important as it provides the appropriate infrastructure for implementing the OR schedule which was the next step in the patient flow improvement project. Defining successful PIPs requires understanding the ongoing processes based on rigorous data analysis. Three main PIPs were defined and implemented in different departments at WCH.

OR clean-up improvement project was the first PIP, defined to enhance the flow of different tasks involved in the clean-up operation. During the course of this project, the staff knowledge was increased on the process. In addition, the OR clean-up process was redesigned and the standardized. The new process OR clean-up process was documented, developing a manual on the process for MSW staff. These achievements led to the increased quality of the process and substantial decrease in the average clean-up time as discussed in detail in section 3.4.

The second PIP, designed and implemented at WCH, was a booking time guideline system to improve the OR patient flow. The main goal of this PIP was to decrease the time difference between the scheduled and the actual elapsed surgical time. This would result in improved OR utilization, less overtime and delay. Moreover, it reduced the stress levels of the surgical staff at WCH. Analysis of the collected surgical data, before implementation of the booking time guideline, shows that the baseline total elapsed time exceeded the estimated time by 68%, which shows significant under-estimation in predicting the required time for surgeries. Following the implementation of the booking time guidelines, there has been a 42% decrease in time discrepancy per case for the seven surgical procedures with lowest variability in surgical elapsed time.

Lean approach has also been used to define and implement several PIPs in different departments providing services to surgical patient flow. In day surgery, lean studies showed that rework due to the incomplete patients' file (missing physical and history assessment forms) and rework related to telephone calls between OR and day surgery, are two important waste areas. Lean approach were successfully applied to day surgery, pre-admit, OR and PACU through defining different improvement projects in order to continually decrease the number of steps, the service time, and amount of required information to serve the patients, which in turn, reduced patients wait time and length of stay (LOS). LOS in day surgery decreased by 9 minutes per patient and in PACU decreased by 2 minutes per patient. Considering the total number of patients which is more than 100 per week, these improvements will add up to make a considerable time (and cost) saving for the hospital. Analysis of collected data through patients' satisfaction surveys revealed that families felt that the quality of care has been improved.

5.1.2 OR Scheduling Optimization

Two novel mathematical models have been developed to optimize the master surgical schedule (MSS). It was shown that an efficient and carefully designed MSS is important to the hospitals as it has a direct impact on the number of procedures, the variability caused by the OR schedule and the waiting lists. In order to define the appropriate MSS for the system, two mathematical models were proposed to optimize OR resource allocation, which could increase the number of performed weekly procedures, efficiently manage the OR time allocation based on the demand and reduce variability.

The first model allocates OR time blocks to elective surgeries and generates OR master surgical schedules using block scheduling method. They satisfy all the operative and post operative resource constraints and include three objectives classified into three priority levels. The objective of the first priority level is to maximize the number of surgeries. The second priority level minimizes the difference in OR scheduled time for surgical groups and the targets and lastly, the third priority level is set to minimize day-to-day variability in the surgeries number in order to smooth daily surgical flow.

In the first model, ten surgery groups were considered. These groups perform elective surgeries in five ORs. The MSS was defined for weekly periods as it is highly preferred in WCH for the MSS to be as similar as possible for every week. In this model, OR blocks were assigned to surgery groups which provided a good flexibility for surgeons within each surgery group to schedule their patients into the allocated blocks. Lexicographic goal programming approach was used to solve the model and the MSS generated by the model shows a 35% increase in the total number of procedures per week compared to the current MSS. In addition, the proposed schedule accuracy in achieving the OR target times for each surgery group is 99% which favourably compares to the models presented in current literature. Furthermore the model proposes 76.4% decrease in the largest deviation in the number of patients between different days of a week. This will decrease the artificial variability between days of a weekly schedule leading to a more predictable utilization and work load which in turn helps the management to plan the OR resources in a more efficient way.

When there is not enough time for emergency cases, some emergency patients will occupy beds in the hospital, waiting for surgery. As a result, some patients may have to be held in the PACU or even in the OR, waiting for beds. This will cause delays and even cancellations within the surgical flow. WCH experience shows that if a predicted portion of OR capacity is set aside in the MSS for the emergency cases, the hospital can provide better access for emergency patients. Therefore, the surgical flow will become smoother and the peaks in the number of patients caused by the unpredicted emergency cases will be reduced which, in turn, will reduce the delays and cancellations in the surgical flow. In response to this issue, the second mathematical model was developed, considering the emergency cases, by assigning a specific portion of OR capacity to these cases.

The second model, similar to the first model, was developed based on block scheduling method. However, as the emergency surgeries are usually preferred to be performed in the afternoon because they may require some time in the morning for pre-surgery preparation; half-day OR blocks of time were defined by breaking full-day blocks into two half-day blocks in the second model. This made the solution procedure easier as it helps to better separate the emergency cases from the normal surgeries. This model was also solved using lexicographic goal programming approach. Results show a considerable increase of 31% in the total number of procedures per week and a schedule accuracy of 98% in allocation of the OR time to the surgery groups based on the defined targets. The proposed model results also show an 88.2% decrease in the largest deviation in the number of patients on different days of a schedule.

Both proposed models have shown that by optimizing the OR resources, the hospital can increase the number of performed weekly procedures without physical expansion, capital requirements and labour increases. Decreasing the variation and delays in elective surgical schedule will substantially improve the utilization of the operating rooms and eliminate a large source of stress on surgeons, nurses and OR staff.

Setting aside capacity for the emergency cases in the second MSS, also results in two very beneficial outcomes. Firstly, a hospital can provide better access to surgical services for these patients. Secondly, the variation caused by emergency cases will be decreased, which will significantly reduce waiting times and improve the quality of care.

The performance of the developed models was also investigated against changing the number of SGs from 8 to 13. The results confirmed the applicability of the models for cases with as high as 14 different surgery groups. Comparison between the solution times for the two proposed models clearly shows the effect of added complexity by considering the emergency cases and adding half-day OR blocks to the second model. Models' performance decreases when the number of SGs is more than 14 while there are still five ORs available.

5.2 Future Research

The proposed models in this thesis were deterministic and developed based on average figures. It would be interesting as a possible future research project to extend these models by introducing variability such as randomness in the duration of surgical procedures and sub-procedures.

As mentioned earlier, an important factor that has a crucial impact on the accuracy of the defined models is a well understanding of different parameters affecting the system function, through data analysis. Therefore, preparation and analysis of more data on the seasonal demand for different specialties would always be helpful as it provides more accurate insight into the system characteristics. This can be considered in defining more accurate models, which in turn will increase the efficiency of the generated schedules. For example the demand may vary during Christmas or summer holidays. Incorporating seasonal variations, which will impact the target times in surgical block schedule and resource utilization, can increase the efficiency of the MSS.

As an alternative approach, a heuristic or meta-heuristic algorithm can also be used to develop a MSS. The advantage of a heuristic algorithm is that it is able to find a good solution in a shorter time than the exact methods. However, the solution generated by the heuristic algorithm may not necessarily be optimal. As a result of decreasing the solution time, it is possible to construct a schedule with a longer cycle time (for example, two or four weeks).

Appendix 1: Model#1 Lingo® Source Codes

The lingo source codes for solving model 1 and model 2 are presented in the appendixes 1 and 2, respectively. To run the models the input data should be entered in the data section of the codes in matrix format. `AV_Sur_SG` and `AV_Equ_SG` are input matrices indicating the number of available surgeons and equipments in each surgery groups in any day of the schedule. Since both the `AV_Sur_SG` and `AV_Equ_SG` define the maximum bound for the number of OR blocks can be allocated to each surgery group on the days of schedule, they can be replaced by one matrix to reduce the number of the constraints. This matrix should be defined as the min matrix of the two matrices. After typing the input data, the lingo model is ready to run.

```
! Specifies the data sets that are used in the model;
MODEL:
SETS:
   DAY/ d1 d2 d3 d4 d5/: AV_OR, AV_Post_Op, NUM_P_DAY, AV_OR_HR;
   SG/ s1 s2 s3 s4 s5 s6 s7 s8 s9 s10/: DUR_SG, MAX_OR, MIN_OR,
   T_OR_HR, UN_T, OV_T, TIME_OR_SG;
   LINKS (DAY, SG): OR_SG, NUM_P_D_SG, AV_Equ_SG, AV_Sur_SG;
ENDSETS
! Restricts the variables to integer values;
@FOR( LINKS( I, J): @GIN( OR_SG( I, J)));
@FOR( LINKS( I, J): @GIN (NUM_P_D_SG( I, J)));
```

```
! Priority 1: The objective function, which maximizes number of
patients during the schedule period or one week;
MAX = NUM_P;
! Priority 2: The objective function, which minimizes the number of
hours, under allocated to surgery groups according to the specified
targets during the schedule period or one week;
MIN = SUM_UN_T;
! Priority 3: The objective function, which minimizes the deviation
in the number of patients between any two days of the schedule or one
week;
MIN = MAX_DEV;
! Calculates the number of patients scheduled during the schedule
period or one week;
NUM_P = @SUM ( Day (I ): NUM_P_Day(I));
! Calculates the number of scheduled on each day of the schedule;
@FOR( DAY ( I):
      NUM_P_Day(I)= @SUM (SG (J): NUM_P_D_SG(I,J)));
! Calculates the deviation between the number of patients for each
combination of two days of the schedule or one week;
@FOR( DAY( I):
      @FOR( DAY( K):
      MAX_DEV >= NUM_P_DAY( I) - NUM_P_DAY( K)));
! Calculates the total OR time assigned to each surgery group during
the schedule period or one week;
@FOR( SG( J):
       TIME_OR_SG (J) = @SUM( DAY( I): OR_SG( I, J) * AV_OR_HR (I)));
```

```
! Calculates the under target hours of OR time assigned to each surgery group during the schedule period or one week;
@FOR( SG (J):
      TIME_OR_SG (J) + UN_T (J) - OV_T (J) = T_OR_HR (J));
! Calculates the total number of under target hours of OR time assigned to surgery groups during the schedule period or one week;
SUM_UN_T = @SUM( SG(J): UN_T (J));
! Guarantees that the number of OR blocks assigned to each surgery group does not exceed the specified upper limit;
@FOR( SG( J):
      @SUM( DAY( I): OR_SG( I, J)) <=
      MAX_OR( J));
! Guarantees that the number of OR blocks assigned to each surgery group is not less than the specified lower limit;
@FOR( SG( J):
      @SUM( DAY( I): OR_SG( I, J)) >
      MIN_OR( J));
! Guarantees that the number of OR blocks assigned to surgery groups does not exceed the number of available OR on any day of the sched
@FOR( DAY( I):
      @SUM( SG( J): OR_SG( I, J)) =
      AV_OR( I));
! Guarantees that the number of patients scheduled does not exceed the number of available post-operative beds on any day of the schedule;
@FOR( DAY( I):
      NUM_P_DAY (I) <=
```

```
    AV_Post_Op( I));
! Prevents a surgery group from being scheduled on a day when the
corresponding surgeon(s) is unavailable;
@FOR( LINKS( I, J):
    OR_SG( I, J) <=
    AV_Sur_SG( I, J));
! Prevents a surgery group from being scheduled on a day when the
corresponding Equipment(s)is unavailable;
@FOR( LINKS( I, J):
    OR_SG( I, J) <=
    AV_Equ_SG( I, J));
! Calculates the number of patient scheduled in each surgery group on
any day of the schedule;
@FOR( DAY( I):
    @FOR( SG( J):
        NUM_P_D_SG (I , J) * DUR_SG (J) <= AV_OR_HR(I) * OR_SG( I
        , J )));
! Specifies the input data;
DATA:
! Specifies number of available full-day OR blocks;
    AV_OR = 5 5 5 5 5;
! Specifies number of available post operative beds;
    AV_Post_Op = 35 35 35 35 35;
! Specifies number of available hours in each full-day OR blocks;
    AV_OR_HR = 8 8 7 8 8;
```

```
! sequence of the surgery groups are as follows in the bellow data:
General Surgery , ENT, Detistry, NeruoSurgery, Ophthalmology, Pmed &
OralSurgery, Orthopedics, PlasticSurgery, Spine, Urology;
! Specifies surgery process duration for each surgery group;
      DUR_SG = 1.5 1 1.5 3.5 1 2 2 1.5 8 1.5;
! Specifies Targets for each surgery group;
      T_OR_HR = 40 40 22 7 10 8 8 14 8 8;
! Specifies the OR block upper limit for each surgery group;
      MAX_OR = 5 5 3 2 3 3 3 3 2 2;
! Specifies the OR block lower limit for each surgery group;
      MIN_OR = 4 4 1 1 1 1 1 1 1 1;
! Specifies the number of available surgeons in each surgery group on
any day of the schedule;
      Av_Sur_SG =  4 8 9 1 1 1 1 1 1 2
                   4 8 1 1 3 1 4 1 1 1
                   4 8 9 1 1 1 4 1 1 1
                   4 8 9 1 1 1 4 1 1 2
                   1 8 9 1 3 1 1 1 1 1;
      ! Specifies the number of available equipments for each surgery
group on any day of the schedule;
      Av_Equ_SG = 1 1 1 1 1 1 1 1 1 1
                  1 1 1 1 1 1 1 1 1 1
                  1 1 1 1 1 1 1 1 1 1
                  1 1 1 1 1 1 1 1 1 1
                  1 1 1 1 1 1 1 1 1 1;
ENDDATA
END
```

Appendix 2: Model#2 Lingo® Source Codes

```
MODEL:
! Specifies the data sets that are used in the model;
SETS:
   DAY/ d1 d2 d3 d4 d5/: AV_OR, AV_OR_H, AV_BED, NUM_P_DAY, AV_OR_HR,
   AV_OR_HR_H;
   SG/ s1 s2 s3 s4 s5 s6 s7 s8 s9 s10 s11/: DUR_SG, MAX_OR, MAX_OR_H,
   MIN_OR, MIN_OR_H, T_OR_HR, UN_T, OV_T, TIME_OR_SG, NUM_F_B_SG,
   NUM_H_B_SG;
   LINKS (DAY, SG): Av_Sur_SG ,Av_Sur_SG_H, Av_Equ_SG, Av_Equ_SG_H,
   OR_SG,OR_SG_H, NUM_P_D_SG, NUM_P_D_SG_H, MAX_OR_SG_H;
ENDSETS
! Restricts the variables to integer values;
@FOR( LINKS( I, J): @GIN( OR_SG( I, J)));
@FOR( LINKS( I, J): @GIN (NUM_P_D_SG( I, J)));
@FOR( LINKS( I, J): @GIN( OR_SG_H( I, J)));
@FOR( LINKS( I, J): @GIN (NUM_P_D_SG_H( I, J)));
! Priority 1: The objective function, which maximizes number of
patients during the schedule period or one week;
MAX = NUM_P;
! Priority 2: The objective function, which minimizes the number of
hours, under allocated to surgery groups according to the specified
targets during the schedule period or one week;
MIN = SUM_UN_T;
```

```
! Priority 3: The objective function, which minimizes the deviation
in the number of patients between any two days of the schedule or one
week;
MIN = MAX_DEV;
! Calculates the number of patients scheduled during the schedule
period or one week;
NUM_P = @SUM (Day (I ): NUM_P_Day(I));
! Calculates the number of procedures (patients) scheduled on each
day of the schedule;
@FOR( DAY ( I):
      NUM_P_Day(I)= @SUM (SG (J): NUM_P_D_SG(I,J) +
      NUM_P_D_SG_H(I,J)));

! Calculates the number of blocks assigned to each sagery group;
@FOR( SG( J): NUM_F_B_SG (J) = @sum( DAY(I): OR_SG (I,J)));
@FOR( SG( J): NUM_H_B_SG (J) = @sum( DAY(I): OR_SG_H (I,J)));
! Calculates the deviation between the number of patients for each
combination of two days of the schedule or one week;
@FOR( DAY( I):
      @FOR( DAY( K):
            MAX_DEV >= NUM_P_DAY( I) - NUM_P_DAY( K)));
! Calculates the total OR time assigned to each surgery group during
the schedule period or one week;
@FOR( SG( J):
       TIME_OR_SG (J) = @SUM( DAY( I): OR_SG( I, J) * AV_OR_HR (I) +
       OR_SG_H( I, J) * AV_OR_HR_H (I)));
```

```
! Calculates the under target hours of OR time assigned to each surgery group during the schedule period or one week;
@FOR( SG (J):
      TIME_OR_SG (J) + UN_T (J) - OV_T (J) = T_OR_HR (J));
! Calculates the total number of under target hours of OR time assigned to surgery groups during the schedule period or one week;
SUM_UN_T = @SUM( SG(J): UN_T (J));
! Guarantees that the number of OR blocks assigned to each surgery group does not exceed the specified upper limit;
@FOR( SG( J):
      @SUM( DAY( I): OR_SG( I, J)) <=
      MAX_OR( J));
@FOR( SG( J):
      @SUM( DAY( I): OR_SG_H( I, J)) <=
      MAX_OR_H( J));
! Guarantees that the number of OR blocks assigned to each surgery group is not less than the specified lower limit;
 @FOR( SG( J):
      @SUM( DAY( I): OR_SG( I, J)) >
      MIN_OR( J));
@FOR( SG( J):
      @SUM( DAY( I): OR_SG_H( I, J)) >
      MIN_OR_H( J));
! Guarantees that the number of OR blocks assigned to surgery groups does not exceed the number of available OR on any day of the schedule;
```

```
@FOR( DAY( I):
      @SUM( SG( J): OR_SG( I, J)) =
      AV_OR( I));
@FOR( DAY( I):
      @SUM( SG( J): OR_SG_H( I, J)) =
      AV_OR_H( I));
! Guarantees that the number of patients scheduled does not exceed the number of available post-operative beds on any day of the schedule;
@FOR( DAY ( I):
      NUM_P_Day(I) <=
      AV_BED( I));
! Prevents a surgery group from being scheduled on a day when the corresponding surgeon(s) is unavailable;
@FOR( LINKS( I, J):
      OR_SG( I, J) + OR_SG_H( I, J) <=
      Av_Sur_SG( I, J));
! Prevents a surgery group from being scheduled on a day when the corresponding Equipment(s)is unavailable;
@FOR( LINKS( I, J):
      OR_SG( I, J)<=
      Av_Equ_SG( I, J));
@FOR( LINKS( I, J):
      OR_SG_H( I, J) <=
      Av_equ_SG_H( I, J));
! Calculates the number of patient scheduled in each surgery group on any day of the schedule;
```

```
@FOR( DAY( I):
      @FOR( SG( J):
            NUM_P_D_SG (I , J) * DUR_SG (J) <= AV_OR_HR( I ) * OR_SG(
            I , J )));
@FOR( DAY( I):
      @FOR( SG( J):
            NUM_P_D_SG_H (I , J) * DUR_SG (J) <= AV_OR_HR_H( I ) *
            OR_SG_H( I , J )));
! Specifies the input data;
DATA:
! Specifies number of available full-day OR blocks;
AV_OR = 4 4 4 4 4;
AV_OR_H = 2 2 2 2 2;
! Specifies number of available post operative beds;
AV_BED = 35 35 35 35 35;
! Specifies number of available hours in each full-day OR blocks;
AV_OR_HR = 8 8 7 8 8;
AV_OR_HR_H = 4 4 4 4 4;
! sequence of the surgery groups are as follows in the bellow data:
General Surgery , ENT, Detistry, NeruoSurgery, Ophthalmology, Oral
surgery & pmed, Orthopedics, PlasticSurgery, Spine, Urology,
OrtopedicEmerg;
! Specifies surgery process duration for each surgery group;
DUR_SG = 1.5 1 1.5 3.5 1 2 2 1.5 8 1.5 2;

! Specifies Targets for each surgery group;
T_OR_HR = 40 40 22 7 10 8 8 14 8 8 19;
```

```
! Specifies the OR block upper limit for each surgery group;
MAX_OR = 5 5 3 1 2 2 1 2 1 2 0 ;
MAX_OR_H = 0 0 1 1 1 1 3 1 0 1 5;
! Specifies the OR block lower limit for each surgery group;
MIN_OR = 4 4 2 0 1 1 0 1 1 1 0;
MIN_OR_H = 0 0 0 1 0 0 1 0 0 0 3;
! Specifies the number of available surgeons in each surgery group on
any day of the schedule;
      Av_Sur_SG = 4 8 9 1 1 1 1 1 1 2 1
                  4 8 1 1 3 4 1 1 1 1 1
                  4 8 9 1 1 4 1 1 1 1 1
                  4 8 9 1 1 4 1 1 1 2 1
                  1 8 9 1 3 1 1 1 1 1 1;
! Specifies the number of available equipments for each surgery group
on any day of the schedule;
      Av_Equ_SG = 1 1 1 1 1 1 1 1 1 1 0
                  1 1 1 1 1 1 1 1 1 1 0
                  1 1 1 1 1 1 1 1 1 1 0
                  1 1 1 1 1 1 1 1 1 1 0
                  1 1 1 1 1 1 1 1 1 1 0;
      Av_Equ_SG_H = 0 0 1 1 1 1 1 1 0 1 1
                    0 0 1 1 1 1 1 1 0 1 1
                    0 0 1 1 1 1 1 1 0 1 1
                    0 0 1 1 1 1 1 1 0 1 1
                    0 0 1 1 1 1 1 1 0 1 1;
ENDDATA
END
```

Appendix 3: Input Data for Mathematical Models

The following tables show the input data used to solve the mathematical models. These tables summarize different types of data required, the limitations and constraints.

Table A3-1: Average procedure time and target times

No.	Group Surgery	Average procedure time (Hour)	Defined Target Time (Hour)
1	General surgery	1.5	40
2	ENT	1	40
3	Dentistry	1.5	22
4	Neruo Surgery	3.5	7
5	Ophthamology	1	10
6	Oral Surgery / P. Med.	2	8
7	Orthopedics	2	8
8	Plastic Surgery	1.5	14
9	Spine	8	8
10	Urology	1.5	8
11	Orthopedic Emergency	2	19

Table A3-2: Available number of surgeons in each surgery group

No.	Surgery Groups	Available # of surgeons				
		Mon	Tue	Wed	Thru	Fri
1	General surgery	4	4	4	4	1
2	ENT	8	8	8	8	8
3	Dentistry	9	1	9	9	9
4	Neruo Surgery	1	1	1	1	1
5	Ophthamology	1	3	1	1	3
6	Oral Surgery / P. Med.	1	4	4	4	1
7	Orthopedics	1	1	1	1	1
8	Plastic Surgery	1	1	1	1	1
9	Spine	1	1	1	1	1
10	Urology	2	1	1	2	1
11	Orthopedic Emergency	1	1	1	1	1

Table A3-3: Available number of equipments in each surgery group (model# 1)

No.	Surgery Groups	Available # of equipment sets (Model #1)				
		Mon	Tue	Wed	Thru	Fri
1	General surgery	1	1	1	1	1
2	ENT	1	1	1	1	1
3	Dentistry	1	1	1	1	1
4	Neruo Surgery	1	1	1	1	1
5	Ophthamology	1	1	1	1	1
6	Oral Surgery / P. Med.	1	1	1	1	1
7	Orthopedics	1	1	1	1	1
8	Plastic Surgery	1	1	1	1	1
9	Spine	1	1	1	1	1
10	Urology	1	1	1	1	1
11	Orthopedic Emergency	1	1	1	1	1

Table A3-4: Available number of OR blocks and post-operative beds

No.	Model #1	Number of OR Blocks	Duration	Max Post Operative Beds
1	Mon	5	8	35
2	Tuesday	5	8	35
3	Wednesday	5	7	35
4	Thursday	5	8	35
5	Friday	5	8	35

Table A3-5: Lower and upper bounds of OR blocks assigned to surgery groups (model# 1)

No.	Surgery Groups	Bounds (Model #1)	
		Min # of Blocks	Max # of blocks
1	General surgery	4	5
2	ENT	4	5
3	Dentistry	1	3
4	Neruo Surgery	1	2
5	Ophthamology	1	3
6	Oral Surgery / P. Med.	1	3
7	Orthopedics	1	3
8	Plastic Surgery	1	3
9	Spine	1	2
10	Urology	1	2

Table A3-6: Available number of equipments during full-day blocks (model# 2)

No.	Surgery Groups	Available # of equipment sets during full-day blocks (Model #2)				
		Mon	Tue	Wed	Thru	Fri
1	General surgery	1	1	1	1	1
2	ENT	1	1	1	1	1
3	Dentistry	1	1	1	1	1
4	Neruo Surgery	1	1	1	1	1
5	Ophthamology	1	1	1	1	1
6	Oral Surgery / P. Med.	1	1	1	1	1
7	Orthopedics	1	1	1	1	1
8	Plastic Surgery	1	1	1	1	1
9	Spine	1	1	1	1	1
10	Urology	1	1	1	1	1
11	Orthopedic Emergency	0	0	0	0	0

Table A3-7: Available number of equipments during half-day blocks (model# 2)

No.	Surgery Groups	Available # of equipment sets during half-day blocks (Model #2)				
		Mon	Tue	Wed	Thru	Fri
1	General surgery	0	0	0	0	0
2	ENT	0	0	0	0	0
3	Dentistry	1	1	1	1	1
4	Neruo Surgery	1	1	1	1	1
5	Ophthamology	1	1	1	1	1
6	Oral Surgery / P. Med.	1	1	1	1	1
7	Orthopedics	1	1	1	1	1
8	Plastic Surgery	1	1	1	1	1
9	Spine	0	0	0	0	0
10	Urology	1	1	1	1	1
11	Orthopedic Emergency	1	1	1	1	1

Table A3-8: Defined bounds on the blocks assigned to the surgery groups (model# 2)

No.	Surgery Groups	Limits (Model #2)			
		Min # of full Blocks	Max # of full blocks	Min # of Half blocks	Max # of Half blocks
1	General surgery	4	5	0	0
2	ENT	4	5	0	0
3	Dentistry	2	3	0	1
4	Neruo Surgery	0	1	1	1
5	Ophthamology	1	2	0	1
6	Oral Surgery / P. Med.	1	2	0	1
7	Orthopedics	0	1	1	3
8	Plastic Surgery	1	2	0	1
9	Spine	1	1	0	0
10	Urology	1	2	0	1
11	Orthopedic Emergency	0	0	3	5

Table A3-9: Lower and upper bounds of OR blocks assigned to surgery groups (model# 2)

No.	Model #2	Number of OR Blocks	Number of Full-day Blocks	Full-day Blocks Duration	Number of Half-day Blocks	Half-day Blocks Duration	Max Post Operative Beds
1	Mon	6	4	8	2	4	35
2	Tuesday	6	4	8	2	4	35
3	Wednesday	6	4	7	2	4	35
4	Thursday	6	4	8	2	4	35
5	Friday	6	4	8	2	4	35

References

Augusto, V., Xie, X, V. Perdomo, V., “Operating theatre scheduling using lagrangian relaxation”, European Journal of Industrial Engineering, vol. 2, no. 2, pp. 172-189, 2008.

Blake, J.T., Dexter, F. and Donald, J., “Operating room manager’s use of integer programming for assigning block time to surgical groups: a case study”, Anesthesia & Analgesia”, vol. 94, no. 1, pp. 143-148, 2001.

Blake, J.T. and Donald, J., “Mount Sinai Hospital uses integer programming to allocate operating room time,” Interfaces, vol. 32, no. 2, pp. 63-73, 2002.

Blake, J.T. and Carter, M.W., “A goal programming approach to strategic resource allocation in acute care hospitals”, European Journal of Operational Research, vol. 140, no. 3, pp. 541-561, 2002.

Beliën, J., Demeulemeester, E., “A branch-and-price approach for integrating nurse and surgery scheduling”, European Journal of Operational Research, vol. 189, no.3, pp. 652-668, 2008.

Beliën, J., Demeulemeester, E., Cardoen, B., “Visualizing the demand for various resources as a function of the master surgery schedule: a case study”, Journal of Medical Systems, vol. 30, no. 5, pp. 343-350, 2006.

Bush, R.W., “Reducing Waste in US Health Care Systems”, American Medical Association, vol. 297, no. 8, pp. 871- 874, 2007.

Cardoen, B., Demeulemeester, E., Beliën, J., “Operating room planning and scheduling: a literature review”, European Journal of Operational Research, vol. 201, pp. 921-932, 2010.

Cardoen, B., Demeulemeester, E., Beliën, J., “Scheduling surgical cases in a daycare environment: a branch-and-price approach”, Katholieke Universiteit Leuven-Faculty of Economics and Applied Economics, research center for operations management, pp. 1-39, 2007.

Chaabane, S., Meskens, N., Guinet, A. and Laurent, M., “Comparison of two methods of operating theatre planning: application in Belgian hospital,” International Conference on Service Systems and Service Management, pp. 83-90, 2006.

Charnetski, J. R., “Scheduling Operating Room Surgical Procedures with Early and Late Completion Penalty Costs,” Journal of Operations Management, vol. 5, no.1, pp. 91-102, 1984.

Coello, C.A., Lamont, G.B. , Van Veldhuizen, D.A., , “Evolutionary algorithms for solving multi-objective problems”, Springer science & business media, 2007.

Cox, T. F., Birchall J. F., Wong H., “Optimizing the Queuing System for an Ear, Nose and Throat Outpatient Clinic,” Journal of Applied Statistics, vol. 12, pp. 113-126, 1985.

Davis, K., Schoen, C., Schoenbaum, S.C., Doty, M.M., Holmgren, A. L., Kriss, J.L., Shea, K. K., “Mirror, Mirror on the Wall: an International update on the comparative performance of American healthcare”, The Commonwealth Fund, 2007.

Deb, K., “Multiobjective Optimization using evolutionary algorithms”, Chichester: John Wiley & Sons, 2001.

Dexter, F. and Epstein, R.H., “Scheduling of cases in an ambulatory center,” Anesthesiology Clinics of North America, vol. 21, no. 2, pp. 387-402, 2003.

Dexter, F., Macario, A., Traub, R.D., Hopwood, M. and Lubarsky, D.A., “An operating room scheduling strategy to maximize the use of operating room block time: computer simulation of patient scheduling and survey of patients’ preferences for surgical waiting time”. Anesthesia & Analgesia, vol. 89, no. 1, pp. 7-20, 1999.

Dexter, F. and Traub, R.D., “Determining staffing requirements for a second shift of anesthetists by graphical analysis of data from operating room information systems,” Journal of the American Association of Nurse Anesthetists (AANA), vol. 68, no. 1, pp. 31-36, 2000.

Dexter, F. and Traub, R.D., “Sequencing cases in operating rooms: predicting whether one surgical case will last longer than another,” Anesthesia & Analgesia, vol. 90, no. 4, pp. 975-979, 2000.

Dexter, F. and Traub, R.D., “How to schedule elective surgical cases into specific operating rooms to maximize the efficiency of use of operating room time,” Anesthesia & Analgesia, vol. 94, no. 4, pp. 933-942, 2002.

Diwekar, U.M., “Introduction to applied optimization”, Norwell: Kluwer Academic Publishers, 2003.

Ehrgott, M., “Multicriteria optimization”, second edition, Springer Berlin-Heidelberg, ISBN: 354023988, 2005.

Eschenauer, H., Koski, J., and Osyczka, A., “Multicriteria design optimization: procedure and applications”, New York: Springer-Verlag, ISBN: 0387506047, 1990.

Evans, G. W., “An Overview of techniques for solving multiobjective mathematical programs”, Management Science, vol. 30, no. 11, pp. 1268-1282, 1984.

Guinet, A. and Chaabane, S., “Operating theatre planning”, International Journal of Production Economics, vol. 85, no. 1, pp. 69-81, 2003.

Hall, Randolph W. (Ed.), “Patient flow: reducing delay in healthcare delivery”, Series: International Series in Operations Research & Management Science , Vol. 91, Springer international series XIII, ISBN: 9780387336350, 2006.

Haraden, C. and Resar, R., “Patient flow in hospitals: understanding and controlling it better,” Frontiers of Health Services Management, vol. 20, no. 4, pp. 3-15, 2004.

Ho, C. J., Lau, H. S., “Minimizing Total Cost in Scheduling Outpatient Appointments”, Management Science, vol. 38, no. 12, pp. 1750-1764, 1992.

Ho, C. J., Lau, H. S., “Evaluating the impact of operating conditions on the performance of appointment scheduling rules in service systems”, European Journal of Operational Research, no. 112, pp. 542-553, 1999.

Hung, G. R., Sandra R., O'Neill, C. B., Gray, A. P., Kissoon, N., “Computer Modeling of Patient Flow in a Pediatric Emergency Department Using Discrete Event Simulation”, Pediatric Emergency Care, vol. 23, pp. 5-10, 2007.

Ignizio, J.P., “A review of goal programming: A tool for multiobjective analysis,” Journal of Operations Research Society, vol. 29, no. 11, pp. 1109–1119, 1978.

Jacobs, F.R., Richard B.C., Aquilano, N.J., “Operations and supply management”, McGraw Hill, 12th edition, pp. 10, 2009.

Jebali, A., Hadj Alouane, A.B. and Ladet, P., “Operating rooms scheduling,” International Journal of Production Economics, vol. 99, no. 1-2, pp. 52-62, 2006.

Jones, D.F., Mirrazavi, S.K. and Tamiz, M., “Multi-objective meta-heuristics: an overview of the current state-of-the-art,” European Journal of Operational Research, 137, no. 1, pp. 1-9, 2002.

Kharrajal S., Albert P., Chaabanel S., “Block scheduling: toward a master surgical schedule”, Service Systems and Service Managemen International Conference, pp. 429-435, 2006.

Keeney, R.L. and Raiffa, H., “Decisions with multiple objectives: Preferences and value tradeoffs”, Second edition, Cambridge University Press, ISBN: 0521438837, 1993.

Kollberg, B., Dahlgaard, J. “Measuring lean initiatives in health care services: issues and findings”, International Journal of Productivity and Performance Management, vol. 56, no. 1, pp. 7-24, 2007.

Kuo, P.C., Schroeder, R.A., Mahaffey, S. and Bollinger, R.R., “Optimization of operating room allocation using linear programming techniques,” Journal of the American College of Surgeons, vol. 197, no. 6, pp. 889-895, 2003.

Lieberman, E.R., “Soviet multi-objective mathematical programming methods: an overview”, Management Science, vol. 7, no. 9, pp. 1147-1165, 1991.

McLaughlin, C.P., Kaluzny, A. D., “Continuous Quality Improvement in Health Care”, Jones and Bartlett, second edition, ISBN: 076372629X, 2004.

Magerlein, J., Martin, J., “Surgical Demand Scheduling: A, Review”, Hospital Research and Educational Trust, pp. 418-433, 1978.

Marler, R.T., Arora, J.S., “Survey of multi-objective optimization methods for engineering”, Struct Multidisc Optim, vol. 26, pp. 369-395, 2004.

McManus, M. L., Long, M. C., Cooper, A., Mandell, J., Berwick D. M., Pagano, M., Litvak, E., “Variability in Surgical Caseload and Access to Intensive Care Services”, American Society of Anesthesiologists, vol. 98, no. 6, pp. 1491- 1496, 2003.

Miettinen, K.M., “Introduction to multiobjective optimization: noninteractive approaches”, Lecture Notes in Computer Science, vol 5252, pp. 1-26, 2008

Miettinen, K., “Nonlinear multiobjective optimization”, Kluwer Academic Publishers, ISBN: 0792382781, 1999.

Oostrum, J.M.V., Houdenhoven, M.v., Hurink, J.L., Hans, E.W., Wullink, G., Kazemier, G., “A master surgical scheduling approach for cyclic scheduling in operating room departments”, OR Spectrum, vol. 30, no. 2, pp. 355-374, 2008.

Oostrum, J.M.V., Parlevliet, T., Wagelmans A.P.M., Kazemier G., "A method for clustering surgical cases to allow master surgical scheduling", Erasmus School of Economics- Medical Center, 2008.

Organization for Economic Co-operation and Development, "The OECD health project private health insurance in OECD countries", OECD, ISBN: 9264015639, 2004.

Ozkarahan, I., "Allocation of surgeries to operating rooms by goal programming," Journal of Medical Systems, vol. 24, no. 6, pp. 339–378, 2000.

Ozkarahan, I., "Allocation of surgical procedures to operating rooms", Journal of Medical Systems, vol. 19, no. 4, pp. 333-352, 1995.

Patterson, P., "A few simple rules for managing block time in the operating room", OR Manager, vol. 20, no. 11, 1, pp. 9-10, 12, 2004.

Rising, E., Baron, R., Averill, B., "A System Analysis of a University Health Service Outpatient Clinic," Operations Research, vol. 21, no. 5, pp. 1030-1047, 1973.

Rohleder, T.R., Sabapathy, D., Schorn, R., "An operating room block allocation model to improve hospital patient flow", Clinical and Investigative Medicine, vol. 28, no. 6, pp. 353-355, 2005.

Roland, B., Martinelly, C.D. and Riane, F, "Operating theatre optimization: a resource-constrained based solving approach", Service Systems and Service Management, 2006 International Conference, pp. 443-448, 2006.

Sier, D., Tobin, P. and McGurk, C., "Scheduling surgical procedures," Journal of the Operational Research Society, vol. 48, no. 9, pp. 884-891, 1997.

Shin, W.S., Ravindran, A., "Interactive multiple objective optimization: Survey", Computers & Operations Research, vol. 18, Issue 1, pp. 97-114, 1991.

Tan, Y.Y., "Multi-objective optimization for scheduling elective surgical patients at the Health Science Centre in Winnipeg", MSc thesis, Department of Mechanical and Manufacturing Engineering, University of Manitoba, 2008.

Testi, A., Tanfani, E. and Torre, G., "A three-phase approach for operating theatre schedules," Health Care Management Science, vol. 10, no. 2, pp. 163-172, 2007.

The Commonwealth Fund, "Canadian hospitals and the healthcare system: views of hospital executives findings from the commonwealth fund international health policy survey", The Commonwealth Fund International Health Policy Survey, 2004.

Valenzuela, C.L., "A simple approach to evolutionary multiobjective optimization", Advanced Information and Knowledge Processing, pp. 55-79, 2005.

Van Oostrum, J.M., Van Houdenhoven, M., Hurink, J.L., Hans, E.W., Wullink, G. and Kazemier, G., "A master surgical scheduling approach for cyclic scheduling in operating room departments," OR Spectrum, vol. 30, no. 2, pp. 355-374, 2006.

Van Veldhuizen, D.A., "Multiobjective evolutionary algorithms: classifications, analyses, and new innovations." Ph.D. thesis, Air Force Institute of Technology, 1999.

Werners, B., “Interactive multiple objective programming subject to flexible constraints”, European Journal of Operational Research, vol. 31, Issue 3, pp. 342-349, 1987.

Weiss, E.N., “Models for determining estimated start times and case orderings in hospital operating rooms”, IIE Transaction, vol. 22, pp. 143-150, 1990.

Weiyong, Z., “Process improvement program management and performance: the mediating role of strategic project selection”, Ph.D. thesis, University of Minnesota, 2006.

Wright, H.I., Kooperberg, C., Bonar, B.A. and Bashein, G., “Statistical modeling to predict elective surgery time: comparison with a computer scheduling system and surgeon-procided estimates”, Anesthesiology, vol. 85, no. 6, pp. 1235-1245, 1996.