ABSTRACT

MCNEAL, KATHRYN ELIZABETH. The Effect of Patient Scheduling in a Gastrointestinal Clinic using Simulation (Under the direction of Javad Taheri).

The problem of determining an optimal scheduling method for multi-phase outpatient clinics where patients need an array of doctors and nurses throughout the appointment is complex. The goal of this thesis is to establish a scheduling rule to maximize the number of patients that can be seen each day at the Durham VA GI Clinic while maintaining acceptable levels of doctor overtime and patient waiting time. Different appointment scheduling rules are generated that combine sequencing of patients and the number of patients in each interval. A discrete event simulation was created using data from the Durham VA GI Clinic, and was used to evaluate the scheduling rules. Schedules with the same total number of patients were compared to determine which one has the lowest objective value, the weighted average of doctor overtime and patient waiting time, for given sets of weights. The best scenarios for each total number of patients between 28 and 36 were analyzed to look for common scheduling rules that work well in all scenarios for each set of weights. A “best” scheduling rule was selected for each set of weights, and the average objective value was found for each number of patients using that rule. By comparing this to the simulation results of the current schedule, the maximum number of patients the clinic should select can be determined based on how much of an increase in average overtime and patient waiting time is acceptable.

The Effect of Patient Scheduling in a Gastrointestinal Clinic using Simulation

by
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Kathryn McNeal is a graduate student in the Industrial and Systems Engineering department at North Carolina State University. She will receive her Master of Science in Spring 2016. She received her Bachelor of Science in Industrial Engineering from Virginia Tech in Spring 2014. She is from Richmond, Virginia where her parents reside.

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1. Introduction

1.1 Veterans Health Administration Background

The Department of Veterans Affairs (VA) provides patient care and federal benefits to Veterans and their dependents, and is made up of three branches: the Veterans Health Administration (VHA), the Veterans Benefits Administration (VBA), and the National Cemetery Administration. The VHA is the largest of the three administrations that make up VA, operating one of the largest health care systems in the world (About VA – VA History). There are currently 152 VA hospitals in the United States that provide care to over 8.3 million Veterans every year (Veterans Health Administration). These medical centers provide a wide array of services such as surgery, orthopedics, radiology, and gastroenterology to Veterans.

In February 2014, there were allegations that 40 veterans died at the Phoenix VA Health Care System (PVAHCS) due to excessive patient waiting times. When the VA Office of Inspector General (OIG) investigated the electronic health records of patients within PVAHCS, they identified 28 instances of clinically significant delays in patient scheduling. Six of these 28 patients were deceased by the time of the investigation. While none of these deaths were able to be conclusively determined as results to the long wait times, during the investigation, OIG identified 3,500 Veterans that were waiting to be scheduled for appointments but were not on PVAHCS's official Electronic Wait List (EWL) and were at risk of never obtaining those appointments (Office of Inspector General, 2014). Over 290,000 veterans were waiting for more than 30 days to get the medical care they needed (US Department of Veterans Affairs, 2015). Many of these patients had to wait for over 90 days. These reports and the investigation that followed quickly gained extensive national media attention, leading to approximately 670 allegations at PVAHCS and other VA medical facilities that wait times were being manipulated to appear better than they were in reality (Office of Inspector General, 2014). According to the OIG's August 26, 2014 report, "…many medical facilities were:

- Using the next available date as the desired date to "0-out" appointment wait times.
- Canceling appointments and rescheduling appointments to make wait times appear to be less than they actually were. We [OIG] substantiated that management at one facility directed schedulers to do this.
- Using paper wait lists rather than official EWLs.
- Canceling consultations (consults) without appropriate clinical review
- Altering clinic utilization rates to make it appear the clinic was meeting utilization goals

"(Office of Inspector General, 2014). Shortly after the initial audits, the Veterans Access, Choice, and Accountability Act of 2014 was put into place, which allocated $16.3 billion to help reduce patient waiting times through increased capacity within VA facilities, allowing access to non-VA facilities when current capacity is insufficient for timely appointments, and other programs (The Veterans Access Choice and Accountability Act of 2014 Summary). As of June 2015, 97 percent of patients were completed within 30 days with 94 percent within 14 days. The efforts to shorten appointment lead times continue, and are the inspiration for this thesis.

1.2 Gastroenterology

Gastroenterology is the branch of medicine that focuses on gastrointestinal (GI) issues, specifically the structure, functions, and diseases of the digestive tract (American Gastroenterological Association, 2010). While gastroenterologists perform a number of different techniques and procedures, the most common are colonoscopy and esophagogastroduodenoscopy (EGD), more commonly known as upper endoscopy (American Gastroenterological Association, 2010).

Colonoscopies involve examining the large intestine, and are a common method of screening for colorectal cancer, along with high-sensitivity fecal occult blood tests (FOBT) and sigmoidoscopies. "Colorectal cancer is the third most common type of non-skin cancer in both men (after prostate cancer and lung cancer) and women (after breast cancer and lung cancer). It is the second leading cause of cancer death in the United States after lung cancer" (National Cancer Institute, 2014). Endoscopies are used to aid in "the evaluation or diagnosis of various problems, including difficult or painful swallowing, pain in the stomach or abdomen, bleeding, ulcers, tumors, and problems with the gallbladder, pancreas and bile ducts" (American Gastroenterological Association, 2010).

1.3 Problem Description and Objective

As with many of the clinics in VA hospitals across the country, the GI clinic at the Durham VA hospital has long waits for patients to make appointments and be seen. Under current scheduling procedures the clinic sees up to 25 patients on Tuesdays, when only colonoscopies and endoscopies are performed. While all days are of interest, Tuesdays are focused on for the purposes of this thesis due to the different patient types and resources available on other days. This thesis will attempt to show that, through improved scheduling practices, the clinic can increase the number of patients they can see in a given day while maintaining current resource levels.

The flow for most patients that come to the clinic is the same, although procedure times are dependent on the type of procedure. Patients start off by entering the clinic according to their appointment times, and waiting in the lobby until the clinic is ready for them. A nurse picks up the patient in the lobby and stays with that patient until he or she is discharged at the end of the process. The patient then visits the prep bay, the procedure room, and finally the recovery bay before being discharged. Procedures can be performed by both fellows and independent doctors. Fellows are doctors that are still in training. The same fellow or independent physician is responsible for the patient’s discharge. Occasionally, patients must leave the clinic due to poor preparation, such as eating before their appointment. When this happens, the patient is discharged prior to going to the procedure room. This process will be discussed more thoroughly in section 3.1.3.

The objective of this thesis is to determine how the clinic should schedule patients to maximize the number of patients the clinic can see in a day while keeping patient waiting time and resource overtime at acceptable levels.

1.4 Analysis Approach

The current clinic system was modeled using the Simio simulation software package. A set of alternate schedules were then generated based on previous research and knowledge of the system. The total number of patients each day in these schedules ranges from 28 to 36, with the exception of the base case, which has 25 patients. Experiments were run for procedures with homogenous patient totals to determine the schedule or schedules with the smallest weighted average of average overtime and average patient waiting time for three different sets of weights. These results were then analyzed to determine if the best schedules across all numbers of patients share common scheduling methods.

2. Literature Review

When modeling patient scheduling, or appointment allocation, in out-patient clinics, studies can be broken up in to two categories. Some studies treat all patients as homogeneous, focusing on the number of patients scheduled per appointment interval. These scheduling methods become more complex as the number of no-shows, the distribution of procedure times, and the time patients arrive in relation to their appointment time are considered. Other studies encompass patients that are heterogeneous, such as new patients and returning patients, and have different procedure times. In general, scheduling methods can vary the block structure and the interval lengths for appointments. Blocks indicate how the patients arrive. For instance, a single-block system has all patients arrive at the beginning of the day. Any specified number of people can arrive at the start of a block. The interval length indicates how far apart the blocks are. This can be a fixed length or it may vary. Many rules have been developed and tested for both homogeneous patients and heterogeneous patients. Some of the major studies are discussed in more detail below, however a comprehensive review of the outpatient clinic appointment allocation literature can be found in Cayirli & Veral (2003).

2.1 Bailey

Norman Bailey (1952) was the first to tackle the specialized topic of appointment allocation in out-patient clinics. In his model, Bailey assumed that the length of appointment intervals were fixed, all patients arrived on time, and patients were homogeneous. The appointment interval was set to the average consultation time, as this was the only process the patient went through. The experiments used 25 appointments per session, regardless of the appointment rules used. Bailey (1952) determined the optimal system to be scheduling appointments at regular intervals, equivalent to the patient's procedure time, with the doctor arriving at the time of the second patient (effectively having two patients scheduled for the first appointment slot). This scheduling rule is used and expanded upon in this paper.

2.2 Ho and Lau

Chrwan-Jyh Ho and Hon-Shiang Lau's (1992) focus was to evaluate different scheduling rules and recommend general rules depending on the clinic environment. The scheduling rules included Bailey's Rule as well as modifications to the rule, such as having three or four patients scheduled for the first appointment slot instead of two and making the intervals slightly longer. Other appointment rules were tested that increased the appointment intervals as the day went on. Unlike Bailey's 1952 study, Ho and Lau (1992) considered the fact that the number of patients scheduled in a day can change the recommended scheduling practice. The simulation created to analyze the different schedules used uniform and exponential service times, three levels of total number of patients, three levels of no shows, and assumed all patients and doctors to be punctual. Ho and Lau determined that there is no single best scheduling rule, and that a rule that is superior in one environment can be very inferior to others (Ho & Lau, 1992).

2.3 Klassen and Rohleder

Kenneth Klassen and Thomas Rohleder (1996) compared multiple scheduling rules, and were the first to incorporate scheduling heterogeneous types of patients that had service times with different standard deviations. Specifically, they used lognormal distributions with a fixed mean in each experiment and two levels of standard deviations. These service times also had different standard deviations. To evaluate schedules, the study measured the server's idle time and the clients' waiting times, which were found using simulation. Klassen and Rohleder (1996) modeled their experiments as a single server system, assuming all patients were scheduled for a specific doctor, and the only process involved was the procedure time. Patients were assumed to be punctual with a fixed rate of 5% being no-shows, skipping their appointment all together. It was found that in every scenario tested, scheduling patients that had service times with low standard deviations was among the best rules (Klassen & Rohleder, 1996).

2.4 Cayirli, Veral, and Rosen

Tugba Cayirli, Emre Veral, and Harry Rosen (2006) also considered heterogeneous patients. Possible schedules were generated using a combination of sequencing rules, which determine the order of the patients, and appointment rules, which determine how many schedules should be scheduled for each block and when those blocks should be scheduled for. The same number of patients were scheduled in all scenarios. In addition to the two types of patients, new patients and returning patients, walk-ins were also considered. They also factored in patients' punctuality and tested the schedules both with a 15% no-show rate and a 0% no-show rate. Cayrili et al (2006) used simulation to evaluate the schedules in a single server, single-phase system. When evaluating the system based on patients' average waiting time, doctor's average waiting time per patient, and doctor's average overtime per patient, it was determined that sequencing ruled had a more significant impact on the system than appointment rules (Cayrili et al, 2006). Different rules were recommended based on the circumstances of the experiment, such as relative importance of patient waiting time compared to doctor waiting time. In their 2008 study, variable appointment interval lengths, based on patient type, were tested using the best performing rules from the 2006 study above (Cayrili et al, 2008). The top five schedules, based on importance given to patient waiting time versus doctor waiting time, included both schedules with and without the interval adjustment (Cayrili et al, 2008).

3. Model Overview

This chapter will describe the simulation model that was created to evaluate the effectiveness of each new schedule in improving the pre-determined success parameters, which are defined in Section 3.3.4. This chapter will also discuss the source and modeling of the data that was used in the simulation, as well as the creation of the alternate schedules.

3.1 Overview of Base Model

This section will outline the details of the base simulation model, where 24 patients are scheduled each day. The model represents a typical Tuesday in the Durham VA GI Clinic. The available resources, schedules, and patient flows are different depending on the day of the week, so the results from this model cannot be directly applied to other days. Screenshots of the actual Simio model will be referenced throughout the section, and can be found in the Appendix.

3.1.1 Resources

The key personnel required for direct patient care are nurses, fellows, attendings, and independent doctors, which were all modeled as workers. A complete list of resources, including their schedules, is given in Appendix A. A technician is also required in the procedure room, but since there is a technician designated to each room that is always available when the room is available, the technicians are not included in the model. Nurses are required to be with the patient from the time they leave the waiting room to the time the patient is discharged. There are twelve nurses in the system. Eight of the nurses work from 8:00 AM to 4:30 PM, while the other four work from 7:30 AM to 6:00 PM. The nurses each take a thirty minute lunch between 11:00 AM and 1:00 PM. This was modeled by reducing the number of available nurses by three throughout the two hour lunch window. This is appropriate since, if required, the nurses can take over for each other. The number of nurses available at any given time are indicated in Table 1.

Table 1 – Nurse Availability

Start Time	End Time	Number of Nurses Available
7:30 AM	8:00 AM	4
8:00 AM	11:00 AM	12
11:00 AM	1:00 PM	9
1:00 PM	4:30 PM	12
4:30 PM	6:00 PM	4

The doctor resources include three fellows, two attendings, and one independent doctor. The fellows perform the procedures, but need approval from the attendings before they can begin the procedures. The independent doctor performs the same procedures as the fellows, but does not need approval from an attending and only performs procedures if all of the fellows are busy. The process for this is shown in Appendix B. The independent doctor can also sign off on procedures for the fellows, however the attending is the first choice, if available. The specific doctor that performs the procedure also discharges the patient. None of the doctors take a break for lunch, as they eat throughout the day whenever they have spare time. All of the fellows are available starting at 7:45 AM and the attendings and independent doctors are available at 8:00 AM. All of the doctor resources remain available through the end of the simulation.

Procedure rooms, prep bays, and recovery bays are also limited resources for the system. There are four procedure rooms and a total of nine bays available. Four of the bays are dedicated to recovery, while the other five are shared between recovery and prep.

3.1.2 Patient Types

There are two types of procedures that are performed on Tuesdays at the Durham VA GI Clinic, colonoscopies (CLN) and endoscopies (EGD). Different entities were used to model patients with each procedure type. While both types of patients follow the same flow, they have different procedure times. In the base case, patient arrivals occur according to Table 2. This schedule is not used every day, but is the target schedule for the clinic and will be used when making comparisons to new schedules. Currently, it is common for fewer than 25 patients to be seen in a given day. It is unclear why this occurs, and it will be monitored in the future.

Table 2 – Base Patient Arrival Schedule

Arrival Time	Number of CLNs	Number of EGDs
7:30 AM	3	1
8:30 AM	3	1
9:30 AM	3	1
10:30 AM	3	1
12:00 PM	2	1
1:00 PM	2	1
2:00 PM	3	0

The times listed in the table are when the patients are brought to the prep room, if the necessary resources are available. The scheduled appointment time is 30 minutes later, as that is when the patient is expected to arrive to the procedure room. Patients are instructed to arrive one hour before their scheduled appointment time, which is the time the actual procedure is scheduled to start. According to nurses and doctors at the Durham VA GI Clinic, it is a reasonable assumption that all patients, aside from the ten percent of patients that miss their appointment altogether, are present 30 minutes before their scheduled appointment time. The patient arrivals were scheduled in the model through the use of an arrival table, which specifies both the time the entity arrives and the type of entity that arrives. Properties were used to designate the number of each type of patient scheduled for each time slot to enable simultaneous comparison of multiple scenarios of how the patients are scheduled each day.

3.1.3 System Flow

This section will elaborate on the flow of patients through the model. Figure 1 shows a simplified layout of the facility. The clinic view of the simulation model can be found in Appendix C. A high-level process flow chart and detailed process flow charts for the prep bays, procedure rooms, and recovery bays can be found in Appendix D1, D2, D3, and D4, respectively.

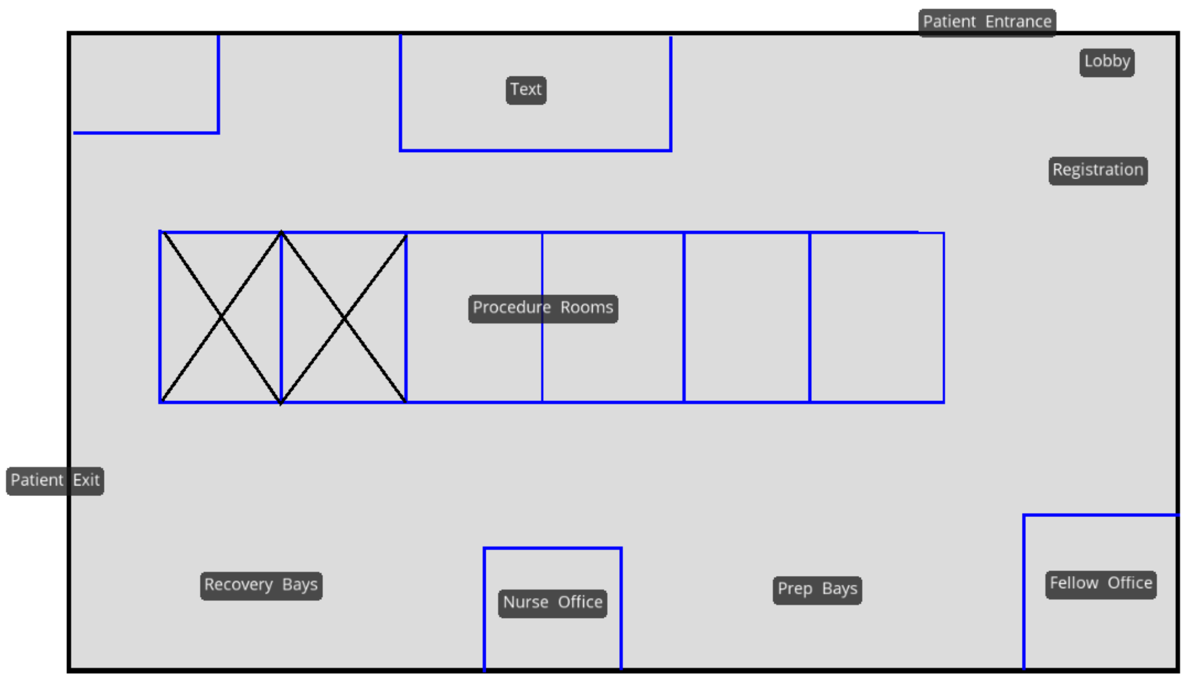

Figure 1 – Durham VA GI Clinic Layout

There are three ways that patients can exit the simulation: a No-Show exit, an Incomplete Exit, and a Complete exit. Patients enter the model at the patient entrance, however there is a probability of 0.1 that the patient does not actually show up for the appointment. If this happens, the entity is sent directly to the No-Show exit, and the global state variable for the number of scheduled entities that have attempted to arrive, is incremented by one.

Otherwise, the entity continues in to the system, the variable is incremented by one, and the global state variable that tracks the number of patients who have arrived that day is incremented by one. The entity then passes through registration. Since the arrival times assume the patients are ready to move to the prep bays, the processing time at the registration server is zero, and is only included for visual purposes. The patient then waits in the lobby until the necessary resources are available for the patient to get prepped. The patient will subsequently move to the prep bays, followed by the procedure rooms, and finally to the recovery bays prior to exiting the system. The detailed processes that occur in each of these locations are described below.

Once the patient is in the lobby, the entity seizes a prep bay and a nurse, after which the prep process occurs. Once the patient is prepped, the time is recorded in an entity state variable. After prep is complete, there is a three percent chance that the patient has been deemed unprepared for the procedure, in which case the associated nurse and prep bay is released, and the patient exits the system through the "Incomplete" exit. The process for the patient leaving the system is shown in Appendix E. If this happens, the global state variable tracking the number of patients who have exited the system is increased by one. An example of this would be if the patient ate before coming in for the procedure. If the patient meets the necessary requirements, it then seizes a procedure room and releases the prep bay.

Once in the procedure room, there is a delay while the nurse hooks up the patient. The first available fellow, or independent doctor if all fellows are busy, is seized, and the name is recorded for future use in an entity state variable. Then one of two scenarios will happen. If the seized resource was a fellow, the fellow goes over the patient's history and physical with the patient. An attending, or independent doctor if all attendings are busy, is then seized, and the fellow gives the attending a brief presentation about the patient and procedure to be performed. After the presentation, the fellow is released, and the attending talks to the patient and signs off on the procedure. The attending is then released, and the original fellow is seized again. In both cases, the procedure time is determined by a data table, according to the entity type. Finally, the procedure is performed, after which the fellow is released. The second scenario, where an independent doctor is seized rather than a fellow, is the same as the fellow's process, but none of the steps involving the attending occur, and the independent doctor remains seized until the procedure is complete. After the fellow or independent doctor leave the room, the patient is cleaned up and prepared to go to recovery before a recovery room is seized.

After the patient seizes the recovery room, the recovery time begins. For the first ten minutes of the recovery, the procedure room continues to be seized to model the room turnover time before the next patient can seize it. All patients must spend at least 30 minutes in the recovery room, so it is not possible for the patient to leave during these first ten minutes. After the recovery period is over, less seven minutes, the same resource that performed the procedure is seized, there is a three minute discharge process, and then the resource is released along with the nurse. After the doctor and nurse are released, there is a four minute delay while the patient gets dressed. Seven minutes was deducted from the recovery time since the times used for the recovery time distribution included the doctor discharge process and the patient getting dressed. Finally, the recovery bay is released, and the patient leaves the system via the "Complete" exit. The global state variable tracking the number of patients who have exited the system, is increased by one. When the last entity that was scheduled for the day has left the system, and the system is empty, the run ends.

3.1.4 Entity Statistics

A tally statistic is used to track and calculate the average time in system for entities that go all the way through recovery. Another global state is used to track how many patients have left the procedure room. Each time a patient leaves the procedure room, a process runs to determine if it was the last patient in the procedure rooms for the day. The same process is also run when entities leave through the Incomplete exit. When one of these occurs, the current time is recorded in a global state variable. This is then used in an output statistic to determine the amount of overtime in the clinic, which is defined in this project as any time when patients are in the procedure rooms after 4:30 PM.

3.2 Data Collection and Input Modeling

Procedure start and stop times were manually recorded from old patient records by nurses for 46 colonoscopy patients and 14 endoscopy patients. A larger set of timestamp data was available from a Microsoft Access database that included the times of the following events:

1. The patient is picked up from the lobby

2. The patient is done being prepped
3. The patient has entered the procedure room
4. The patient has entered the recovery room
5. The patient has been discharged

From these timestamps, the prep time was found by subtracting the picked up timestamp from the prepped timestamp. Similarly, the recovery time was found by subtracting the timestamp from the patient entering the recovery bay from the discharge timestamp. Seventeen minutes were subtracted from the recovery times since they were accounted for in the procedure room turnover, discharge delay, and the patient getting dressed. Any recovery times less than 30 minutes were discarded as inaccurate data since patients remain in recovery for at least 30 minutes. There was no recovery data available that did not already account for these additional delays.

The Arena Input Analyzer software was used to fit the data for the preparation, colonoscopy procedure, and recovery processes to appropriate distributions. Figure 2 shows the recovery time distribution as modeled using Arena Input Analyzer. The square error and the p-value for the chi-square test were used to determine which distribution to fit the data to, where a low square error and a high p-value were desired. Table 3 shows the distribution, square error, and p-value for each set of times, in the format used by Arena. The parameters for each distribution, as shown in Arena's format, can be found in Appendix F. Since only 14 data points were available for EGD procedures, which was not enough to create a sufficiently accurate distribution, expert opinion was used by getting an estimated minimum, maximum, and mode of the procedure time. These were then used to fit a pert distribution for the EGD procedure times.

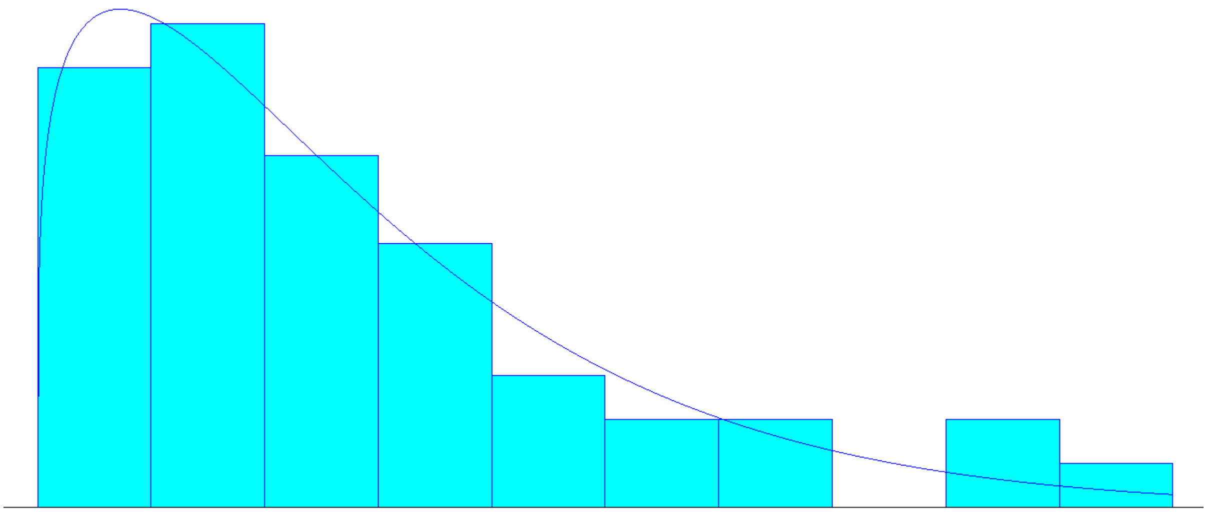

Figure 2 - Recovery Time Distribution in Arena Input Analyzer

Table 3 – Processing Time Distributions

	Expression (minutes)	Square Error	Chi Square P-value
Prep Time	2 + GAMM(8.77, 2.66)	0.013989	0.176
CLN Procedure Time	13 + EXPO(15.1)	0.014790	0.265
Recovery Time	31-17+WEIB(13.1,1.22)	0.005478	> 0.75
EGD Procedure Time	PERT(5,10,75)	N/A	N/A

The remaining delay times were given as expert opinion from nurses and doctors at the clinic and can be found in Table 4.

Table 4 – Additional Delay Times

Process Step	Delay Time (minutes)
Hookup	5
History and Physical	Uniform(8,13)
Presentation	1
Attending Procedure Sign-off	3
Post-Procedure Cleanup	5
Room Turnover Time	10
Discharge	3
Get Dressed	4

3.3 Alternate Scenarios

In this study, it is assumed that there is a fixed demand of 6 EGD patients each day. The demand for CLN procedures, however, is assumed to be elastic, meaning there will be as many CLN patients as there are room for in the schedule. Scenarios were developed using the naming scheme in Table 5. The schedules for each scenario listed in the table can be found in Appendix G.

Table 5 – Scenario Key

Scheduling Method	Scenario Name	Description
Sequencing	A-_._	EGD procedures spread throughout the day
	B-_._	EGD procedures at the end of the day
	C-_._	EGD procedures at the beginning of the day
Initial Blocks Rules	_-1._	4 procedures/hour throughout the day
	_-2._	8 procedures in first block, 4/hour rest of the day
	_-3._	7 procedures in first block, 4/hour rest of the day
	_-4._	6 procedures in first block, 4/hour rest of the day
	_-5._	5 procedures in first block, 4/hour rest of the day
	_-6._	5 procedures in first four blocks, 4/hour rest of the day
	_-7._	5 procedures in first three blocks, 4/hour rest of the day
	_-8._	5 procedures in first two blocks, 4/hour rest of the day
End of Day Rules	_-_.1	original description through entire day
	_-_.2	original description with only 3 procedures in last slot
	_-_.3	original description with only 2 procedures in last slot
	_-_.4	original description with 3 procedures in second to last slot and 2 procedure in last slot
	_-_.5	original description with 2 procedures in the second to last slot and the last slot
Single Block	D_	all patients scheduled at the beginning of day (D1 has 36 patients and decrements by 1 with each scenario, with D9 having 28 patients)

The schedules from Table 5 were developed using a combination of methods from the literature, as discussed in more detail in Chapter 2. In most cases, these scenarios are a slight modification from those in the literature as those in the literature only discussed patients seeing a single doctor, while the schedules in Table 5 pool patients for four doctors.

Since the procedure room is the limiting resource at the GI Clinic, causing a bottleneck, the schedules are built around the procedure room availability. Based on initial runs of the base model, the 95% confidence intervals of the average time procedure rooms are occupied by each patient type are 54.998 +- 1.375 minutes for EGDs and 62 +- 1.025 minutes for CLNs. Since the confidence intervals do not overlap, they are statistically different. Since both means are near 1 hour, and ease of implementation is a key requirement for the schedules, 1 hour block intervals are used for those schedules with multiple blocks.

Scenarios that begin with A, B, or C indicate schedules with multiple blocks, always 1 hour apart, while scenarios beginning with D indicate single block schedules where all patients arrive at the start of the day. The sequencing of EGD and CLN patients is considered since they have different mean times with different standard deviations. The standard deviation for the average time the procedure room is used is 11.667 minutes for EGD's and 15.1 minutes for CLN's. Combining that with the mean data given above, EGD's have both a smaller mean time in the procedure room and a smaller variance. Klassen and Rohleder (1996) found that scheduling low-variance patients at the beginning of the day enhances system performance, however, the study did not consider the effect of the procedure times also having different means. To see if this affects the sequencing decision, three sequences are used in the schedules for this thesis. Sequence A spreads the EGD procedures throughout the day, with one in each block, starting at the beginning of the day until there are no more EGD procedures to be scheduled. This is the sequence currently used by the Durham VA GI Clinic. Sequence B schedules EGD patients at the end of the day, while Sequence C schedules them at the start of the day. Since all patients arrive at the start of the day for Sequence D, the only difference between those scenarios is the number of patients scheduled.

The second value in the scenario name, the Initial Blocks Rule, indicates what version of Bailey's Rule is employed, if any. Traditionally, Bailey's Rule schedules two patients in the first block, and then single patients in each block after that for one doctor (Bailey, 1952). The first Initial Block Rule schedules four patients for the first block since there are four doctors. The second one is the most traditional version adapted to our scenario of multiple doctors, and eight patients are scheduled for the first block, two per doctor, followed by four per block for the rest of the day. Due to concerns about the increase in patient waiting time this could result in, the third through fifth options vary the number of patients in the first block to 7, 6, and 5, respectively. The sixth through eighth Initial Block Rules spread these additional patients over the first blocks in an effort to reduce the waiting time while still having additional patients built in to the schedule in case a procedure finishes early or there is a no-show.

The third value in the scenario name, the End of Day Rule, indicates how patients are scheduled in the last two appointment slots of the day, according to the Table 5 descriptions. Ho and Lau's variable-interval rule calls for appointment intervals to increase towards the end of the day (1992). In an attempt to utilize the concept behind this rule of spreading the work out at the end of the day to catch up on backlogged patients, the number of patients scheduled during the last two blocks of the day is reduced, as indicated in Table 5. This is a simple modification since the patients are pooled for all of the doctors.

3.4 Performance Measures

Combining the sequencing and scheduling rules in Table 5, there are a total of 130 scenarios to be tested, including the current base case. The primary objective of these schedules is to maximize the number of procedures that can be performed in a day. The secondary objectives are to limit average overtime and average patient waiting times. The clinic defines the average waiting time as the time the patient spends in the waiting room prior to being taken to a prep bay, and that is the definition used in this paper. Since the acceptable thresholds for these parameters are undefined, we aim to minimize:

Equation 1:

$$\alpha x + \beta y$$

where x and y are average patient waiting time and average overtime, respectively, and α and β are their weights. Equation 1 will also be referred to as the objective or objective value throughout the paper.

4. Analysis

4.1 – Verification

Colonoscopy and endoscopy patients are represented by blue and orange entities, respectively, to aid in visual verification of the Simio simulation model. Every time a worker resource is seized, it moves to a specific node and parks there. Each of these busy nodes is unique to a certain step in the process. When the worker is released, it returns to and parks at its home node.

Data tables are used to create the arrival schedule and determine the procedure time for each patient. The arrival schedule specifies the number of each type of patient to arrive during each time slot through the use of properties. For verification, each property was given a different default value, and no-shows were set to zero. The procedure times were temporarily set to 30 and 60 minutes for colonoscopy and endoscopy patients, respectively. The animation of the simulation was monitored to ensure that the expected number of entities arrived at each appointment time. The simulation was stepped through to ensure that exactly the specified procedure time passed during the time the fellows were at the "Procedure Busy" node for both types of patients. The same process of setting delay times to exact values, and then stepping through, sometimes with breakpoints if animation could not be used for verification, was used for every delay step in the model processes.

To verify the routing of the no-show patients directly out of the system, the link weight was changed to 1. As expected, all patients left through the No-Show exit without entering the rest of the system. Similarly, once the no-show probability was reset, the probability of a patient leaving prematurely due to poor prep was set to 1, and all patients that arrived for their appointments exited through the incomplete exit.

Each resource, including both rooms and personnel, was limited to one to verify that the seize and release steps were working as expected, and that entities could not continue through the system until the required resource became available. Then the fellow resource was set to zero to confirm that the process routed to the independent doctor logic for the procedure, and no attending was sent to a busy node. The fellow was returned to 1 while the independent was set to zero to verify the fellow's logic as well. All resource capacities were then reset to their initial values, and their off-shift symbols were colored red. The simulation was run to completion and the animation was monitored to ensure that the appropriate number of each resource were colored red, indicating they were off-shift, at any point during the simulation, according to their respective work schedules.

Next, it had to be verified that patients continued to seize the same fellow or independent doctor they originally seized, since patients do not switch doctors during their time in the clinic. This was done by attaching a label to both entity types with entity state variable "Doctor" as the text. Immediately after seizing either a fellow or doctor for the first time, that entity's "Doctor" was updated with the name of the last resource seized. The model was then stepped through to verify that if it was a fellow who first saw the patient, prior to getting the attending's signoff on the procedure, the same fellow was then sent to a procedure specific node when the attending left the room. It was used again when patients were ready for discharge to check that the same fellow or independent doctor visited the node designated for discharging when the patient was done with recovery.

Finally, the stopping condition for the simulation was verified. Status labels were created for the number of entities that left through all three exits. As expected, once the sum of those three labels reached the number of entities scheduled for the day, the simulation stopped. Similarly, a status label was created for the time that the last patient left the procedure room for verification, and the label changed to the appropriate time when the last entity left.

4.2 – Validation

To validate the system, the 95 percent confidence intervals for three key parameters were found for both the real world system and the simulation model (Table 6). The first parameter used for comparison is the average time patients spent in the prep bay. This was defined as the elapsed time from when patients are picked up from the waiting room to when they arrive in the procedure room. All entities except for those that were deemed as no-shows were included in this average. The second parameter is the average time entities spent in the procedure room, which starts when the patient enters the procedure room and ends when the patients arrives in the recovery room. This average, as well as the one for the third parameter, did not include entities who were no-shows or left the system prematurely due to improper preparation. The time spent in the recovery bay was not included in validation since the only data available was that which the distribution was created from. This time, however, will be captured in the last validation parameter. The third and final comparison was made for the average time patients spent in the system. For the clinic timestamps, this was defined as the elapsed time from when a patient is picked up to when they are discharged. For the simulation, however, it is the elapsed time between the patient arriving and the patient exiting the system. The patient arrival times for the simulation were adjusted to represent the time the patients should be picked up from the waiting room since, for this study, we are not concerned with the time patients wait due to showing up unnecessarily early. Since the data that the distributions were created from was from days with different numbers of patients, sometimes significantly fewer than the baseline goal of 25, the validation was performed for three different validation scenarios:

1. The baseline schedule (Table 2)
2. The baseline schedule, less one CLN patient from each time slot
3. The baseline schedule, less two CLN patients from each time slot

Since the baseline schedule is the current goal for the Durham VA GI Clinic, there was no need to consider schedules with more patients than the baseline in the validation. The confidence intervals for these three scenarios in comparison to the confidence intervals from the data can be found in Tables 6, 7, and 8.

Table 6 – Validation of Baseline Schedule

	Durham VA GI Clinic		Simulation Model (Validation Scenario 1)	
95% CI (minutes)	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Average time in Prep Bay	26.6916	34.0487	27.4779	30.0903
Average Time in Procedure Room	49.1749	58.9138	50.7892	52.0558
Average Time in System	123.6336	143.4325	125.0167	130.3169

Table 7 – Validation of Baseline Schedule, Less One Patient in Each Block

	Durham VA GI Clinic		Simulation Model (Validation Scenario 2)	
95% CI (minutes)	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Average time in Prep Bay	26.6916	34.0487	24.5918	26.7236
Average Time in Procedure Room	49.1749	58.9138	49.7047	51.9175
Average Time in System	123.6336	143.4325	121.4182	126.6124

Table 8 – Validation of Baseline Schedule, Less Two Patients in Each Block

	Durham VA GI Clinic		Simulation Model (Validation Scenario 2)	
95% CI (minutes)	Lower Bound	Upper Bound	Lower Bound	Upper Bound
Average time in Prep Bay	26.6916	34.0487	24.4803	27.1303
Average Time in Procedure Room	49.1749	58.9138	47.3928	49.8626
Average Time in System	123.6336	143.4325	119.1322	123.7742

The timestamps from 63 patients were used to generate the confidence intervals for the Durham VA GI Clinic times. The simulation confidence intervals are from 50 runs of the simulation. Since the confidence intervals overlap for all of the parameters in all three scenarios, the times cannot be declared statistically different.

4.3 – Comparison of Models

4.3.1 – Analysis Methodology

To determine the schedule that maximizes the number of patients seen in a day while minimizing the weighted average of overtime and patient waiting time, 10 sets of scenarios were used for experimentation, each containing all of the scenarios for a given total number of patients, show in Table 9. In the experiments, α was the weight for the average patient waiting time in the objective value, and β was the weight for the average overtime.

Three experiments were run for each of the sets in Table 9:

Experiment 1: $\alpha = 0$ $\beta = 1$

Experiment 2: $\alpha = 0.5$ $\beta = 0.5$

Experiment 3: $\alpha = 1$ $\beta = 0$

Any weights could have been selected, but these were chosen for general analysis of the scheduling methods.

In these experiments, the Simio KN add-in was used in an attempt determine which scenario minimized Equation 1 for each set. The KN add-in uses the sequential procedure developed by Kim and Nelson to find the scenario with the minimum objective value. In the case of this project, each scenario, as defined in Table 5, corresponds to a schedule, or row from Table 9. Each column in table 9 indicates a separate experiment. The first row gives the name for the set of scenarios being used in the experiment, and the second row gives the number of patients scheduled in every scenario for that set. All rows after the second row indicate scenarios that have that number of patients. There are more scenarios that have 32 patients than any other number due to the nature of the scheduling methods.

Table 9 – Experimental Scenario Sets

Set Name:	Set 25	Set 28	Set 29	Set 30	Set 31	Set 32	Set 33	Set 34	Set 35	Set 36
Total Patients	25	28	29	30	31	32	33	34	35	36
	Current	A-1.5	A-1.4	A-1.3	A-1.2	A-1.1	A-2.4	A-2.3	A-2.2	A-2.1
		B-1.5	A-5.5	A-4.5	A-3.5	A-2.5	A-3.3	A-3.2	A-3.1	A-6.1
		C-1.5	B-1.4	A-5.4	A-4.4	A-3.4	A-4.2	A-4.1	A-6.2	B-2.1
		D-9	B-5.5	A-8.5	A-5.3	A-4.3	A-5.1	A-6.3	A-7.1	B-6.1
			C-1.4	B-1.3	A-7.5	A-5.2	A-6.4	A-7.2	B-2.2	C-2.1
			C-5.5	B-4.5	A-8.4	A-6.5	A-7.3	A-8.1	B-3.1	C-6.1
			D-8	B-5.4	B-1.2	A-7.4	A-8.2	B-2.3	B-6.2	D-1
				B-8.5	B-3.5	A-8.3	B-2.4	B-3.2	B-7.1	
				C-1.3	B-4.4	B-1.1	B-3.3	B-4.1	C-2.2	
				C-4.5	B-5.3	B-2.5	B-4.2	B-6.3	C-3.1	
				C-5.4	B-7.5	B-3.4	B-5.1	B-7.2	C-6.2	
				C-8.5	B-8.4	B-4.3	B-6.4	B-8.1	C-7.1	
				D-7	C-1.2	B-5.2	B-7.3	C-2.3	D-2	
					C-3.5	B-6.5	B-8.2	C-3.2		
					C-4.4	B-7.4	C-2.4	C-4.1		
					C-5.3	B-8.3	C-3.3	C-6.3		
					C-7.5	C-1.1	C-4.2	C-7.2		
					C-8.4	C-2.5	C-5.1	C-8.1		
					D-6	C-3.4	C-6.4	D-3		
						C-4.3	C-7.3			
						C-5.2	C-8.2			
						C-6.5	D-4			
						C-7.4				
						C-8.3				
						D-5				

When running the experiments, the user inputs a minimum number of replications allowed per scenario, a maximum number of replications allowed per scenario, a confidence level, and an indifference zone. The add-in then runs the minimum number of replications for each scenario, at which point any runs that can be determined at a 95% confidence level to have an objective value that is higher than the current best scenario or within the indifference zone. The add-in then continues to perform additional replications of the scenarios and eliminate additional scenarios once the above condition is true, until either one scenario is left or the maximum number of replications for each scenario has been reached. Once the KN add-in was used, analysis of the results showed that many reasonably good schedules, and sometimes the optimal schedule, were getting eliminated by the add-in. It proved difficult to determine which eliminated scenarios needed to be re-included, so a new approach was taken to find the scenarios with the lowest objective value for each set.

In the new approach, all scenarios were run for at least 25 replications. If any of the objective value means were 0 with a half-width of 0 at that point, all scenarios were then run for 100 replications. A scenario is determined to be statistically worse than another scenario if it has a confidence interval lower bound that is greater than the other scenario's confidence interval upper bound. All scenarios are compared to the scenario with the lowest confidence interval upper bound for the objective value. After the initial 25 or 100 replications, any scenarios that have a statistically worse objective value were removed. The number of replications for all of the remaining scenarios was then increased. This process continued until only one scenario remained, or each remaining scenario had been run for 500 replications. If the 500 replications had been reached, and all of the confidence intervals were smaller than 1 minute, all remaining scenarios were kept. If the confidence interval was larger than 1 minute, then additional replications were run on the remaining scenarios until they were eliminated by the above procedure or the confidence intervals were less than 1 minute in size. The purpose of these experiments is to determine the best scheduling methods for each set of α and β and determine if there is a pattern between optimal scenarios in different sets. The results and analysis of these experiments are discussed in Section 4.3.2. The results for the scenarios indicated by the pattern between optimal scenarios, regardless of the confidence interval, were then compared across the different sets. This was done to analyze the overtime and waiting time costs of adding additional patients, and is discussed in section 4.3.3.

4.3.2 – Analysis of Schedules

Table 10 highlights the scenarios that were selected as optimal for Experiment 1, when $\alpha = 0$ and $\beta = 1$. The numerical results can be found in Appendix H1. This first experiment models the case where only overtime is considered when evaluating schedules. Unsurprisingly, the single block scenarios (Scenario D_'s) are selected for nearly every set. For the first four sets, only single block scenarios are selected. As more patients are added to the schedule, the average overtime for the single block scenarios increases from zero, allowing other schedules to be more competitive. Once the mean overtime for the single blocks is statistically greater than zero, nearly all of the schedules following the B sequence, with EGD's scheduled at the end of the day, are included. The closest combination of these two scheduling methods, Sequencing B with Initial Block Rule 2 (Scenario B-2._), is selected in every set it is present in. These results indicate that when patient waiting time is not a factor that is considered, scheduling a single block with all patients arriving at the beginning of the day is optimal. In the more realistic case where overtime is the primary concern, but patient waiting time cannot be completely disregarded, EGD's should be scheduled for the end of the day, and twice the typical number of patients should be scheduled in the first block (Scenario B-2._).

Table 11 highlights the scenarios that were selected as optimal for Experiment 2, when $\alpha = 0.5$ and $\beta = 0.5$. The numerical results can be found in Appendix H2. This experiment models the case where overtime and patient waiting time are weighted equally when evaluating schedules. Similar to the sets with larger numbers of patients from Experiment 1, every scenario in Experiment 2 that was selected across all sets followed sequence B. Initial Block Rule 1 and End of Day Rule 1 were both selected everywhere they were present, both together and separate. This indicates that either one of the rules can be varied, but not both at the same time. To increase the number of patients from one patient per doctor per block, the Initial Blocks Rule should be changed. To reduce the number of patients, one of the End of Day Rules should be selected. Sequence B should be selected regardless of which block scheduling rules are selected.

Table 12 highlights the scenarios that were selected as optimal for Experiment 3, when $\alpha = 1$ and $\beta = 0$. The numerical results can be found in Appendix H3. This final experiment models the case where only patient waiting time is considered when evaluating schedules. All schedules that employ Initial Block Rule 1, for any sequence, are amongst best schedules in their respective sets for minimizing patient waiting time. Once the number of patients exceeds 32, other Initial Block Rules must be used to meet the additional demand. For all sets where the number of patients exceeds 32 the Sequence C schedule that uses the first end of day rule and the highest possible Initial Blocks Rule is one of the best solutions. This is expected since having shorter procedure times with less variability early in the day postpones the occurrence of a back-up in the system which is what leads to longer patient waiting times.

While the additional scenarios in Tables 10, 11, and 12 that were not mentioned above achieve the objective equally as well as the ones mentioned, the focus of this paper is to develop general scheduling rules, based on the clinic's weighted values for overtime and patient waiting time.

Table 10 – Experiment 1 Best Scenarios

Set Name:	Set 25	Set 28	Set 29	Set 30	Set 31	Set 32	Set 33	Set 34	Set 35	Set 36
Total Patients	25	28	29	30	31	32	33	34	35	36
	Current	A-1.5	A-1.4	A-1.3	A-1.2	A-1.1	A-2.4	A-2.3	A-2.2	A-2.1
		B-1.5	A-5.5	A-4.5	A-3.5	A-2.5	A-3.3	A-3.2	A-3.1	A-6.1
		C-1.5	B-1.4	A-5.4	A-4.4	A-3.4	A-4.2	A-4.1	A-6.2	B-2.1
		D-9	B-5.5	A-8.5	A-5.3	A-4.3	A-5.1	A-6.3	A-7.1	B-6.1
			C-1.4	B-1.3	A-7.5	A-5.2	A-6.4	A-7.2	B-2.2	C-2.1
			C-5.5	B-4.5	A-8.4	A-6.5	A-7.3	A-8.1	B-3.1	C-6.1
			D-8	B-5.4	B-1.2	A-7.4	A-8.2	B-2.3	B-6.2	D-1
				B-8.5	B-3.5	A-8.3	B-2.4	B-3.2	B-7.1	
				C-1.3	B-4.4	B-1.1	B-3.3	B-4.1	C-2.2	
				C-4.5	B-5.3	B-2.5	B-4.2	B-6.3	C-3.1	
				C-5.4	B-7.5	B-3.4	B-5.1	B-7.2	C-6.2	
				C-8.5	B-8.4	B-4.3	B-6.4	B-8.1	C-7.1	
				D-7	C-1.2	B-5.2	B-7.3	C-2.3	D-2	
					C-3.5	B-6.5	B-8.2	C-3.2		
					C-4.4	B-7.4	C-2.4	C-4.1		
					C-5.3	B-8.3	C-3.3	C-6.3		
					C-7.5	C-1.1	C-4.2	C-7.2		
					C-8.4	C-2.5	C-5.1	C-8.1		
					D-6	C-3.4	C-6.4	D-3		
						C-4.3	C-7.3			
						C-5.2	C-8.2			
						C-6.5	D-4			
						C-7.4				
						C-8.3				
						D-5				

Table 11 – Experiment 2 Best Scenarios

Set Name:	Set 25	Set 28	Set 29	Set 30	Set 31	Set 32	Set 33	Set 34	Set 35	Set 36
Total Patients	25	28	29	30	31	32	33	34	35	36
	Current	A-1.5	A-1.4	A-1.3	A-1.2	A-1.1	A-2.4	A-2.3	A-2.2	A-2.1
		B-1.5	A-5.5	A-4.5	A-3.5	A-2.5	A-3.3	A-3.2	A-3.1	A-6.1
		C-1.5	B-1.4	A-5.4	A-4.4	A-3.4	A-4.2	A-4.1	A-6.2	B-2.1
		D-9	B-5.5	A-8.5	A-5.3	A-4.3	A-5.1	A-6.3	A-7.1	B-6.1
			C-1.4	B-1.3	A-7.5	A-5.2	A-6.4	A-7.2	B-2.2	C-2.1
			C-5.5	B-4.5	A-8.4	A-6.5	A-7.3	A-8.1	B-3.1	C-6.1
			D-8	B-5.4	B-1.2	A-7.4	A-8.2	B-2.3	B-6.2	D-1
				B-8.5	B-3.5	A-8.3	B-2.4	B-3.2	B-7.1	
				C-1.3	B-4.4	B-1.1	B-3.3	B-4.1	C-2.2	
				C-4.5	B-5.3	B-2.5	B-4.2	B-6.3	C-3.1	
				C-5.4	B-7.5	B-3.4	B-5.1	B-7.2	C-6.2	
				C-8.5	B-8.4	B-4.3	B-6.4	B-8.1	C-7.1	
				D-7	C-1.2	B-5.2	B-7.3	C-2.3	D-2	
					C-3.5	B-6.5	B-8.2	C-3.2		
					C-4.4	B-7.4	C-2.4	C-4.1		
					C-5.3	B-8.3	C-3.3	C-6.3		
					C-7.5	C-1.1	C-4.2	C-7.2		
					C-8.4	C-2.5	C-5.1	C-8.1		
					D-6	C-3.4	C-6.4	D-3		
						C-4.3	C-7.3			
						C-5.2	C-8.2			
						C-6.5	D-4			
						C-7.4				
						C-8.3				
						D-5				

Table 12 – Experiment 3 Best Scenarios

Set Name:	Set 25	Set 28	Set 29	Set 30	Set 31	Set 32	Set 33	Set 34	Set 35	Set 36
Total Patients	25	28	29	30	31	32	33	34	35	36
	Current	A-1.5	A-1.4	A-1.3	A-1.2	A-1.1	A-2.4	A-2.3	A-2.2	A-2.1
		B-1.5	A-5.5	A-4.5	A-3.5	A-2.5	A-3.3	A-3.2	A-3.1	A-6.1
		C-1.5	B-1.4	A-5.4	A-4.4	A-3.4	A-4.2	A-4.1	A-6.2	B-2.1
		D-9	B-5.5	A-8.5	A-5.3	A-4.3	A-5.1	A-6.3	A-7.1	B-6.1
			C-1.4	B-1.3	A-7.5	A-5.2	A-6.4	A-7.2	B-2.2	C-2.1
			C-5.5	B-4.5	A-8.4	A-6.5	A-7.3	A-8.1	B-3.1	C-6.1
			D-8	B-5.4	B-1.2	A-7.4	A-8.2	B-2.3	B-6.2	D-1
				B-8.5	B-3.5	A-8.3	B-2.4	B-3.2	B-7.1	
				C-1.3	B-4.4	B-1.1	B-3.3	B-4.1	C-2.2	
				C-4.5	B-5.3	B-2.5	B-4.2	B-6.3	C-3.1	
				C-5.4	B-7.5	B-3.4	B-5.1	B-7.2	C-6.2	
				C-8.5	B-8.4	B-4.3	B-6.4	B-8.1	C-7.1	
				D-7	C-1.2	B-5.2	B-7.3	C-2.3	D-2	
					C-3.5	B-6.5	B-8.2	C-3.2		
					C-4.4	B-7.4	C-2.4	C-4.1		
					C-5.3	B-8.3	C-3.3	C-6.3		
					C-7.5	C-1.1	C-4.2	C-7.2		
					C-8.4	C-2.5	C-5.1	C-8.1		
					D-6	C-3.4	C-6.4	D-3		
						C-4.3	C-7.3			
						C-5.2	C-8.2			
						C-6.5	D-4			
						C-7.4				
						C-8.3				
						D-5				

4.3.3 – Key Findings

For each experiment, a single scenario was selected from each set using the scheduling rules proposed in Section 4.3.2. The scenarios and data for the reduced experiments can be found in Tables 13, 14, and 15. Figures 3, 4, and 5 were produced to show the percent increase additional patients cause on the objective value. Confidence intervals were not used in calculating the percent increase in the objective value, so the values shown are approximations. Since the model does not capture everything that happens in the system, percentage increase is a more accurate measurement than a direct increase in minutes would be.

Table 13 – Experiment 1 Incremental Analysis

Set #	Scenario	Number of Patients	Increase in Patients	Objective (minutes)	% Increase in Objective From 25 Patients
1	Current	25	0	0.2284	0.00
2	D9	28	3	0.0000	0.00
3	D8	29	4	0.0260	0.00
4	D7	30	5	0.0000	0.00
5	D6	31	6	0.5032	1.20
6	D5	32	7	0.9214	3.03
7	D4	33	8	1.8933	7.29
8	D3	34	9	4.6801	19.50
9	D2	35	10	8.5574	36.47
10	D1	36	11	13.4406	57.86

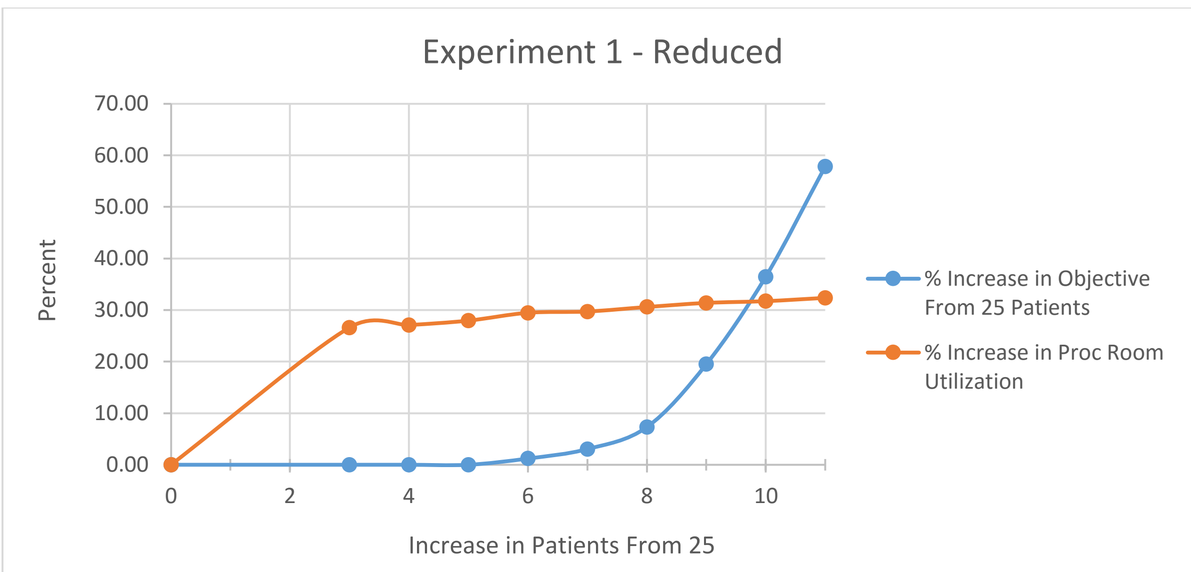

Figure 3– Experiment 1 Incremental Analysis

Table 14 – Experiment 2 Incremental Analysis

Set #	Scenario	Number of Patients	Increase in Patients	Objective (minutes)	% Increase in Objective From 25 Patients
1	Current	25	0	0.2284	0.00
2	B-1.5	28	3	0.7240	2.17
3	B-1.4	29	4	0.7113	2.11
4	B-1.3	30	5	0.6956	2.05
5	B-1.2	31	6	1.0822	3.74
6	B-1.1	32	7	2.0700	8.06
7	B-5.1	33	8	2.9818	12.06
8	B-4.1	34	9	4.8677	20.32
9	B-3.1	35	10	7.8613	33.43
10	B-2.1	36	11	12.0078	51.58

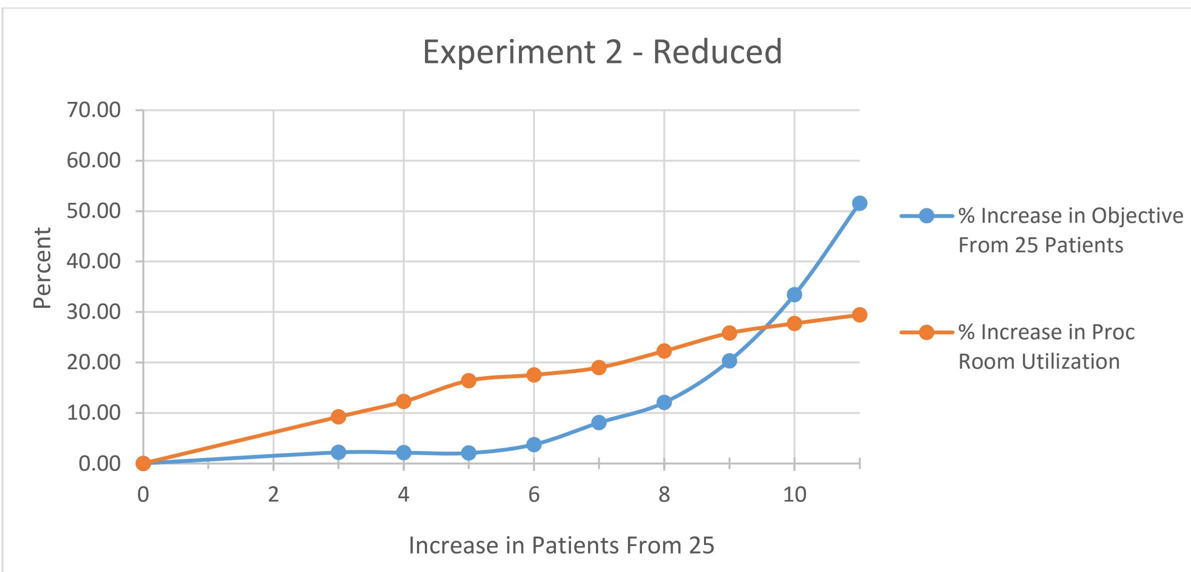

Figure 4 – Experiment 2 Incremental Analysis

Table 15 – Experiment 3 Incremental Analysis

Set #	Scenario	Number of Patients	Increase in Patients	Objective (minutes)	% Increase in Objective From 25 Patients
1	Current	25	0	0.2390	0.00
2	C-1.5	28	3	1.0703	3.48
3	C-1.4	29	4	1.0618	3.44
4	C-1.3	30	5	1.1260	3.71
5	C-1.2	31	6	1.1241	3.70
6	C-1.1	32	7	1.1698	3.89
7	C-5.1	33	8	1.9072	6.98
8	C-8.1	34	9	2.2899	8.58
9	C-7.1	35	10	3.5250	13.75
10	C-6.1	36	11	6.0549	24.33

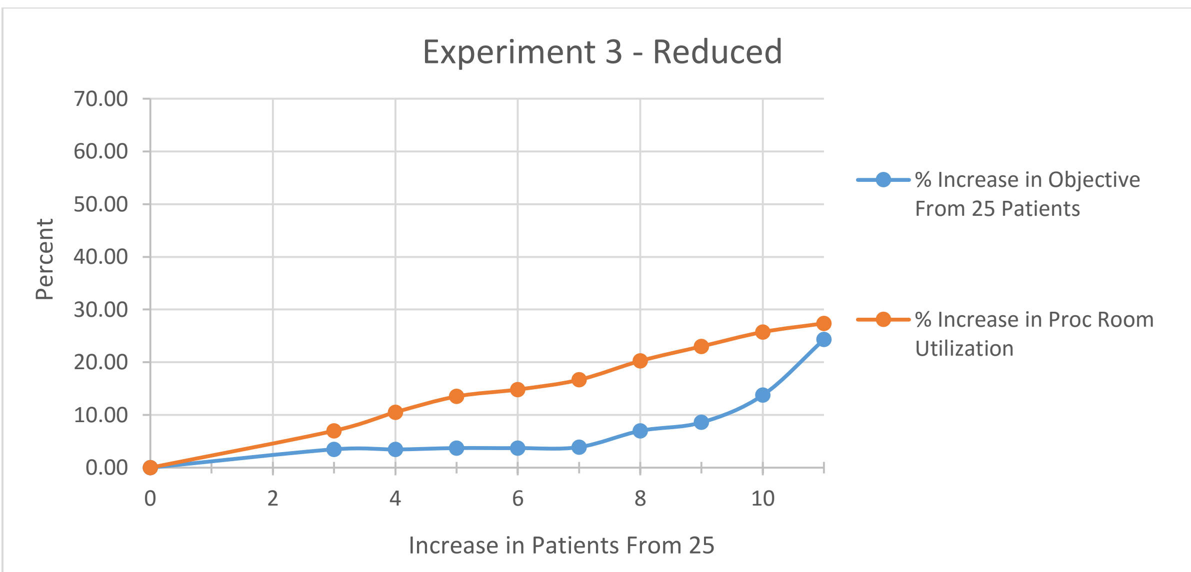

Figure 5 – Experiment 3 Incremental Analysis

These graphs are especially useful in determining how many patients the clinic should schedule in a day. If the clinic is willing to accept up to a 10 percent increase in their objective value, they should schedule 33 patients if using Experiment 1 weights and 32 patients if using Experiment 2 or Experiment 3 weight. If the clinic is willing to accept the necessary increase in the objective value to get to 28 patients, an increase of 3, it is recommended that the clinic increase to at least 30 patients given the objective value weights in Experiments 1 and 2. Likewise, it is recommended that the clinic not increase patients at all or increase to at least 32 patients given the objective value weights in Experiment 3, because there is effectively zero increase in the objective value once 28 patients are scheduled.

4.4 – Sensitivity Analysis

Sensitivity analysis was performed on Experiment 2, where overtime and patient waiting time are equally weighted since that appears to be the most reasonable of the three scenarios for the clinic. The prep time, recovery time, CLN procedure time, and EGD procedure time were created in Simio as input parameters. When a scenario is run, Simio generates response sensitivity data for those input parameters on each response variable, including a tornado chart. The tornado chart generated by Simio lists the input parameters in decreasing order of sensitivity, starting at the top. The shaded region in each row shows the sensitivity coefficient, which is the linear regression parameter for the parameter on the selected response. The tornado chart for Scenario B-1.4 with the objective value selected as the response when α = 0.5 and β = 0.5 is shown in Figure 6. The sensitivity coefficients for each scenario in Experiment 2 are listed in Table 16. As seen in the table, the CLN procedure time coefficient is the largest coefficient in all but one scenario, meaning it has the largest effect on the objective value. Since the model is highly sensitive to the CLN procedure time, if additional data is collected, that's what it should be for. Due to insufficient data to create a distribution on the EGD procedure time, aside from modeling a pert distribution from the estimated minimum, mode and max, it would be beneficial for additional data to be collected for procedure times for both types of patients.

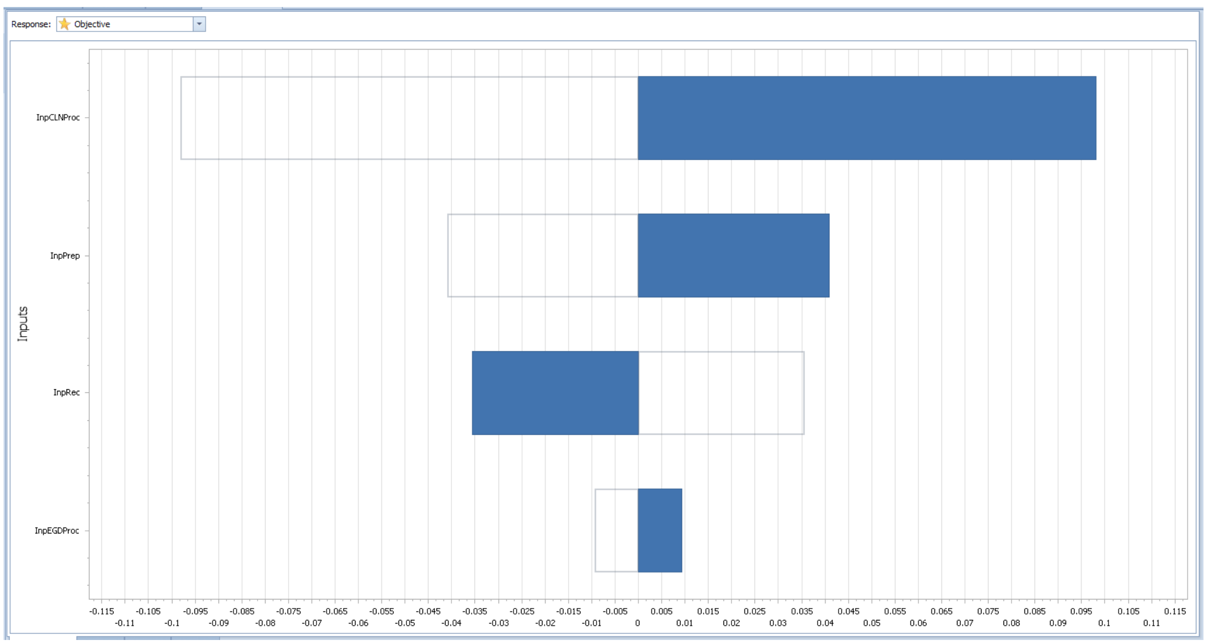

Figure 6 – B-1.5 Tornado Chart

Table 16 – Sensitivity Coefficients, Experiment 2

	Sensitivity Coefficients			
Scenario	CLN Procedure Time	Prep Time	EGD Procedure Time	Rec Time
Current	0.03	0.14	-0.011	0.011
B-1.5	0.032	0.073	0.032	0.036
B-1.4	0.098	0.041	0.009	-0.036
B-1.3	0.122	0.034	0.015	-0.044
B-1.2	0.195	0.084	0.05	-0.019
B-5.3	0.171	0.141	0.048	0.068
B-1.1	0.464	0.189	0.128	0.119
B-5.2	0.346	0.147	0.071	-0.124
B-8.3	0.332	0.152	0.071	0.19
B-4.2	0.513	0.156	0.189	0.202
B-5.1	0.645	0.324	0.214	0.122
B-8.2	0.502	0.304	0	0.22
B-4.1	0.92	0.314	0.266	-0.024
B-8.1	0.752	0.287	0.275	0.111
B-3.1	1.263	0.353	0.356	-0.029
B-7.1	1.346	0.227	0.262	-0.122
B-2.1	1.726	0.312	0	0.004
B-6.1	1.845	0.412	0	0.002

5. Conclusion

A base simulation model was created in Simio of the processes in the Durham VA GI Clinic. This simulation was used to model a base case day of 25 EGD and CLN patients. Three Sequencing methods, eight Initial Block Rules, and 5 End of Day rules were combined to make 120 scenarios (Table 5). Including the nine Single Block scenarios and the base case, there were a total of 130 scenarios. These scenarios were then run for three sets of α and β, weights of average patient waiting time and average overtime, respectively. The 130 scenarios were then run in the simulation using each set of α and β to determine which scenarios for a given number of daily patients minimized the weighted average of overtime at the clinic and patient waiting time. The optimal scenarios from the simulations were analyzed for patterns in scheduling methods, and from that analysis, the following recommendations emerged:

If $\alpha = 0$ and $\beta = 1$:

- Use a single block and have all patients arrive at the beginning of the block.
- If wait time is not completely disregarded, schedule with Sequence B and Initial Blocks Rule 2.

If $\alpha = 0.5$ and $\beta = 0.5$:

- Use Sequence B and either Initial Blocks Rule 1 or End of Day Rule 1, whichever allows for the proper number of patients.

If $\alpha = 1$ and $\beta = 0$:

- Use Sequence C and Initial Blocks Rule 1, if possible for the selected number of patients, or End of Day Rule 1 combined with the highest possible Initial Blocks Rule.

Analysis was performed on the percent increase in the objective value for each increase in the total number of patients. This analysis can be used to determine how many patients should be scheduled in the clinic each day, and indicates that the clinic should see at least five to seven more patients each day or more depending on the clinic's tolerance for increases in overtime and patient waiting time.

6. Future Work

This thesis modeled and created scheduling rules for the Tuesday operations, when only EGD and CLN patients are scheduled, and no anesthesiologist is required. Adding additional patient types and additional resources such as anesthesiologists are opportunities for future work on this topic. Additionally, the model could be broken down in to more detail to capture the specific activities that happen during prep and during the procedure. After the model was completed, a large set of additional data was received for procedure times for different patients. This data could be used to enhance the distributions used in this model as well as create new ones for other types of patients.

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APPENDICES

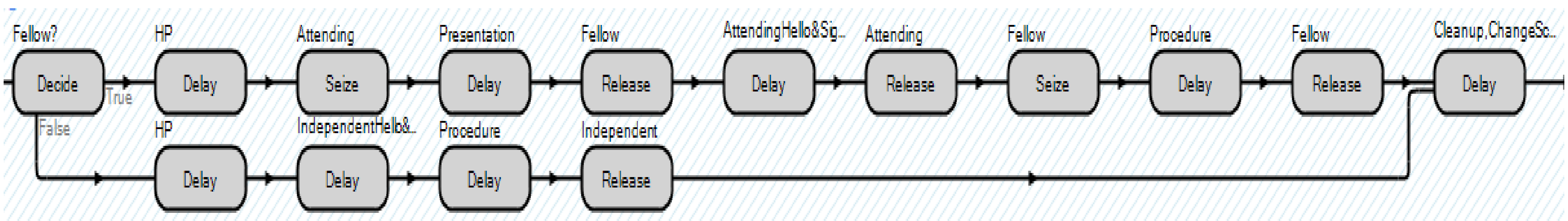
Appendix A1 – Resource List and Schedule Names

Resource Name	**Schedule**
Procedure Rooms	4 Available All Day
Bays – prep or recovery	5 Available All Day
Bays – recovery only	9 Available All Day
Attendings	2 Available from 8AM – End of Day
Fellows	3 Available from 7:45AM – End of Day
Independent Doctors	1 Available from 8AM – End of Day
Nurses	Nurse Schedule (Appendix A2)

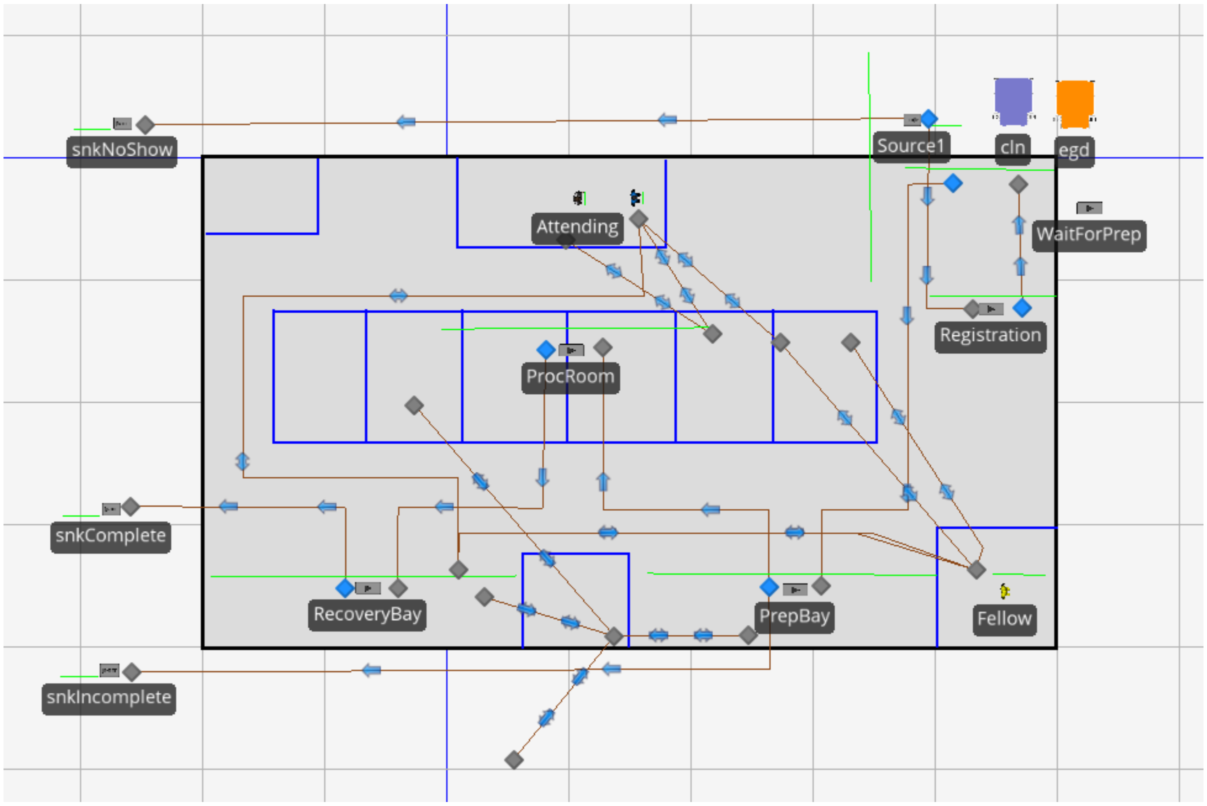
Appendix A2 – Nurse Schedule

Start Time	End Time	Number of Nurses Available
7:30 AM	8:00 AM	4
8:00 AM	11:00 AM	12
11:00 AM	1:00 PM	9
1:00 PM	4:30 PM	12
4:30 PM	6:00 PM	4

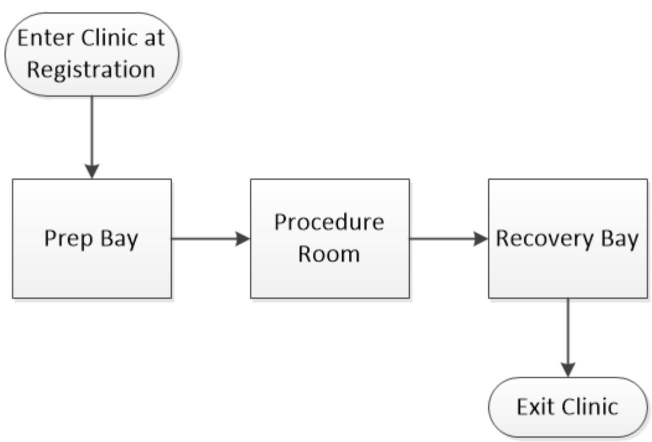
Appendix B – Fellow vs. Independent Doctor Process



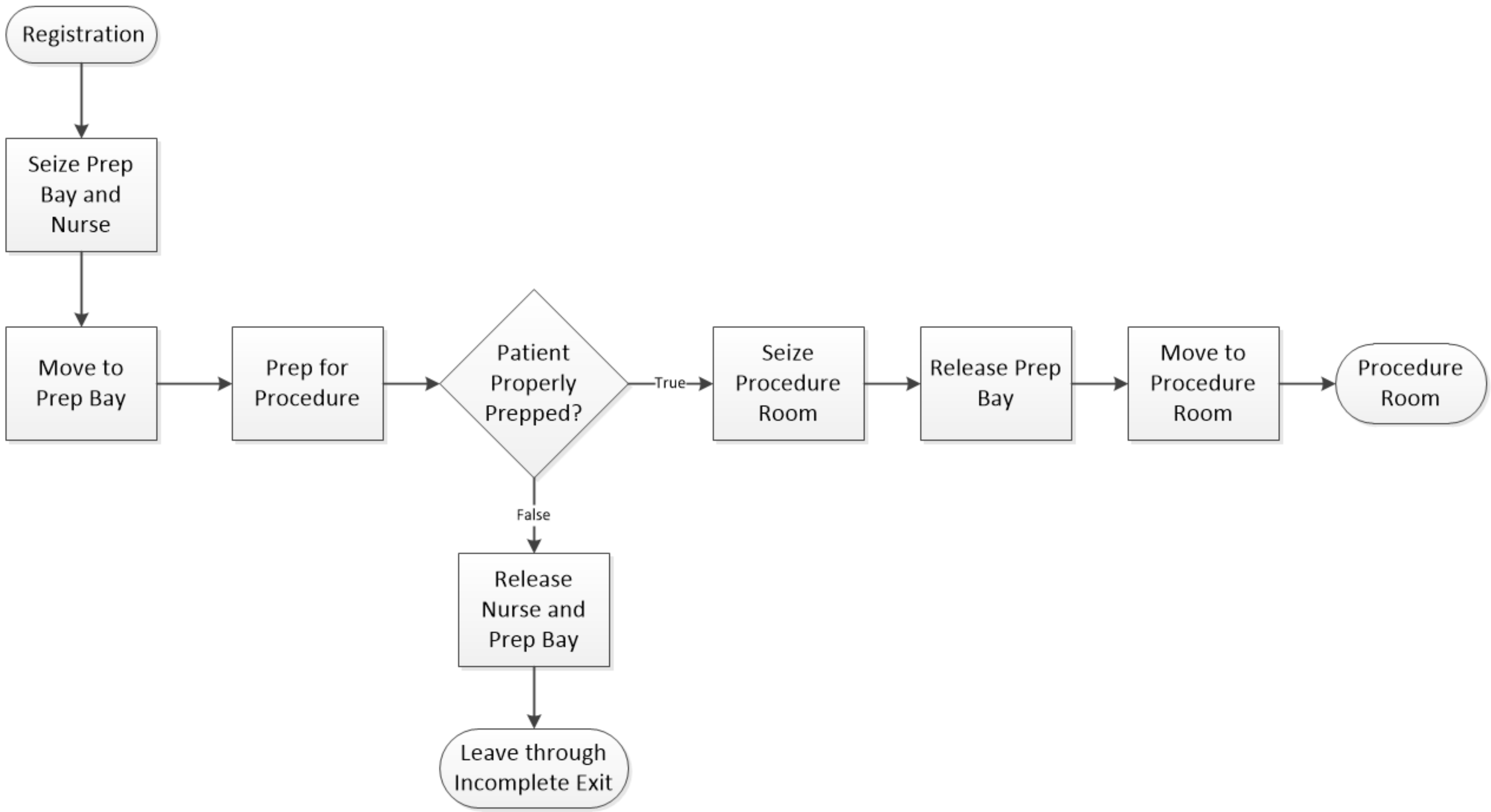
Appendix C – Facility View of Clinic Simulation



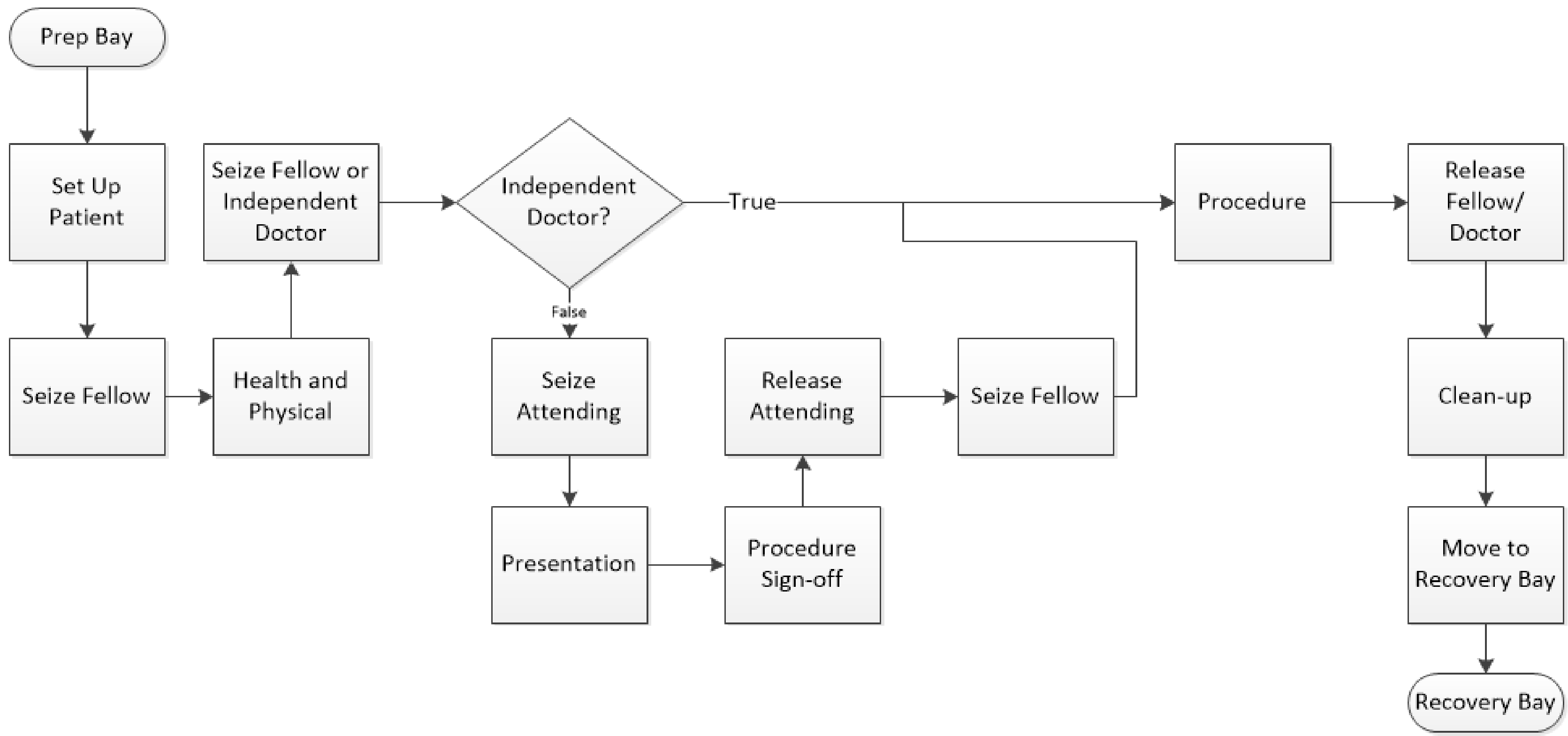
Appendix D1 – Basic Clinic Flow



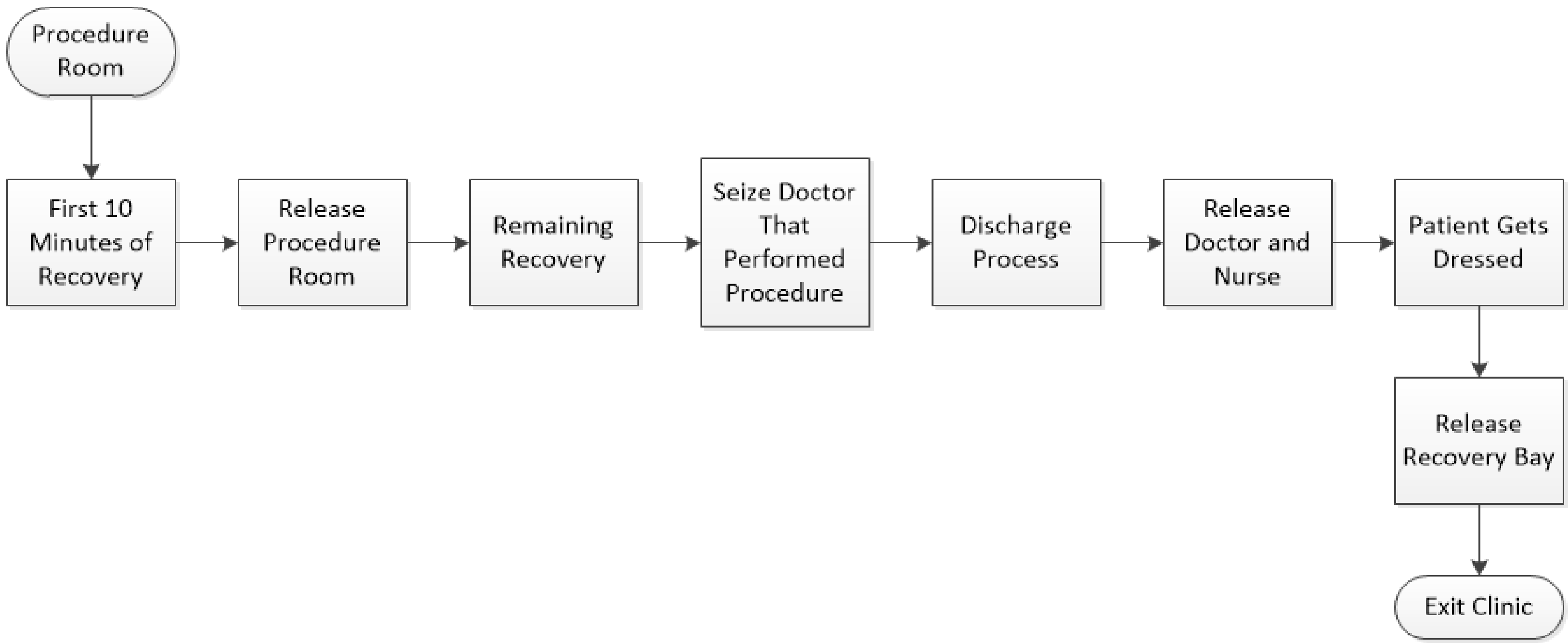
Appendix D2 – Prep Bay Flow



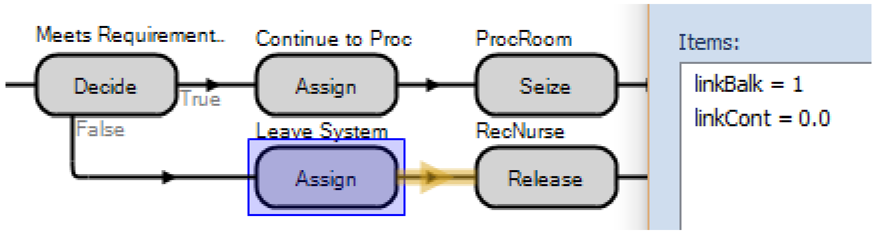
Appendix D3 – Procedure Room Flow



Appendix D4 – Recovery Bay Flow



Appendix E – Incomplete Patients Leave System Process



Appendix F – Arena Distribution Formats

Distribution Name	Arena Format
Gamma	GAMM(Beta, Alpha)
Exponential	EXPO(Mean)
Weibull	WEIB(Beta, Alpha)

Appendix G1 – Current Patient Schedule

Scenario	Patient Type	7:30 AM	8:30 AM	9:30 AM	10:30 AM	12:00 PM	1:00 PM	2:00 PM	Total
Current	CLN	3	3	3	3	2	2	3	**25**
	EGD	1	1	1	1	1	1	0	

Appendix G2 – Experimental Patient Schedules

Scenario	Patient Type	7:30 AM	8:30 AM	9:30 AM	10:30 AM	11:30 AM	12:30 PM	1:30 PM	2:30 PM	Total
A-1.1	CLN	3	3	3	3	3	3	4	4	**32**
	EGD	1	1	1	1	1	1	0	0	
A-1.2	CLN	3	3	3	3	3	3	4	3	**31**
	EGD	1	1	1	1	1	1	0	0	
A-1.3	CLN	3	3	3	3	3	3	4	2	**30**
	EGD	1	1	1	1	1	1	0	0	
A-1.4	CLN	3	3	3	3	3	3	3	2	**29**
	EGD	1	1	1	1	1	1	0	0	
A-1.5	CLN	3	3	3	3	3	3	2	2	**28**
	EGD	1	1	1	1	1	1	0	0	
A-2.1	CLN	7	3	3	3	3	3	4	4	**36**
	EGD	1	1	1	1	1	1	0	0	
A-2.2	CLN	7	3	3	3	3	3	4	3	**35**
	EGD	1	1	1	1	1	1	0	0	
A-2.3	CLN	7	3	3	3	3	3	4	2	**34**
	EGD	1	1	1	1	1	1	0	0	
A-2.4	CLN	7	3	3	3	3	3	3	2	**33**
	EGD	1	1	1	1	1	1	0	0	
A-2.5	CLN	7	3	3	3	3	3	2	2	**32**
	EGD	1	1	1	1	1	1	0	0	
A-3.1	CLN	6	3	3	3	3	3	4	4	**35**
	EGD	1	1	1	1	1	1	0	0	
A-3.2	CLN	6	3	3	3	3	3	4	3	**34**
	EGD	1	1	1	1	1	1	0	0	
A-3.3	CLN	6	3	3	3	3	3	4	2	**33**
	EGD	1	1	1	1	1	1	0	0	
A-3.4	CLN	6	3	3	3	3	3	3	2	**32**
	EGD	1	1	1	1	1	1	0	0	

Appendix G2 (cont)

Scenario	Patient Type	7:30 AM	8:30 AM	9:30 AM	10:30 AM	11:30 AM	12:30 PM	1:30 PM	2:30 PM	Total
A-3.5	CLN	6	3	3	3	3	3	2	2	**31**
	EGD	1	1	1	1	1	1	0	0	
A-4.1	CLN	5	3	3	3	3	3	4	4	**34**
	EGD	1	1	1	1	1	1	0	0	
A-4.2	CLN	5	3	3	3	3	3	4	3	**33**
	EGD	1	1	1	1	1	1	0	0	
A-4.3	CLN	5	3	3	3	3	3	4	2	**32**
	EGD	1	1	1	1	1	1	0	0	
A-4.4	CLN	5	3	3	3	3	3	3	2	**31**
	EGD	1	1	1	1	1	1	0	0	
A-4.5	CLN	5	3	3	3	3	3	2	2	**30**
	EGD	1	1	1	1	1	1	0	0	
A-5.1	CLN	4	3	3	3	3	3	4	4	**33**
	EGD	1	1	1	1	1	1	0	0	
A-5.2	CLN	4	3	3	3	3	3	4	3	**32**
	EGD	1	1	1	1	1	1	0	0	
A-5.3	CLN	4	3	3	3	3	3	4	2	**31**
	EGD	1	1	1	1	1	1	0	0	
A-5.4	CLN	4	3	3	3	3	3	3	2	**30**
	EGD	1	1	1	1	1	1	0	0	
A-5.5	CLN	4	3	3	3	3	3	2	2	**29**
	EGD	1	1	1	1	1	1	0	0	
A-6.1	CLN	4	4	4	4	3	3	4	4	**36**
	EGD	1	1	1	1	1	1	0	0	
A-6.2	CLN	4	4	4	4	3	3	4	3	**35**
	EGD	1	1	1	1	1	1	0	0	
A-6.3	CLN	4	4	4	4	3	3	4	2	**34**
	EGD	1	1	1	1	1	1	0	0	
A-6.4	CLN	4	4	4	4	3	3	3	2	**33**
	EGD	1	1	1	1	1	1	0	0	
A-6.5	CLN	4	4	4	4	3	3	2	2	**32**
	EGD	1	1	1	1	1	1	0	0	
A-7.1	CLN	4	4	4	3	3	3	4	4	**35**
	EGD	1	1	1	1	1	1	0	0	

Appendix G2 (cont)

Scenario	Patient Type	7:30 AM	8:30 AM	9:30 AM	10:30 AM	11:30 AM	12:30 PM	1:30 PM	2:30 PM	Total
A-7.2	CLN	4	4	4	3	3	3	4	3	**34**
	EGD	1	1	1	1	1	1	0	0	
A-7.3	CLN	4	4	4	3	3	3	4	2	**33**
	EGD	1	1	1	1	1	1	0	0	
A-7.4	CLN	4	4	4	3	3	3	3	2	**32**
	EGD	1	1	1	1	1	1	0	0	
A-7.5	CLN	4	4	4	3	3	3	2	2	**31**
	EGD	1	1	1	1	1	1	0	0	
A-8.1	CLN	4	4	3	3	3	3	4	4	**34**
	EGD	1	1	1	1	1	1	0	0	
A-8.2	CLN	4	4	3	3	3	3	4	3	**33**
	EGD	1	1	1	1	1	1	0	0	
A-8.3	CLN	4	4	3	3	3	3	4	2	**32**
	EGD	1	1	1	1	1	1	0	0	
A-8.4	CLN	4	4	3	3	3	3	3	2	**31**
	EGD	1	1	1	1	1	1	0	0	
A-8.5	CLN	4	4	3	3	3	3	2	2	**30**
	EGD	1	1	1	1	1	1	0	0	
B-1.1	CLN	4	4	4	4	4	4	2	0	**32**
	EGD	0	0	0	0	0	0	2	4	
B-1.2	CLN	4	4	4	4	4	4	1	0	**31**
	EGD	0	0	0	0	0	0	3	3	
B-1.3	CLN	4	4	4	4	4	4	0	0	**30**
	EGD	0	0	0	0	0	0	4	2	
B-1.4	CLN	4	4	4	4	4	3	0	0	**29**
	EGD	0	0	0	0	0	1	3	2	
B-1.5	CLN	4	4	4	4	4	2	0	0	**28**
	EGD	0	0	0	0	0	2	2	2	
B-2.1	CLN	8	4	4	4	4	4	2	0	**36**
	EGD	0	0	0	0	0	0	2	4	
B-2.2	CLN	8	4	4	4	4	4	1	0	**35**
	EGD	0	0	0	0	0	0	3	3	
B-2.3	CLN	8	4	4	4	4	4	0	0	**34**
	EGD	0	0	0	0	0	0	4	2	

Appendix G2 (cont)

Scenario	Patient Type	7:30 AM	8:30 AM	9:30 AM	10:30 AM	11:30 AM	12:30 PM	1:30 PM	2:30 PM	Total
B-2.4	CLN	8	4	4	4	4	3	0	0	**33**
	EGD	0	0	0	0	0	1	3	2	
B-2.5	CLN	8	4	4	4	4	2	0	0	**32**
	EGD	0	0	0	0	0	2	2	2	
B-3.1	CLN	7	4	4	4	4	4	2	0	**35**
	EGD	0	0	0	0	0	0	2	4	
B-3.2	CLN	7	4	4	4	4	4	1	0	**34**
	EGD	0	0	0	0	0	0	3	3	
B-3.3	CLN	7	4	4	4	4	4	0	0	**33**
	EGD	0	0	0	0	0	0	4	2	
B-3.4	CLN	7	4	4	4	4	3	0	0	**32**
	EGD	0	0	0	0	0	1	3	2	
B-3.5	CLN	7	4	4	4	4	2	0	0	**31**
	EGD	0	0	0	0	0	2	2	2	
B-4.1	CLN	6	4	4	4	4	4	2	0	**34**
	EGD	0	0	0	0	0	0	2	4	
B-4.2	CLN	6	4	4	4	4	4	1	0	**33**
	EGD	0	0	0	0	0	0	3	3	
B-4.3	CLN	6	4	4	4	4	4	0	0	**32**
	EGD	0	0	0	0	0	0	4	2	
B-4.4	CLN	6	4	4	4	4	3	0	0	**31**
	EGD	0	0	0	0	0	1	3	2	
B-4.5	CLN	6	4	4	4	4	2	0	0	**30**
	EGD	0	0	0	0	0	2	2	2	
B-5.1	CLN	5	4	4	4	4	4	2	0	**33**
	EGD	0	0	0	0	0	0	2	4	
B-5.2	CLN	5	4	4	4	4	4	1	0	**32**
	EGD	0	0	0	0	0	0	3	3	
B-5.3	CLN	5	4	4	4	4	4	0	0	**31**
	EGD	0	0	0	0	0	0	4	2	
B-5.4	CLN	5	4	4	4	4	3	0	0	**30**
	EGD	0	0	0	0	0	1	3	2	
B-5.5	CLN	5	4	4	4	4	2	0	0	**29**
	EGD	0	0	0	0	0	2	2	2	

Appendix G2 (cont)

Scenario	Patient Type	7:30 AM	8:30 AM	9:30 AM	10:30 AM	11:30 AM	12:30 PM	1:30 PM	2:30 PM	Total
B-6.1	CLN	5	5	5	5	4	4	2	0	**36**
	EGD	0	0	0	0	0	0	2	4	
B-6.2	CLN	5	5	5	5	4	4	1	0	**35**
	EGD	0	0	0	0	0	0	3	3	
B-6.3	CLN	5	5	5	5	4	4	0	0	**34**
	EGD	0	0	0	0	0	0	4	2	
B-6.4	CLN	5	5	5	5	4	3	0	0	**33**
	EGD	0	0	0	0	0	1	3	2	
B-6.5	CLN	5	5	5	5	4	2	0	0	**32**
	EGD	0	0	0	0	0	2	2	2	
B-7.1	CLN	5	5	5	4	4	4	2	0	**35**
	EGD	0	0	0	0	0	0	2	4	
B-7.2	CLN	5	5	5	4	4	4	1	0	**34**
	EGD	0	0	0	0	0	0	3	3	
B-7.3	CLN	5	5	5	4	4	4	0	0	**33**
	EGD	0	0	0	0	0	0	4	2	
B-7.4	CLN	5	5	5	4	4	3	0	0	**32**
	EGD	0	0	0	0	0	1	3	2	
B-7.5	CLN	5	5	5	4	4	2	0	0	**31**
	EGD	0	0	0	0	0	2	2	2	
B-8.1	CLN	5	5	4	4	4	4	2	0	**34**
	EGD	0	0	0	0	0	0	2	4	
B-8.2	CLN	5	5	4	4	4	4	1	0	**33**
	EGD	0	0	0	0	0	0	3	3	
B-8.3	CLN	5	5	4	4	4	4	0	0	**32**
	EGD	0	0	0	0	0	0	4	2	
B-8.4	CLN	5	5	4	4	4	3	0	0	**31**
	EGD	0	0	0	0	0	1	3	2	
B-8.5	CLN	5	5	4	4	4	2	0	0	**30**
	EGD	0	0	0	0	0	2	2	2	
C-1.1	CLN	0	2	4	4	4	4	4	4	**32**
	EGD	4	2	0	0	0	0	0	0	
C-1.2	CLN	0	2	4	4	4	4	4	3	**31**
	EGD	4	2	0	0	0	0	0	0	

Appendix G2 (cont)

Scenario	Patient Type	7:30 AM	8:30 AM	9:30 AM	10:30 AM	11:30 AM	12:30 PM	1:30 PM	2:30 PM	Total
C-1.3	CLN	0	2	4	4	4	4	4	2	**30**
	EGD	4	2	0	0	0	0	0	0	
C-1.4	CLN	0	2	4	4	4	4	3	2	**29**
	EGD	4	2	0	0	0	0	0	0	
C-1.5	CLN	0	2	4	4	4	4	2	2	**28**
	EGD	4	2	0	0	0	0	0	0	
C-2.1	CLN	2	4	4	4	4	4	4	4	**36**
	EGD	6	0	0	0	0	0	0	0	
C-2.2	CLN	2	4	4	4	4	4	4	3	**35**
	EGD	6	0	0	0	0	0	0	0	
C-2.3	CLN	2	4	4	4	4	4	4	2	**34**
	EGD	6	0	0	0	0	0	0	0	
C-2.4	CLN	2	4	4	4	4	4	3	2	**33**
	EGD	6	0	0	0	0	0	0	0	
C-2.5	CLN	2	4	4	4	4	4	2	2	**32**
	EGD	6	0	0	0	0	0	0	0	
C-3.1	CLN	1	4	4	4	4	4	4	4	**35**
	EGD	6	0	0	0	0	0	0	0	
C-3.2	CLN	1	4	4	4	4	4	4	3	**34**
	EGD	6	0	0	0	0	0	0	0	
C-3.3	CLN	1	4	4	4	4	4	4	2	**33**
	EGD	6	0	0	0	0	0	0	0	
C-3.4	CLN	1	4	4	4	4	4	3	2	**32**
	EGD	6	0	0	0	0	0	0	0	
C-3.5	CLN	1	4	4	4	4	4	2	2	**31**
	EGD	6	0	0	0	0	0	0	0	
C-4.1	CLN	0	4	4	4	4	4	4	4	**34**
	EGD	6	0	0	0	0	0	0	0	
C-4.2	CLN	0	4	4	4	4	4	4	3	**33**
	EGD	6	0	0	0	0	0	0	0	
C-4.3	CLN	0	4	4	4	4	4	4	2	**32**
	EGD	6	0	0	0	0	0	0	0	
C-4.4	CLN	0	4	4	4	4	4	3	2	**31**
	EGD	6	0	0	0	0	0	0	0	

Appendix G2 (cont)

Scenario	Patient Type	7:30 AM	8:30 AM	9:30 AM	10:30 AM	11:30 AM	12:30 PM	1:30 PM	2:30 PM	Total
C-4.5	CLN	0	4	4	4	4	4	2	2	**30**
	EGD	6	0	0	0	0	0	0	0	
C-5.1	CLN	0	3	4	4	4	4	4	4	**33**
	EGD	5	1	0	0	0	0	0	0	
C-5.2	CLN	0	3	4	4	4	4	4	3	**32**
	EGD	5	1	0	0	0	0	0	0	
C-5.3	CLN	0	3	4	4	4	4	4	2	**31**
	EGD	5	1	0	0	0	0	0	0	
C-5.4	CLN	0	3	4	4	4	4	3	2	**30**
	EGD	5	1	0	0	0	0	0	0	
C-5.5	CLN	0	3	4	4	4	4	2	2	**29**
	EGD	5	1	0	0	0	0	0	0	
C-6.1	CLN	0	4	5	5	4	4	4	4	**36**
	EGD	5	1	0	0	0	0	0	0	
C-6.2	CLN	0	4	5	5	4	4	4	3	**35**
	EGD	5	1	0	0	0	0	0	0	
C-6.3	CLN	0	4	5	5	4	4	4	2	**34**
	EGD	5	1	0	0	0	0	0	0	
C-6.4	CLN	0	4	5	5	4	4	3	2	**33**
	EGD	5	1	0	0	0	0	0	0	
C-6.5	CLN	0	4	5	5	4	4	2	2	**32**
	EGD	5	1	0	0	0	0	0	0	
C-7.1	CLN	0	4	5	4	4	4	4	4	**35**
	EGD	5	1	0	0	0	0	0	0	
C-7.2	CLN	0	4	5	4	4	4	4	3	**34**
	EGD	5	1	0	0	0	0	0	0	
C-7.3	CLN	0	4	5	4	4	4	4	2	**33**
	EGD	5	1	0	0	0	0	0	0	
C-7.4	CLN	0	4	5	4	4	4	3	2	**32**
	EGD	5	1	0	0	0	0	0	0	
C-7.5	CLN	0	4	5	4	4	4	2	2	**31**
	EGD	5	1	0	0	0	0	0	0	
C-8.1	CLN	0	4	4	4	4	4	4	4	**34**
	EGD	5	1	0	0	0	0	0	0	

Appendix G2 (cont)

Scenario	Patient Type	7:30 AM	8:30 AM	9:30 AM	10:30 AM	11:30 AM	12:30 PM	1:30 PM	2:30 PM	Total
C-8.2	CLN	0	4	4	4	4	4	4	3	**33**
	EGD	5	1	0	0	0	0	0	0	
C-8.3	CLN	0	4	4	4	4	4	4	2	**32**
	EGD	5	1	0	0	0	0	0	0	
C-8.4	CLN	0	4	4	4	4	4	3	2	**31**
	EGD	5	1	0	0	0	0	0	0	
C-8.5	CLN	0	4	4	4	4	4	2	2	**30**
	EGD	5	1	0	0	0	0	0	0	
D-1	CLN	30								**36**
	EGD	6								
D-2	CLN	29								**35**
	EGD	6								
D-3	CLN	28								**34**
	EGD	6								
D-4	CLN	27								**33**
	EGD	6								
D-5	CLN	26								**32**
	EGD	6								
D-6	CLN	25								**31**
	EGD	6								
D-7	CLN	24								**30**
	EGD	6								
D-8	CLN	23								**29**
	EGD	6								
D-9	CLN	22								**28**
	EGD	6								

Appendix H1 – Experiment 1 Best Scenario Results

Set #	Scenario	Objective (minutes)		Overtime (minutes)		Waiting Time (minutes)		Proc Room Utilization (%)	
		Mean	HW	Mean	HW	Mean	HW	Mean	HW
1	Current	0.2284	0.2027	0.2284	0.2027	0.2390	0.0161	63.9295	0.5034
2	D9	0.0000	0.0000	0.0000	0.0000	125.5425	1.6289	80.9356	0.2904
3	D8	0.0260	0.0509	0.0260	0.0509	132.5725	1.6091	81.2480	0.3131
4	D7	0.0000	0.0000	0.0000	0.0000	138.8943	5.5803	81.7964	1.1253
5	B-1.2	1.0341	0.3695	1.0341	0.3695	1.1302	0.1323	75.1380	0.4990
	B-3.5	0.7454	0.3529	0.7454	0.3529	6.8524	0.4594	76.6029	0.5631
	B-4.4	0.8366	0.3842	0.8366	0.3842	4.0366	0.2817	76.6273	0.5306
	B-5.3	0.6199	0.2975	0.6199	0.2975	2.1273	0.1569	76.2779	0.5143
	B-7.5	0.4174	0.2827	0.4174	0.2827	5.0129	0.4171	77.1902	0.5531
	B-8.4	0.4793	0.2359	0.4793	0.2359	3.1437	0.2744	76.7343	0.5444
	D6	0.5032	0.3520	0.5032	0.3520	148.0397	1.6715	82.7673	0.2794
6	B-2.5	1.4993	0.4324	1.4993	0.4324	10.9506	0.4828	78.1640	0.4054
	B-3.4	1.2845	0.3703	1.2845	0.3703	6.8056	0.3310	78.4927	0.3738
	B-4.3	1.0059	0.4055	1.0059	0.4055	4.1376	0.3029	78.3752	0.4980
	B-5.2	1.2207	0.3130	1.2207	0.3130	2.0740	0.1138	77.2836	0.3466
	B-6.5	1.0771	0.3274	1.0771	0.3274	7.1183	0.3772	78.3621	0.3875
	B-7.4	1.0854	0.3333	1.0854	0.3333	4.9326	0.2924	78.6299	0.3700
	B-8.3	1.0737	0.3434	1.0737	0.3434	3.0939	0.1955	78.1417	0.3525
	D5	0.9214	0.3262	0.9214	0.3262	152.8871	1.2127	82.9246	0.2007
7	B-2.4	2.3904	0.4588	2.3904	0.4588	10.9832	0.4185	79.9075	0.3013
	B-3.3	2.1822	0.4400	2.1822	0.4400	6.9609	0.3075	80.1135	0.3053
	B-4.2	2.4484	0.4339	2.4484	0.4339	4.0231	0.1840	79.4283	0.2966
	B-6.4	2.1874	0.4198	2.1874	0.4198	7.2713	0.3504	79.8141	0.3104
	B-7.3	2.2062	0.4236	2.2062	0.4236	5.1506	0.2707	79.9040	0.3029
	B-8.2	2.1550	0.4047	2.1550	0.4047	3.0736	0.1761	79.1540	0.2967
	D4	1.8933	0.4853	1.8933	0.4853	159.0024	1.2538	83.4830	0.1883
8	B-2.3	4.0924	0.4488	4.0924	0.4488	11.1045	0.3191	81.2238	0.2052
	B-3.2	4.6824	0.4672	4.6824	0.4672	6.9635	0.2222	80.9439	0.2056
	B-6.3	4.6327	0.4648	4.6327	0.4648	7.6671	0.2663	81.2189	0.1995
	B-7.2	4.7273	0.4620	4.7273	0.4620	5.1523	0.1987	80.9155	0.1989
	D3	4.6801	0.4874	4.6801	0.4874	167.1147	0.8010	83.9899	0.1181
9	B-2.2	7.5747	0.4692	7.5747	0.4692	11.0206	0.2372	82.1347	0.1406
10	B-2.1	13.0181	0.4926	13.0181	0.4926	11.1343	0.1971	82.7710	0.1069

	D1	13.4406	0.4928	13.4406	0.4928	410.7867	0.9672	84.6143	0.0634

Appendix H2 – Experiment 2 Best Scenario Results

Set #	Scenario	Objective (minutes)		Overtime (minutes)		Waiting Time (minutes)		Proc Room Utilization (%)	
		Mean	HW	Mean	HW	Mean	HW	Mean	HW
1	Current	0.2284	0.2027	0.2284	0.2027	0.2390	0.0161	63.9295	0.5034
2	B-1.5	0.7240	0.1446	0.3647	0.2569	1.0832	0.1179	69.8303	0.5491
3	B-1.4	0.7113	0.1645	0.3445	0.2764	1.0781	0.1223	71.7575	0.5256
4	B-1.3	0.6956	0.3724	0.3092	0.2762	1.0819	0.1932	74.4177	0.9561
5	B-1.2	1.0822	0.2211	1.0341	0.3695	1.1302	0.1323	75.1380	0.4990
	B-5.3	1.3736	0.1760	0.6199	0.2975	2.1273	0.1569	76.2779	0.5143
6	B-1.1	2.0700	0.4251	2.9494	0.7636	1.1906	0.1424	76.0695	0.4618
	B-5.2	1.6981	0.2728	1.2857	0.4819	2.1105	0.1578	77.2016	0.4890
	B-8.3	2.2178	0.3322	1.1309	0.4911	3.3046	0.3040	78.4080	0.5152
7	B-4.2	3.3258	0.4478	2.5633	0.7144	4.0883	0.3047	79.2012	0.4649
	B-5.1	2.9818	0.4962	3.7855	0.9107	2.1781	0.1669	78.1625	0.4760
	B-8.2	2.7219	0.4366	2.1467	0.6576	3.2972	0.3095	79.4308	0.4634
8	B-4.1	4.8677	0.4610	5.5998	0.7780	4.1356	0.2159	80.4346	0.3108
	B-8.1	4.0030	0.4071	4.8386	0.6881	3.1675	0.2044	80.1014	0.3116
9	B-3.1	7.8613	0.4991	8.6868	0.7957	7.0358	0.2700	81.6594	0.2265
	B-7.1	7.1886	0.4779	8.9878	0.7766	5.3895	0.2484	81.4865	0.2249
10	b-2.1	12.0078	0.4921	12.8264	0.7505	11.1893	0.3027	82.7343	0.1631
	b-6.1	11.5101	0.4905	14.8871	0.7792	8.1332	0.2561	82.6775	0.1542

Appendix H3 – Experiment 3 Best Scenario Results

Set #	Scenario	Objective (minutes)		Overtime (minutes)		Waiting Time (minutes)		Proc Room Utilization (%)	
		Mean	HW	Mean	HW	Mean	HW	Mean	HW
1	Current	0.2390	0.0161	0.2284	0.2027	0.2390	0.0161	63.9295	0.5034
2	A-1.5	0.9629	0.0912	1.7644	0.7718	0.9629	0.0912	68.5928	0.5326
	B-1.5	1.0832	0.1179	0.3647	0.2569	1.0832	0.1179	69.8303	0.5491
	C-1.5	1.0703	0.1086	1.1989	0.5175	1.0703	0.1086	68.4006	0.5181
3	A-1.4	0.9542	0.0910	1.3752	0.5348	0.9542	0.0910	70.8142	0.5004
	B-1.4	1.0781	0.1223	0.3445	0.2764	1.0781	0.1223	71.7575	0.5256
	C-1.4	1.0618	0.1092	1.6105	0.6388	1.0618	0.1092	70.6532	0.5036
4	A-1.3	0.9835	0.0944	2.8343	0.8556	0.9835	0.0944	73.0073	0.4945
	B-1.3	1.1373	0.1339	0.2638	0.1939	1.1373	0.1339	74.1045	0.5135
	C-1.3	1.1260	0.1224	2.2175	0.6615	1.1260	0.1224	72.5670	0.4971
5	A-1.2	0.9752	0.0940	2.9968	0.7834	0.9752	0.0940	74.1320	0.4857
	B-1.2	1.1302	0.1323	1.0341	0.3695	1.1302	0.1323	75.1380	0.4990
	C-1.2	1.1241	0.1253	4.6472	1.0623	1.1241	0.1253	73.4060	0.4708
6	A-1.1	1.0202	0.0988	7.5906	1.2007	1.0202	0.0988	75.1558	0.4492
	B-1.1	1.1906	0.1424	2.9494	0.7636	1.1906	0.1424	76.0695	0.4618
	C-1.1	1.1698	0.1308	8.0130	1.2337	1.1698	0.1308	74.5840	0.4412
7	A-5.1	1.8794	0.0875	8.4048	0.8074	1.8794	0.0875	77.2806	0.2698
	C-5.1	1.9072	0.0847	8.8276	0.8139	1.9072	0.0847	76.8772	0.2620
8	A-8.1	2.8640	0.3340	11.8988	2.5424	2.8640	0.3340	78.9108	0.6363
	C-8.1	2.2899	0.2548	9.9980	2.0369	2.2899	0.2548	78.6404	0.6655
9	c-7.1	3.5250	0.6186	10.6850	3.5005	3.5250	0.6186	80.3818	0.9230
10	c-6.1	6.0549	0.4800	19.6670	2.2239	6.0549	0.4800	81.4362	0.3988