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Report Final Project

Re-Design of the Pre-Anesthetic Evaluation Clinic at Leiden University Medical Center

M.E. Zonderland
S0006645
April - November 2007

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LUMC
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Summary

Like many other hospitals, Leiden University Medical Center organizes preoperative screening for elective surgery patients in an outpatient clinic. The screening process involves a visit to the secretary, nurse and anesthesiologist. Patients either have an appointment or arrive on walk-in basis. Appointments originate partly from patients sent away previously by the secretary because it is too busy for instant evaluation, and partly from patients that need further preparation prior to their visit to the anesthesiologist. This preparation consists mainly of acquiring patient information from other doctors and/or hospitals. After the patient's visit a significant amount of back-office activities has to be performed by staff. Prolonged patient waiting times and increasing workload for staff call for an improvement in the design of the clinic.

By using a multi-class open queuing network model, critical factors influencing patient waiting time and staff workload are identified. Among these critical factors are the scheduling of appointments during periods of high walk-in arrivals, conflicting tasks to be performed by the secretary and ill preparation of appointment patients. Uncertainty about the medical condition of the patient results in long consultation times at the anesthesiologists. Furthermore patients can only be approved for surgery by the anesthesiologist if all test results are available. Since testing for appointment patients is carried out during the appointment and not during the first visit, test results become available a few days after the appointment, resulting in a list of patients to be approved. These patients have to be approved by another anesthesiologist than the one who performs the consultation. This causes irritation among the anesthesiologists since they consider it very undesirable to (dis)approve a patient they did not see themselves.

Mid-2007 a new working routine resulting from this analysis was introduced at the clinic. The new working routine comes down to scheduling appointment patients during periods of low walk-in demand, and the nurse dismissing patients after she evaluated them, instead of the secretary sending patients away prior to any evaluation. If necessary, the nurse takes blood samples from the patient and decides if other measures should be taken prior to surgery. These test results are available when the appointment takes place, and therefore the anesthesiologist can immediately decide if the patient can undergo surgery.

Patients are dismissed by the nurse if there are four or more patients already waiting for the anesthesiologist. A queuing model is used to enable a trade-off between patient waiting time for the anesthesiologist and the number of patients dismissed per hour by the nurses. Unfortunately the results of the model are inconclusive, so the current boundary of four patients is maintained. Subsequently a simulation study is performed to provide guidelines for the opening hours of the clinic. The current practice of the one hour closing for lunch results in long waiting times and discomfort for patients arriving around the lunch break. Various configurations for lunch are tested with the simulation model. An alternative set-up for lunch based on the outcomes of the simulation study, namely no closing and staff members having lunch in shifts based on profession, has been implemented recently. Preliminary experiences with the new routine, appointment system, and opening hours are very positive.

Abbreviations and Terminology

ASA Score A six category physical status classification system for assessing a patient before surgery, established in 1963 by the American Society of Anesthesiologists (ASA) [2], [4]. See also Appendix A.

Co-morbidity The presence of one or more disorders (or diseases) in addition to a primary disease or disorder [13].

ECG An electrocardiogram (ECG) is a graphic produced by an electrocardiograph, which records the electrical activity of the heart over time [17].

GPL The 'Grafische Patiënten Lijst' (GPL) is a feature in *PDMS* which allows the hospital to track the movement of patients during their visit at the *PAC*.

LOS The length of stay (LOS) is a term commonly used to measure the duration of a single episode of hospitalization [35].

LUMC Leiden University Medical Center. The hospital in which the *PAC*, the topic of this research study, is situated.

Nurse Practitioner A nurse practitioner is a registered nurse who has completed advanced nursing education (generally a master's degree) and training in the diagnosis and management of common medical conditions, including chronic illnesses [39].

PAC Pre-Anesthetic Evaluation Clinic. The PAC in the *LUMC* is the topic of this research study.

PDMS The 'Patiënt Data Management Systeem' (PDMS) is the electronic medical record of the patient.

Phlebotomy Incision into or needle puncture of a vein for the purpose of drawing blood [42].

Plaster-check clinic A facility were patients go for follow-up visits after a previous visit to the accident and emergency department.

Resident Physician A licensed medical school graduate doing further training in one of the specialties of medicine.

Senior Physician A licensed medical school graduate who has completed his training in one of the specialties of medicine.

Triage In the clinic, the word triage is used to describe a quick scan of the patient's physical condition in order to estimate the time needed for treatment. This is not the true meaning of triage, which is defined as a system used by medical or emergency personnel to ration limited medical resources when the number of injured needing care exceeds the resources available to perform care so as to treat those patients in most need of treatment who are able to benefit first [57].

ZIS The 'Ziekenhuis Informatie Systeem' (ZIS) allows the LUMC to electronically maintain all information known about the patient, define treatment costs and make appointments.

List of Symbols

Symbol	Definition
a_r	fraction patients in class r that get an appointment
D_{n_3}	probability that a patient arriving at station 3 joins the queue if there are n_3 patients present at station 3
e_i	effective capacity of station i
$E(L)$	mean number of patients present in the system
$E(L_i)$	mean number of patients present at station i
$E(L_{Q,i})$	mean number of patients in the queue at station i
$E(S_i)$	mean average service time at station i
$E(S_{r,i})$	mean service time for patients of class r at station i
$E(V_r)$	mean length of stay at the PAC for patients of class r
$E(W_{Q,i})$	mean waiting time at station i
$E(W_{Q,i(M/M/c)})$	mean waiting time for the $M/M/c$ queue at station i
f_3^*	fraction of patients that in equilibrium decides not to join queue 3
γ	arrival rate at station 1 originating from the Poisson process
G_i	normalization constant for station i
λ_i	aggregated arrival rate at station i
N	total number of patients
n_r	number of patients of class r
n_d	number of patients dismissed by nurses per hour
$P_{i,j}$	routing probability of aggregated flow from station i to station j
$Q_{i,j}$	portion of arrival flow into station j originating from station i
$Q_{r,1}$	portion of arrival flow into station 1 originating from arrival flow patient class r
ρ_i	aggregated occupation rate per server at station i
$\rho_{i,r}$	occupation rate patients class r per server at station i
s_i	number of servers at station i
$SCV_{A,i}$	squared coefficient of variance arrivals at station i
$SCV_{A,r,1}$	squared coefficient of variance arrivals patients class r at station 1
$SCV_{D,i}$	squared coefficient of variance departure process at station i
$SCV_{i,j}$	squared coefficient of variance of aggregated flow from station i to station j
$SCV_{S,i}$	squared coefficient of variance service time at station i
$SCV_{S,r,i}$	squared coefficient of variance service time patients class r at station i
$SD(S_{r,i})$	standard deviation of service time patients class r at station i
ζ_r	arrival rate of patients of class r

Preface

The main goal of the project described in the proceeding chapters of this report is to improve the design of the Pre-Anesthetic Evaluation Clinic at Leiden University Medical Center. For me, finishing this project is the last step involved in obtaining a Master's Degree in Applied Mathematics. The last seven months provided me with very positive experiences. I enjoyed my activities a lot and moreover I got the opportunity to guide the remodeling of a small part of the hospital. Therefore I would like to thank Fred Boer and Martie van Beuzekom for enabling me to carry out this project. Their willingness to discuss and ultimately implement my suggestions, and their positive attitude and enthusiasm were of great help.

I would like to thank Richard Boucherie for his useful comments, honesty, flexibility regarding our meetings and interest in my project. I would like to thank Jan-Kees van Ommeren and Erwin Hans for reviewing my report, and Erwin Hans for bringing me in contact with Fred Boer. Special thanks go to Bertjan Kobus and Amy Poulino for reading my report, and to Anna Schakel for being talkative during the hard hours of the day. Also I would like to thank clinic staff for their cooperation.

And last but not least, I would like to thank my parents for supporting me in pursuing a second study and for liking (almost) everything that I do.

Maartje Zonderland
Leiden, November 2007

Contents

1 Introduction

This chapter provides background information about pre-anesthetic evaluation and the Leiden University Medical Center. The problem definition, split up in the objective for the research and the research question is given. Finally the methodology followed is described.

1.1 Background

Like many other hospitals, Leiden University Medical Center (LUMC) organizes the pre-anesthetic evaluation of patients scheduled for elective surgery in an outpatient clinic. This screening process involves multiple staff members and a great amount of back office activities. Long waiting times for patients and a high workload for staff, demand for an improvement in the design of the Pre-Anesthetic Evaluation Clinic (PAC) at the LUMC.

1.1.1 Pre-Anesthetic Evaluation

Patients scheduled for an elective surgery are evaluated at the PAC by an anesthesiologist. Supported by the secretary and the nurses, the anesthesiologist tries to obtain a thorough understanding of the physical condition of the patient. To decrease the risk of surgery for the patient as much as possible, additional measures to improve the patient's physical condition are proposed by the anesthesiologist, and also the surgical procedure and the anesthesia are discussed. Ultimately it is the anesthesiologist who decides if the patient can undergo the surgery, and not the referring surgeon. Typically, the part of the evaluation in which the patient is physically present at the PAC takes about 40 to 45 minutes, waiting times excluded. The back office activities involved with the screening process are very time consuming. If an instant evaluation of the patient is not possible, he is given an appointment and sent home. These appointments take place in the near future, and unlike as in some other hospitals, the PAC does not have a waiting list.

1.1.2 Leiden University Medical Center

In 1996, the Faculty of Medicine of the University of Leiden and the Academic Hospital in Leiden merged into one organization: the Leiden University Medical Center, which is one of the eight university medical centers in the Netherlands. In the remarkable building next to the main train station of the ancient city of Leiden, over more than 7000 professionals work together to accomplish the five core tasks of the LUMC [38]:

- Patient care: routine care, high-level clinical care and in particular high-level reference care
- Research: both fundamental and bedside, health care oriented research
- Education for the faculties of Medicine and Biomedical Sciences
- Specialist medical training
- Additional training, both post-doctoral and post-vocational

1.2 Problem Definition

As mentioned in the previous paragraph, a re-design of the PAC should be developed. The research conducted to propose a re-design is guided by the research question stated next.

1.2.1 Research Question

What causes the current waiting times for patients and the workload for staff at the PAC? Is it possible to decrease waiting times for patients and workload for staff by altering the design of the PAC?

1.2.2 Method

To identify critical factors influencing patient waiting time and staff workload, the PAC is represented with a multi-class Open Queuing Network model. After identification of the critical factors, five alternatives with measures to improve performance are proposed. Mid-2007 one of these alternatives was chosen by clinic staff to be implemented, resulting in a more balanced experienced workload. Subsequently two other models are developed. The first model is a queuing model which is used to enable a trade-off between patient waiting time for the anesthesiologist and the number of patients sent away daily. The model is inconclusive and therefore the current boundary is maintained. The second model is a simulation model, which is used to compare various configurations for the lunch break. The simulation study is motivated by the set-up of the lunch break, which results in high workload for staff and long patient waiting time around lunch. An alternative set-up for lunch based on the outcomes of the simulation study has been implemented October 2007.

1.3 Outline

The research executed to improve the design of the PAC is summarized in the proceeding chapters of this report and organized as follows. In Chapter 2 a summary of the literature studied is given. The routines at the PAC are described in Chapter 3. With the insights provided by the investigation of the routines, an approximation model of the current design at the PAC is developed in Chapter 4 to enable bottleneck analysis and to get an insight in the performance. Data recorded from patient visits is used for calibration. This process is outlined in Chapter 5. In Chapter 6 the results for the approximation model are given, together with five possible alternative designs. At the end of this chapter one of these alternative designs is chosen to be implemented at the PAC. In Chapter 7 a new model is defined which enables a trade-off between the waiting time for patients at the anesthesiologist and the number of patients dismissed per hour by the nurses. The results for this model are given in Chapter 8. In Chapter 9 the set-up of the simulation study performed to investigate the effects of the lunch break in the new design is described. In this chapter four possible configurations for lunch are presented. In the proceeding Chapter 10 the simulation outcomes for the new design are compared with the outcomes for the new design combined with one of the lunch configurations. At the end of this chapter one of the configurations for lunch is chosen for implementation. The report finishes with conclusions and recommendations in Chapter 11, followed by the reference list and appendices.

2 Literature Study

This chapter discusses the literature studied for this project. The first paragraph covers the topic of pre-anesthetic evaluation clinics to provide a basic understanding of the subject. The second paragraph reviews articles in which concepts from stochastic operations research are applied to outpatient clinics.

2.1 Pre-Anesthesia Evaluation Clinics

The concept of the Pre-Anesthesia Evaluation Clinic is first described by Lee in 1949 [33]. The author states that the purpose of the clinic is “to examine and treat the patient, so that he will arrive in the operating theater as strong and as healthy as possible”. The main advantage of opening a PAC is the improvement in the preparation of the patient for surgery. The anesthesiologist evaluates the patient in an earlier stage and therefore is able to adjust the patient’s condition if necessary. He can also reassure the patient about the surgery and discuss the previous anesthetic history. Lee finishes article with: “by making themselves competent to run such a department efficiently, anesthesiologists would have a further contribution to make to the recovery and rehabilitation of the surgical patient”. Loder and Richardson discuss a PAC founded in 1950 at Petersborough Memorial Hospital in Northans, United Kingdom [36]. The article is of general nature and describes the patient types present at the clinic, their medical condition, the routines at the clinic and the advantages and disadvantages of opening such a clinic. The only disadvantage mentioned in this article regards patients needing a re-evaluation because they were on the waiting list for surgery and their condition might have deteriorated in the meantime.

It is only since the 1990s that PACs are mentioned more often in literature, except for [22]. In this article Frost reports about her experiences with a PAC in the Bronx Municipal Hospital Center which started in 1972. The author states that the reasons for founding a PAC are decreasing the length of stay for patients in the hospital and decreasing the costs involving patient care. Experiences with the clinic at this hospital are positive, patients have the opportunity to discuss their anesthesia with the anesthesiologist, and preparation of surgical patients has improved resulting in a lower surgery cancellation rate.

The most important reasons to start a PAC, identified by Lew, Pavlin, and Amundsen [34], are: decreasing the expectation of death during surgery, increase quality and decrease costs of preoperative care, and enable the patient to function on a desirable level again as soon as possible. Pollard [43] states that the cost reduction is achieved partly by decreasing the number of preoperative tests performed on a patient. Excessive testing can result in patient injury and delay. The cost reduction also results from a decrease in the length of stay for patients.

Pre-Anesthetic Evaluation is defined by the American Society of Anesthesiologists as “the process of clinical assessment that precedes the delivery of anesthesia care for surgery and for nonsurgical procedures” and should at least include (1) review of medical records, (2) a patient interview, (3) a directed pre-anesthetic examination, (4) preoperative tests when indicated, and (5) other consultations when appropriate [3]. The moment of evaluation at the clinic takes place from thirty to two [34], or even one day [21] prior to surgery. Holt et al. discuss in [26] the results of a survey executed at a congress among anesthesiologists. The study shows that PACs are common in the medical institutions of the respondents (69% of respondents works at an institution which has a PAC). Further research regarding PACs is needed to further increase the advantage of preoperative evaluation, since there are still delays on the day of surgery caused by a lack of information about the condition of the patient. This problem is also encountered by Gibby and Schwab [23]: “for many patients, optimal medical understanding was not achieved during the planned pre-anesthetic evaluation”.

Next to [22] and [36] there are various articles available describing the implementation of and/or experiences with a PAC. Barra Bisinotto et al. [5] outline the implementation of a PAC in a university hospital in Brazil. The authors depict the advantages of a PAC, the set-up of the new clinic and the results of the implementation. The implementation was experienced as difficult, because sending patients to the PAC is not routine yet in the hospital. A couple of surgeons even refuse to send patients to the clinic. Sometimes surgeons decide which patients should be referred to the PAC ([5], [36], [14], [21]). In other cases all patients that have to undergo an operation are referred ([22], [31], [48]). Conway, Goldberg and Chung [14] describe the implementation of a PAC in the Toronto Hospital in Toronto, Ontario, Canada. In [21] Fischer discusses the implementation and effectiveness of a PAC in Stanford Medical Center in California, the United States. The main interest of the article are the financial aspects of such a clinic.

Klei et al. [31] discuss the effect of preoperative evaluation in the University Hospital in Utrecht on three outcome measures: (1) surgeries canceled for medical reasons, (2) the number of patients that can be admitted the same day[1], and (3) the length of stay in the hospital. Although implementing the PAC resulted in improvement in all three outcomes, the degree of improvement was less than expected. The authors recognize that once the clinic is part of the regular practice pattern in the hospital, further improvement will come into being. Rutten, Post, and Smelt [48] report about the introduction of a PAC in 1992 in hospital de Weezenlanden, Zwolle, the Netherlands. The authors conclude that since the implementation of the PAC, anesthetic care has improved and less routine testing is performed. The length of hospital stay has also decreased. The re-design of the preoperative evaluation process in the Cleveland Clinic in Cleveland, Ohio, the United States, is outlined by Parker et al. in [41]. Before the re-design all patients were extensively screened, but due to capacity restrictions this is not possible anymore. Since the re-design computer terminals are used to perform a first triage. Patients with low health risk and non-invasive surgical procedures are evaluated on the day of surgery by an anesthesiologist. The remaining patients visit the PAC, and in this clinic only preoperative evaluation is executed, optimizing patients for surgery is done in another clinic. The re-design resulted in cost reduction and a shorter length of stay for those patients evaluated in the clinic. These results reflect the importance of triage.

[1] Because of the existence of the PAC, patients scheduled for minor surgery can be admitted immediately after evaluation instead one day prior to surgery because the anesthesiologist still has to evaluate them.

2.2 Stochastic Operations Research applied to Outpatient Clinics

Except for [15], no articles have been found in this literature study that apply concepts from stochastic operations research to pre-anesthesia evaluation clinics in particular. However, there are numerous articles available that apply these concepts to outpatient clinics[2]. Since the PAC is a kind of outpatient clinic, these articles can be very useful.

As early as in 1952, both Bailey [7] and Welch [59] report that long waiting times for patients are a common phenomenon in outpatient clinics. According to articles published recently, not much has changed the last fifty years (see for example [16] and [15]). Decreasing the waiting time for patients and on the other hand decreasing the idle time for health care providers is a trade-off that is often mentioned in literature ([27], [30], [20], [6], [10]). In an attempt to reduce patient waiting times, much effort is dedicated to controlling the arrival process of patients to the clinic. Usually this is done by introducing an appointment system, sometimes combined with the possibility for patients to walk in. It is certainly not always allowed for patients to walk in. In the survey made by Cayirli and Veral [11], which is solely dedicated to appointment scheduling in outpatient services, only five out of eighty studies mention walk-in patients. Table 1 gives an overview of the articles reviewed for this literature study regarding controlling the arrival process of patients.

Author(s)	**Reference**	**Walk-ins considered**
Babes & Sarma	[6]	yes
Bailey	[7]	no
Welch	[59]	no
Brahimi & Worthington	[10]	no
Fetter & Thompson	[20]	yes
Dexter	[15]	yes
Vissers	[58]	yes
Jennings	[27]	no
Cayirli, Veral, & Rosen	[12]	yes
Harper & Gamlin	[24]	no
Reilly, Vijay, & Fries	[45]	yes
Klassen & Rohleder	[30]	no
O'Keefe	[40]	no
Rising, Baron, & Averill	[46]	yes

Table 1: Articles reviewed with respect to controlling the arrival process of patients

Babes and Sarma [6] report on an outpatient clinic in the developing country of Algeria. In this clinic some patients were untreated even after numerous visits. An appointment system was introduced by management to ensure that all patients receive treatment, and to reduce waiting times for patients. The simulation model described in the article is used to determine the number of appointments and the number of doctors to be scheduled each day. Bailey is one of the first authors writing about queues and appointment systems in outpatient departments [7]. In 1954 Bailey publishes a second article about queuing theory applied to health care problems [8]. The problems studied in this article are (1) the number of hospital

[2] Also known as ambulatory care facilities.

beds needed on wards, (2) the length and frequency of clinic sessions, needed to deal with the demand for outpatient care, and (3) suitable appointment systems for outpatient clinic sessions. Also in 1952, Welch [59] identifies two main factors that influence the design of appointment systems: (1) the punctuality of staff and patients, and (2) consultation time. Queuing theory is used to give practical recommendations for designing appointment systems.

Brahimi and Worthington [10] use a queuing model which allows for analysis of transient behavior of a system [9] to design an appointment system for a *plaster-check clinic*. In the queuing model of the plaster-check clinic the arrival process is the appointment system, there is one server which represents the doctor, and the service time distribution is fitted with sample data. Comparing various alternative appointment schedules to the current appointment system resulted in the implementation of a new appointment system. In [20] a simulation model of an outpatient department is outlined by Fetter and Thompson which is superficially described earlier in [19]. The authors identify seven factors that influence the relationship among the patients' waiting time and the doctors' idle time: (1) appointment interval, (2) consultation time, (3) patient arrival pattern, (4) number of no shows, (5) number of walk-in patients, (6) physician arrival pattern, and (7) interruptions in patient consultations. With the simulation model the influence of each factor on the idle time and waiting time can be considered separately. A part of the article is dedicated to 'the problem of walk-ins' which is, according to Fetter and Thompson, "often considered the reverse side of the now-show problem". The authors point out the importance of considering walk-in patients as a separate entity, and state that the unpunctuality in arrivals of appointment patients (often because they are too early) combined with the existence of walk-in patients, results in two separate arrival processes at the clinic which are in essence both random. In this article the existence of walk-in patients is considered as a characteristic of the clinic, and no judgment about this characteristic is pronounced. This is opposite to what Dexter states in [15]: "this review article is clinically relevant to anesthesiologists working in pre-anesthesia evaluation clinics without appointments, because the best service that such anesthesiologists can provide to their patients will be worse than that considered in this article". Dexter does not take into account the extra visit to the hospital involved with an appointment. In his article three factors are identified that can increase patient waiting time: (1) lack of patient punctuality for appointment patients, in which coming too early is also considered as a lack of punctuality, (2) provider tardiness, in which the provider starts the clinic session too late, and (3) the presence of walk-in patients. The definition of a walk-in patient is loose; in this article walk-in patients are those patients who need immediate evaluation whilst in the previous article discussed ([20]) these are patients who just arrive without an appointment. After identifying these three factors, Dexter discusses three strategies to decrease waiting times: (1) decrease mean and standard deviation of consultation times, (2) accept provider idle time, and (3) offer activities to waiting patients. The article concludes with the observation that PACs have long waiting times because the mean and standard deviation of the consultation times are so large.

Vissers defines in [58] three characteristics that describe an appointment system: (1) the number of patients scheduled on the first appointment time of the clinic session, (2) the number of patients scheduled on the same appointment time during the clinic session, and (3) the length of an appointment interval. Computer simulation is used to determine the effect of varying parameters associated with this three characteristics on the patient waiting time and provider idle time. Vissers advises to schedule empty appointments according to the proportion of patients arriving at the clinic unexpected (the walk-in patients). A different approach is used by Jennings in [27]. For each patient the doctor estimates how much time consultation will take, and then the appointment interval is adjusted according to this estimation. To avoid provider idle time, appointments should be scheduled successively. This article is about a single provider facility, in contrast to the other articles discussed here which regard multiple provider facilities. Cayirli, Veral, and Rosen [12] use a simulation model to design an appointment system and take into account the presence of walk-in patients: "the study examines the effect of presence of walk-ins and patient punctuality - two factors largely neglected in literature". To include walk-in patients into the model, P_W is introduced: the number of patients walking in as a percentage of all patients. Performance measures are patient waiting time, provider idle time and provider over time.

Harper and Gamlin investigate the effect of different appointment systems in an ear, nose and throat clinic by means of a simulation model [24]. Critical factors are identified that influence the waiting time for patients and the build up of queues in the clinic: (1) the time the first patient is called in, (2) the distribution of appointments over the day, and (3) the number of appointments planned simultaneously. A delay schedule model for a walk-in clinic is discussed by Reilly, Vijay, and Fries in [45]. All patients walk in at first and then choose if they want to stay for treatment, or come back later with an appointment. The patient's choice is supported by an estimation of the delay (waiting time) for the patient on the moment of arrival. The delay scheduling regulates the absorption of patients into the clinic. A simulation model is used to determine a delay rule which predicts the delay as precise as possible. Subsequently the simulation model is used to review alternatives regarding staffing levels in the clinic. Klassen and Rohleder [30] compare various scheduling rules known from literature with a simulation model of a single server system. The goal of the study is decreasing provider idle time and patient waiting time. Rising, Baron, and Averill [46] evaluate the performance of a university outpatient clinic. Daily arrival patterns are analyzed resulting in scheduling more appointment patients during periods of less walk-in arrivals. First historical data is used to smooth patient arrivals over the week. Next a simulation model is developed to smooth demand over the day. Performance measures are (1) throughput rate of patients, (2) patient waiting time, (3) the number of physicians needed, (4) time needed for patient evaluation, and (5) physician work morale. Efficiency did improve after smoothing patient arrival rates.

O'Keefe [40] states that: "however good the modeling of a particular system, the design or alteration of an appointment system is primarily a political problem". He stresses the importance of solving the real problem and not an abstract mathematical problem with a non-implementable solution. Like the articles discussed before, the author's aim is to decrease patient waiting time and provider idle time. Six measures are proposed to accomplish this: (1) make sure clinical sessions are started on time by providers, (2) avoid creating a pool of patients at the beginning of a clinic session, (3) avoid distractions during clinic sessions, (4) provide better scheduling of patients, (5) provide education on the operation of the clinic, and (6) improve facilities for waiting patients. Ultimately only measure (2), (5) and (6) are implemented, mostly because doctors can not be encouraged of the importance of all measures. In all articles stated in Table 1 which involve multiple doctors ([59], [46], [20], [40], [10], [6], [12], [24], [45]) patients are treated in a first come first serve manner by the first available doctor. However sometimes a senior physician treats casualties [24].

Next to the articles reviewed up to now, there are also articles available that apply concepts from stochastic operations research to other aspects of outpatient clinics. Hashimoto and Bell [25] use a simulation model to improve staff scheduling at the Internal Medicine University Faculty Clinic of the University of New Mexico, the United States. Patients are seen sequentially by four staff members. The main goal of the study is to decrease the length of stay for patients. In the new schedule resulting from the study, staffing levels are adapted according to the expected number of patients present in the clinic at any moment of the day. Dunnill and Pounder [16] provide a review of literature with respect to outpatient clinics and focus on five subjects: (1) surveys of patient attitudes and satisfaction, (2) teaching in outpatient clinics, (3) running an outpatient clinic, (4) factors affecting non-attendance of patients, and (5) managing the patient waiting time. Regarding the latter, the focus is on waiting time prior to clinic visits and not on waiting time during visits. The authors state that "A well-run clinic will not only improve the experience of patients but also the working lives of clinic staff". Another simulation model is developed by Edwards et al. [18], which enables the comparison of two queuing systems used in an outpatient setting. This involves two existing appointment-based clinics, one using multiple networks of single server queues and the other using one network with parallel servers at each queue. In this clinic as many queues as servers are formed and patients are sent to the shortest queue. The latter system appears to be superior.

Swisher, Jacobson, Jun, and Balci describe in [53] and [54] a simulation model which supported the design and implementation of the Queston Physician Network in the United States. The Queston Physician Network consists of outpatient clinics and information centers that manage non-medical operations involved with outpatient care. The model focuses on the relation between the outpatient clinic and the information center. The articles provide a simulation model for a single outpatient clinic combined with a single information center, but the authors strive to expand the model for multiple facilities. To re-design *phlebotomy* and specimen collection centers at a medical diagnostic laboratory, Rohleder, Bischak, and Baskin [47] develop a simulation model. The main interest of the study is how many centers and capacity is needed to fulfill a certain demand. Stafford and Aggarwal consider an university outpatient clinic where the major portion of arrivals is due to walk-in patients. The clinic has a complex structure with multiple facilities. A simulation model is used to investigate the influence of (1) the size of the calling population, (2) the number of input channels to the clinic, and (3) the level of staffing in individual facilities. All occur to be critical factors for the performance of the clinic.

This chapter concludes with a survey and a bibliography. Jun, Jacobson, and Swisher [28] provide an extensive survey regarding application of discrete-event simulation in health care clinics. Topics covered in the survey are (1) patient flow, (2) allocation of resources, and (3) discussions for further research directions. A bibliography about queues applied to health care is supplied by Preater [44]. Topics covered in the bibliography are (1) appointments, outpatients and waiting lists, (2) departments, (3) ambulances, (4) compartmental modeling, and (5) miscellaneous.

3 Routines at the Pre-Anesthetic Evaluation Clinic

In this chapter the set-up of the PAC before the re-design is illustrated with a floor-map, and the various patient types present at the PAC and their routing are discussed. Also a brief description of the medical staff and the tasks they perform is given.

In order to make a risk analysis for elective surgery, patients at the LUMC are screened by an anesthesiologist prior to their surgery. This screening takes place at the PAC, situated in the main LUMC building. Successively to the appointment with their surgeon, patients are supposed to visit the PAC. Most patients arriving at the PAC are immediately evaluated, but some leave with an appointment or with the suggestion to come back early morning the next working day. The anesthetic department strives to instantly evaluate as many patients as possible, since an appointment means an extra visit to the hospital.

3.1 Floor-map

In Figure 1 a simplified floor-map of the PAC is shown. Patients announce themselves at the secretary's desk. If the patient can stay for an immediate evaluation, or if the patient has an appointment, he is sent to the waiting room to await further treatment. For most patients this treatment consists of a visit to the nurse, followed by a visit to the anesthesiologist. While the anesthesiologists use the same consultation room all day, the nurses do not have their own room but take one of the two rooms available for them. In between consultations patients are put in the waiting room.

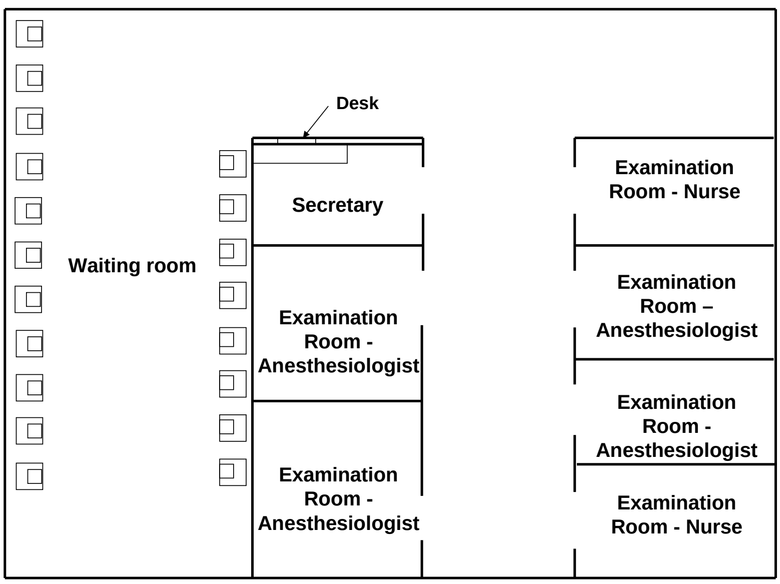

Figure 1: Floor-map of the PAC

When the patient arrives at the secretary's desk, he brings his medical record and a form filled in by the referring surgeon with him. The medical record meant here is the paper file which exists next to the electronic file of the patient. After inserting relevant data from the form filled in by the referring surgeon into *PDMS*, the secretary puts the paper record on the nurse's pile. The physical location of the record shows staff that there is a patient waiting for them. So if the patient has to be consulted by a nurse, the record is put on the nurse's pile, and if the patient has to be consulted by a anesthesiologist, the record is put on the anesthesiologist's pile.

3.2 Patient Types

Patients arriving at the secretary's desk can be divided into four types:

- Patients leaving without evaluation
- Adult walk-in patients
- Adult appointment patients
- Children

Upon arrival, the secretary performs *triage* by making an estimation of the patient's *ASA Score* (see also Appendix A) and *co-morbidity*, supported by a questionnaire filled in by the referring surgeon. This estimation is not necessarily correct. After the triage, the secretary assigns an ASA Score to the patient. Since this assigned ASA Score is in fact a combination of the estimation of the patient's ASA Score and the patient's co-morbidity, using the term ASA Score is not correct. The 'ASA Score' in this case is a clinical judgment and not a rating. However, since this is the daily practice at the PAC, the term ASA Score for this clinical judgment is used throughout this report. Patients with ASA Score 1 or 2 are considered non-complex, while patients with ASA Score 3 or 4 are considered complex.

Now the four patient types as mentioned above are discussed in detail.

3.2.1 Patients Leaving without Evaluation

Routing: Secretary → Home

Patients leave without evaluation for various reasons:

a. The secretary assigns ASA Score 3 or 4 to an adult. With this ASA Score patients are considered complex, which means their visit to the PAC has to be prepared in advance. This takes time and therefore they come back later on appointment basis. Only if the patient lives far away from the hospital or needs emergency surgery, he can have an instant evaluation.

b. The secretary assigns ASA Score 1 or 2 to an adult or the patient is a child, which normally means the patient can stay for instant evaluation, but it is too busy. There are no strict criteria to define the boundary between busy and not busy, so the decision to inform the patient about the number of people that have to be served before him depends on the judgment of the secretary. Now the patient is informed, he can choose to wait, come back later with an appointment, or come back early morning the next day.

c. The secretary assigns ASA Score 1 or 2 to an adult or the patient is a child, but the patient arrives too late. Too late can either be too close to the lunch break, in which the patient can choose if he wants to wait for the afternoon session, or it can be too close to the afternoon closing. Again the patient is given an appointment or is told to come back the next day. There are no strict criteria to define the boundary between on time and too late, so this is again a subjective decision depending on the judgment of the secretary.

3.2.2 Adult walk-in Patients

Routing: Secretary → Nurse → Anesthesiologist → Home

There are three types of adult walk-in patients:

a. Adults with ASA Score 1 or 2 who stay for instant evaluation.

b. Adults with ASA Score 3 or 4 who live far away from the hospital and can stay for an instant evaluation, since an appointment would require additional traveling.

c. Adults with ASA Score 3 or 4 considered emergency patients (surgery required within three days) and who have to be evaluated immediately to enable the surgery scheduled in the near future.

3.2.3 Adult appointment Patients

Regular routing: Secretary → Nurse → Anesthesiologist → Home
Alternative routing: Secretary → Anesthesiologist → Nurse → Home

Adult appointment patients are treated by the anesthesiologist that has prepared the appointment in advance by extensive reading of the medical record. If the assigned anesthesiologist is available when the patient arrives, the patient visits the anesthesiologist first and successively visits the nurse. Usually, the patient is the first person to be served when the anesthesiologist comes available. The anesthesiologist does not wait for the scheduled patient to arrive. However, sometimes when the anesthesiologist finishes treating a patient and the appointment patient is almost to arrive, he uses the idle time to continue the preparation of the appointment by further reading the medical record and starts to insert the patient's data into PDMS. There are two types of appointment patients considered:

a. Adults with ASA Score 1 or 2 who left without evaluation earlier (3.2.1, type 1b and 1c, except children).

b. Adults with ASA Score 3 or 4, sent away previously (type 1a). These appointments need preparation in advance, which consists of reading the patient's medical record by the anesthesiologist and collecting data regarding earlier treatment. The latter part of the preparation is performed by a nurse. Usually the nurse prepares all appointments for the next day in a one hour session in the afternoon. This preparation seems trivial but is very important: if it is performed correctly it can decrease the consultation time at the anesthesiologist dramatically.

3.2.4 Children

Routing: Secretary → Anesthesiologist → Home

A patient is considered a child if he is under 16 years of age. Most (> 95%) of the children evaluated at the PAC are assigned ASA Score 1 or 2. All examinations the children need are performed by the anesthesiologist, so these patients never visit the nurse. Clinic staff thrives to evaluate all children instantly, but this is not always possible. Then the child is scheduled for an appointment, and the routing for these appointment patients is identical to that of children walking in.

The routing of the various patient types results in the routing scheme shown in Figure 2. Not all patient types are treated equally. The nurses and anesthesiologists prioritize appointment patients over walk-in patients, and tend to prioritize children whenever possible. The secretary welcomes patients in a first come, first serve order but also prioritizes when she is inserting data into PDMS and performing triage. This prioritizing depends mainly on the amount of pressure other staff members put on her to finish certain tasks.

3.3 Staff

There are three types of employees that work at the PAC. At present, there are one medical secretary, two nurses and four anesthesiologists working each day. The screening of the patient involves a lot of tasks. In Table 2 an overview of the tasks per employee type is given. The third column of the table resulted from discussion with staff.
Next to the preparation of appointment patients, there are a number of other back office activities that have to be performed. These mainly consist of gathering additional information from other anesthesiologists and/or other hospitals, which is needed to give the approval for surgery. These activities are performed by either the secretary or one of the nurses.

3.3.1 The Secretary

There is one secretary available who works full-time. If the secretary is not present due to illness or holidays, one of the nurses takes over her job. If the patient can stay for an instant evaluation, the secretary starts inserting the patient data into PDMS. During this process, she is disturbed many times by the phone, by patients, and by fellow staff members demanding additional information. Since the nurses can only collect a patient from the waiting room once the patient data is inserted into PDMS, it is very important that the secretary inserts this data as quickly as possible. Upon arrival, the patients also have to fill in a questionnaire which is used by the anesthesiologist to get an overview of the medical history of the patient. If the patient is instantly evaluated, he fills in the questionnaire immediately and then hands

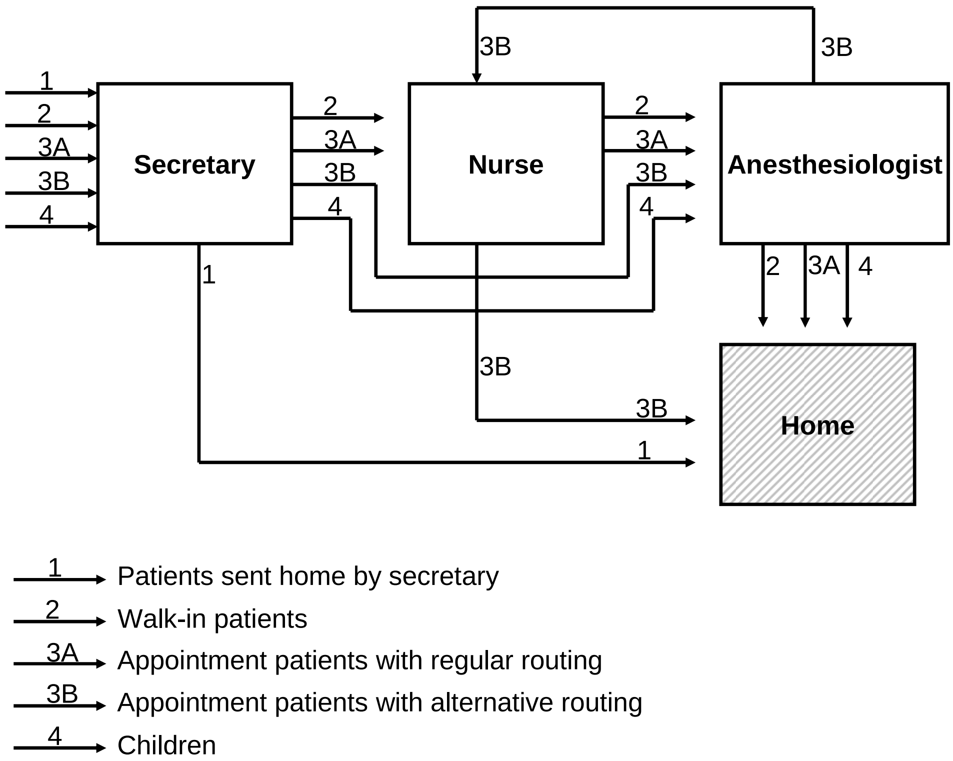

Figure 2: Routing of patient types

it back to the secretary. If he is sent home, he is supposed to fill in the questionnaire at home and bring it with him the next time he visits the PAC.

3.3.2 The Nurses

There are five nurses available who are scheduled in irregular shifts, in such a way that each day two nurses are available. Not all procedures mentioned in Table 2 are performed on each patient; performing an ECG and drawing blood are optional and depend on the physical condition of the patient. A protocol helps the nurse to decide whether she has to perform the optional procedures on a patient.

3.3.3 The Anesthesiologists

There are three types of medical professionals who perform anesthetic consultations: two *resident physicians*, one *nurse practitioner* and one *senior physician*. In the proceeding chapters of this report, these professionals will be referred to as 'the anesthesiologist'.

Employee	**Task**	**Could also be performed by**
Secretary	Welcome patients	Nurse
	Answer questions from patients	Nurse
	Answer phone	Nurse
	Insert patient data in PDMS (I)	Nurse, Anesthesiologist
	Insert patient data in *ZIS*	Nurse
	Perform triage	Nurse, Anesthesiologist
	Make appointments for patients	Nurse
Nurse	Measure height and length	Anesthesiologist
	Measure blood pressure	Anesthesiologist
	Perform *ECG*	Anesthesiologist
	Draw blood	Anesthesiologist
	Insert patient data in PDMS (II)	Secretary, Anesthesiologist
	Prepare appointment patients	Secretary
Anesthesiologist	Medical examination	
	Review medical history	
	Insert patient data in PDMS (III)	
	Approve patient for surgery	

Table 2: Overview of tasks per employee

The resident physicians are still in training, and therefore most of them need more time for a consult than the experienced senior physician. There are about 50 anesthetic resident physicians who have to work at the PAC one day each four or five weeks, based on an alternating schedule. This leaves them relatively uninformed about how a case should be managed. It is attempted to have one experienced resident physician and one less experienced resident physician working at the PAC each day.

The nurse practitioner is under constant supervision of the senior physician. There is one nurse practitioner who is only allowed to treat non-complex patients. The senior physician evaluates test results of complex patients, coaches the resident physicians, supervises the nurse practitioner and performs consultations if there are many patients waiting. There are about five senior physicians available. Next to treating patients, the anesthesiologists spend time on other activities like looking for lost medical records and making phone calls.

3.4 Opening Hours

The PAC is opened on working days. The opening hours are 8:00 - 12:30 and 13:30 - 16:30. Note that the PAC closes between 12:30 and 13:30. The interval 12:30 - 13:00 is used for wrapping up, while the interval 13:00 - 13:30 is used for lunch. Although the secretary, nurses and the anesthesiologists have the same interval for lunch, the anesthesiologists lunch separately. During this break, patients that arrive can sit in the waiting room, but they are welcomed at 13:30.

In Table 3 the appointment schedule is shown. Not all appointment slots are used each day. The consultation by phone is for patients that recently had surgery and need to have another procedure done. They do not need the extensive screening again. The emergency appointments are for patients who need emergency surgery, which is a surgery scheduled within three days. Evaluation of these patients, either on ward or at the PAC, is performed by one of the anesthesiologists working at the PAC.

Morning		**Afternoon**	
Appointment Type	**Time**	**Appointment Type**	**Time**
ASA 3&4 (complex)	08:00	ASA 3&4 (complex)	14:30
ASA 3&4 (complex)	08:15	ASA 1&2 (non-complex)	15:00
Consultation by phone	08:50	ASA 3&4 (complex)	15:30
ASA 3&4 (complex)	09:00	ASA 1&2 (non-complex)	16:00
ASA 1&2 (non-complex)	09:30		
ASA 3&4 (complex)	10:00		
ASA 1&2 (non-complex)	10:30		
Emergency	11:00		

Table 3: Appointment schedule

4 Approximation Model for the Current Design

This chapter describes the approximation model which represents the current routines at the PAC.

4.1 Model Assumptions

To allow for a thorough analysis of the current design, some assumptions are made. The patient classes as described in Chapter 3 are reduced to the following four classes:

S	Adults and children sent home with an appointment
W	Adults with ASA Score 1 or 2
A	Adults with ASA Score 3 or 4
K	Children

All these classes have their own arrival and service time distributions.

For class **S**, only those patients of patient class 1 (3.2.1) who get an appointment are taken into account. There is no data available about the number of patients told to come back the next day without an appointment.

Class **W** represents patient class 2a (3.2.2 sub a) and patient class 3a (3.2.3 sub a). This class consists of all adult patients with ASA Score 1 or 2. No distinction is made between appointment and non-appointment patients.

Class **A** represents patient class 2b and 2c (3.2.2 sub b,c), and patient class 3b (3.2.3 sub b). This class consists of all adult patients with ASA Score 3 or 4. No distinction is made between appointment and non-appointment patients. All patients of class A are assumed to use the regular routing, which is Secretary → Nurse → Anesthesiologist. Using the alternative routing is a state-dependent decision, which can not be analyzed in this model. Since all patients of class A visit the secretary, the nurse and the anesthesiologist regardless of what their routing is, it is assumed in this model that all patients use this routing.

Class **K** represents patient class 4 (3.2.4) entirely, no distinction is made based on ASA Scores or whether children have an appointment or not.

The simplified patient flows as described above are shown in Figure 3. The prioritizing of appointment patients at the nurses and anesthesiologists and the tendency to prioritize children is not considered in this model. Also, the prioritizing by the secretary is not modeled here. Because it is not possible to distinct between individual employees, the nurses and anesthesiologists are assumed to have mutually identical service time distribution functions. The back office activities mentioned in Chapter 3 are left out since they can be carried out when there are no patients and are interrupted once a patient arrives.

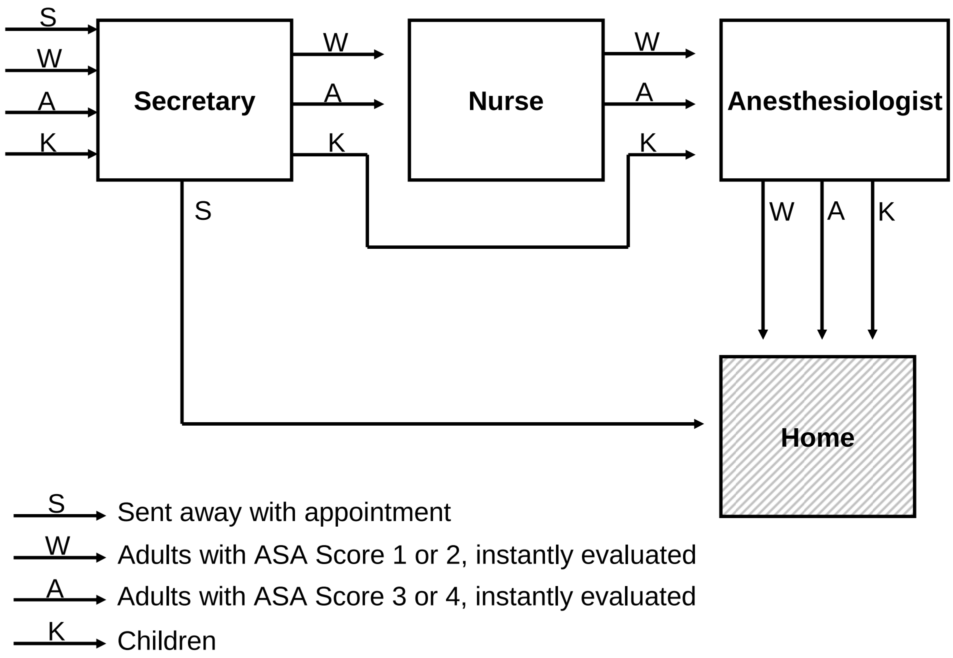

Figure 3: Simplified patient flows for the approximation model

4.2 The Model

The routines at the PAC can now be modeled as a multi-class Open Queuing Network (OQN). To approximate the performance measures of the OQN, the complete reduction method as discussed in [61] is used. The complete reduction method consists of three steps:

1. Reduce the R class OQN to a single class OQN by aggregating the R classes

2. Analyze the single class OQN

3. Use disaggregation to obtain the performance measures per class for the R class OQN

There are r distinct patient classes, $r = [1..4]$ and i stations, $i = [1..3]$ with

$r = 1$	Class **S**	$i = 1$	Secretary
$r = 2$	Class **W**	$i = 2$	Nurse
$r = 3$	Class **A**	$i = 3$	Anesthesiologist
$r = 4$	Class **K**		

The number of staff members available at station i is equal to s_i. Because the secretary is disturbed a lot, she has an effective capacity of e_1. Because the anesthesiologists spend a lot of time on activities other than treating patients, they have an effective capacity of e_3.

The parameters listed below are used for calculations with the complete reduction method. The parameters originate from the arrival and service time distributions of the patient classes and stations, to be determined in Chapter 5.

ζ_r	Arrival rate for patient class r
$E(S_{r,i})$	Mean service time for patient class r at station i
$SCV_{A,r,1}$	Squared coefficient of variance (SCV) of arrivals for patient class r at station 1
$SCV_{S,r,i}$	SCV of service time for patient class r at station i

4.2.1 Step 1: Reduction to a Single Class OQN

For each station, the aggregated occupation rate per server and aggregated arrival rate are calculated. The aggregated occupation rates are

$$\rho_1 = \sum_{r=1}^{4} \rho_{1,r} \quad (1)$$

$$\rho_2 = \sum_{r=2}^{3} \rho_{2,r} \quad (2)$$

$$\rho_3 = \sum_{r=2}^{4} \rho_{3,r} \quad (3)$$

In which

$$\rho_{1,r} = \zeta_r E(S_{r,1}) \frac{1}{e_1 s_1} \quad \text{for } r = [1..4] \quad (4)$$

$$\rho_{2,r} = \zeta_r E(S_{r,2}) \frac{1}{s_2} \quad \text{for } r = [2,3] \quad (5)$$

$$\rho_{3,r} = \zeta_r E(S_{r,3}) \frac{1}{e_3 s_3} \quad \text{for } r = [2..4] \quad (6)$$

For the validity of the model it is required that ρ_i and $\rho_{i,r} < 1$ for all i and r. The aggregated arrival rates for station i are

$$\lambda_1 = \sum_{r=1}^{4} \zeta_r \quad (7)$$

$$\lambda_2 = \sum_{r=2}^{3} \zeta_r \quad (8)$$

$$\lambda_3 = \sum_{r=2}^{4} \zeta_r \quad (9)$$

4.2.2 Step 2: Analysis of the Single Class OQN

For station 1, the SCV of the arrival process is defined as

$$SCV_{A,i} = w_1 \sum_{r=1}^{4} Q_{r,1} SCV_{r,1} + 1 - w_1 \tag{10}$$

in which

$$w_1 = \frac{1}{1 + 4(1-\rho_1)^2(v_1 - 1)} \tag{11}$$

$$v_1 = \frac{\lambda_1^2}{\sum_{r=1}^{4} \zeta_r^2} \tag{12}$$

$$Q_{r,1} = \frac{\zeta_r}{\lambda_1} \tag{13}$$

The mean service time at station 1 is equal to

$$E(S_1) = \frac{1}{\lambda_1} \sum_{r=1}^{4} \zeta_r E(S_{r,1}) \tag{14}$$

The SCV of the mean service time at station 1 is equal to

$$SCV_{S,1} = \frac{1}{\lambda_1 E^2(S_1)} \sum_{r=1}^{4} \zeta_r E^2(S_{r,1})(SCV_{S,r,1} + 1) - 1 \tag{15}$$

The SCV of the arrival process at station 2 is defined as

$$SCV_{A,2} = P_{1,2} SCV_{D,1} + 1 - P_{1,2} \tag{16}$$

In which $SCV_{D,1}$ is the SCV of the departure process at station 1 and $P_{1,2}$ is the routing probability of the aggregated flow from station 1 to station 2:

$$SCV_{D,1} = (1 - \rho_1^2) SCV_{A,1} + \rho_1^2 SCV_{S,1} \tag{17}$$

$$P_{1,2} = \frac{\sum_{r=2}^{3} \zeta_r}{\lambda_1} \tag{18}$$

The mean service time at station 2 is equal to

$$E(S_2) = \frac{1}{\lambda_2} \sum_{r=2}^{3} \zeta_r E(S_{r,2}) \tag{19}$$

The SCV of the mean service time at station 2 is defined as

$$SCV_{S,2} = \frac{1}{\lambda_2 E^2(S_2)} \sum_{r=2}^{3} \zeta_r E^2(S_{r,2})(SCV_{S,r,2} + 1) - 1 \tag{20}$$

The SCV of the arrival process at station 3 is defined as

$$SCV_{Ar,3} = w_3 \left(Q_{2,3}SCV_{2,3} + Q_{1,3}SCV_{1,3}\right) + 1 - w_3 \tag{21}$$

with

$$w_3 = \frac{1}{1 + 4(1-\rho_3)^2(v_3 - 1)} \tag{22}$$

$$v_3 = \frac{1}{Q_{2,3}^2 + Q_{1,3}^2} \tag{23}$$

$$Q_{2,3} = \sum_{r=2}^{3} \frac{\zeta_r}{\lambda_3} \tag{24}$$

$$Q_{1,3} = \frac{\zeta_4}{\lambda_3} \tag{25}$$

$$SCV_{1,3} = P_{1,3}SCV_{D,1} + 1 - P_{1,3} \tag{26}$$

$$P_{1,3} = \frac{\zeta_4}{\lambda_1} \tag{27}$$

$$SCV_{2,3} = SCV_{D,2} \tag{28}$$

$$SCV_{D,2} = 1 + (1-\rho_2^2)(SCV_{A,2} - 1) + \frac{\rho_2^2}{\sqrt{s_2}}(SCV_{S,2} - 1) \tag{29}$$

in which $SCV_{2,3}$ is the SCV of the patient flow from station 2 to station 3, $SCV_{1,3}$ the SCV of the patient flow from station 1 to station 3, $SCV_{D,2}$ the SCV of the departure process at station 2 and $P_{1,3}$ the routing probability of the aggregated flow from station 1 to station 3. Note that the routing probability of the aggregated flow from station 2 to station 3 is equal to 1. The mean service time at station 3 is equal to

$$E(S_3) = \frac{1}{\lambda_3} \sum_{r=2}^{4} \zeta_r E(S_{r,3}) \tag{30}$$

and the SCV of the service time at station 3 is equal to

$$SCV_{S,3} = \frac{1}{\lambda_3 E^2(S_3)} \sum_{r=2}^{4} \zeta_r E^2(S_{r,3})(SCV_{S,r,3} + 1) - 1 \tag{31}$$

4.2.3 Step 3: Performance Measures per Patient Class

Now the performance measures per patient class can be obtained, using the SCV's and mean service times calculated in step 2. The mean waiting time at station 1 is equal for all patient classes and is defined as

$$E(W_{Q,1}) = \frac{SCV_{A,1} + SCV_{S,1}}{2} \frac{\rho_1}{1-\rho_1} \frac{E(S_1)}{e_1} \tag{32}$$

The mean waiting time at station 2 is equal for all patient classes and is defined as

$$E(W_{Q,2}) \quad = \quad \frac{SCV_{A,2} + SCV_{S,2}}{2} E\left(W_{Q,2(M/M/c)}\right) \tag{33}$$

in which

$$E\left(W_{Q,2(M/M/c)}\right) \quad = \quad \frac{(s_2\rho_2)^{s_2}}{s_2!G_2} \frac{1}{(1-\rho_2)^2} \frac{E(S_2)}{s_2} \tag{34}$$

and

$$G_2 \quad = \quad \sum_{n=0}^{s_2-1} \frac{(s_2\rho_2)^n}{n!} + \frac{(s_2\rho_2)^{s_2}}{(1-\rho_2)s_2!} \tag{35}$$

The mean waiting time at station 3 is equal for all patient classes and is defined as

$$E(W_{Q,3}) \quad = \quad \frac{SCV_{A,3} + SCV_{S,3}}{2} E\left(W_{Q,3(M/M/c)}\right) \tag{36}$$

in which

$$E\left(W_{Q,3(M/M/c)}\right) \quad = \quad \frac{(s_3\rho_3)^{s_3}}{s_3!G_3} \frac{1}{(1-\rho_3)^2} \frac{E(S_3)}{e_3 s_3} \tag{37}$$

and

$$G_3 \quad = \quad \sum_{n=0}^{s_3-1} \frac{(s_3\rho_3)^n}{n!} + \frac{(s_3\rho_3)^{s_3}}{(1-\rho_3)s_3!} \tag{38}$$

The mean length of stay at the PAC for patients of class r depends on the stations the patient visits and is equal to

$$E(V_1) \quad = \quad E(W_{Q,1}) + \frac{E(S_{S,1,1})}{e_1} \tag{39}$$

$$E(V_2) \quad = \quad \sum_{i=1}^{3} E(W_{Q,i}) + \frac{E(S_{S,2,1})}{e_1} + E(S_{S,2,2}) + E(S_{S,2,3}) \tag{40}$$

$$E(V_3) \quad = \quad \sum_{i=1}^{3} E(W_{Q,i}) + \frac{E(S_{S,3,1})}{e_1} + E(S_{S,3,2}) + E(S_{S,3,3}) \tag{41}$$

$$E(V_4) \quad = \quad E(W_{Q,1}) + \frac{E(S_{S,4,1})}{e_1} + E(W_{Q,3}) + E(S_{S,4,3}) \tag{42}$$

Note that the effective capacity of the secretary is accounted for in the mean time a patient spends in service, but that the effective capacity of the anesthesiologist is not accounted for in the mean time a patient spends in service. This is because the secretary is disturbed while she is helping patients, while the anesthesiologist is not disturbed during consultations.

The number of patients in the queue at station i is equal to

$$E(L_{Q,i}) = \lambda_i E(W_{Q,i}) \tag{43}$$

The number of patients present at station i is equal to the number of patients in the queue plus the mean number of patients in service:

$$E(L_1) = E(L_{Q,1}) + \frac{\lambda_1 E(S_1)}{e_1} \tag{44}$$

$$E(L_i) = E(L_{Q,i}) + \lambda_i E(S_i) \quad \text{for } i = [2,3] \tag{45}$$

The number of patients present in the system is equal to the sum of the patients present at the three stations:

$$E(L) = \sum_{i=1}^{3} E(L_i) \tag{46}$$

5 Calibration

This chapter gives an overview of the data analysis carried out for this project.

During his stay at the PAC, the physical location of the patient is constantly monitored by a feature in PDMS: the Graphical Patient List (*GPL*). This feature involves a floor-map of the PAC and an icon that represents the patient. When the patient arrives and the secretary fills in the patient's data in PDMS, she assigns his icon a chair in the waiting room on the floor-map. Each time the patient moves to another part of the PAC, like one of the nurse's examination rooms, one of the anesthesiologists' examination rooms or the waiting room again, his icon is dragged into this room in GPL. This tracking of patient moves provides useful data to determine the average length of stay in the different examination rooms. Because employees sometimes forget to relocate the patient in GPL, not all moves are correctly monitored and not all available data could be used. Since the time the patient spends at the secretary's desk is not monitored separately but only recorded as time in the waiting room, this time had to be estimated by observation. Patient class S is only mentioned if relevant, since this patient class is sent away immediately. Only data from admitted patients is available in GPL. $r = [1, 2, 3, 4]$ corresponds to patient classes S, W, A, K respectively.

5.1 Distribution of Patients among Patient Classes

For data analysis, data was used from the period June 1, 2006 - May 31, 2007. During this year, the PAC was opened 249 days and 6260 separate visits of patients have been recorded in GPL. 403 of these visits were not monitored correctly, and therefore 5857 visits could be evaluated to determine the distribution of the patients among patient classes W, A, and K as defined in Chapter 4. The percentage of evaluated visits, out of recorded visits is equal to 93.56%. Table 4 summarizes the distribution of the patients among the patient classes in which n_r is the number of patients of class r and N is the total number of patients.

Patient class	n_r	% of N
W	4234	72.29
A	505	8.62
K	1118	19.09

Table 4: Distribution of patients among patient classes

5.2 Appointments

All appointments are registered in an agenda. Combining the appointments of patients in this agenda with their ASA Scores as recorded in PDMS provides the fraction of patients that get an appointment (a_r), as can be seen in Table 5. It is apparent that currently the PAC does not perform well, since almost one third of adults with ASA Score 1 or 2 get an appointment instead of instant evaluation.

Patient class	n_r	# of appointments	a_r
W	4234	1288	0.30
A	505	352	0.70
K	1118	133	0.12

Table 5: Distribution of appointments among patient classes

5.3 Patient Arrivals

In this paragraph patient arrivals per weekday and patient arrivals during the day are considered per patient class. An overview of the aggregated arrival of all patients per weekday and per month can be found in Appendix B.

5.3.1 Arrivals per Weekday

The number of patient arrivals per weekday is summarized in Table 6. The standard deviation is in the table abbreviated by SD. Notice the decrease in patient arrivals on Friday.

Patient Class/ Day	# days evaluated	W Mean	SD	A Mean	SD	K Mean	SD
All	249	17.06	5.19	2.02	1.40	4.51	2.55
Monday	46	18.46	4.18	1.72	1.20	4.54	2.27
Tuesday	50	19.18	4.18	2.38	1.64	5.32	2.88
Wednesday	52	16.40	4.49	2.31	1.37	5.23	2.90
Thursday	51	19.24	5.09	2.20	1.37	4.20	2.13
Friday	50	11.84	3.16	1.50	1.22	3.14	1.84

Table 6: Patient arrivals per weekday per patient class

5.3.2 Arrivals during the Day

To determine the arrival pattern during the day, data from November 2006 were used. November was chosen because this was the most average month in the year evaluated: the number of patients that arrived on average per day in this month almost equals the number of patients that arrived on average per day during the evaluated year (see Appendix B). The number of arrivals of patient classes A and K were too small to consider separately to determine an arrival rate, therefore the aggregated arrivals per interval of the three patient classes W, A and K were used. Table 7 shows the mean and standard deviation of the arrival rate per interval. This arrival rate represents patients who can stay for instant evaluation. Notice the dip in the interval 12:30-13:30 (the lunch break) and the apex just after lunch. Around 10:30 the secretary starts sending patients away because it is getting too busy. This results in a decreasing arrival rate. For this calculation, Fridays were not taken into account, since the mean number of arrivals for all patient classes on Fridays is significantly lower than on the other days of the week. In Figure 4 the mean aggregated arrival rate per interval is shown graphically.

Interval	**Mean**	**SD**
08:00-08:30	1.17	0.79
08:30-09:30	3.50	2.04
09:30-10:30	3.83	1.29
10:30-11:30	3.11	1.41
11:30-12:30	2.50	1.47
12:30-13:30	0.28	0.57
13:30-14:30	5.89	1.91
14:30-15:30	3.83	2.20
15:30-16:30	0.94	0.87

Table 7: Aggregated patient arrivals per interval

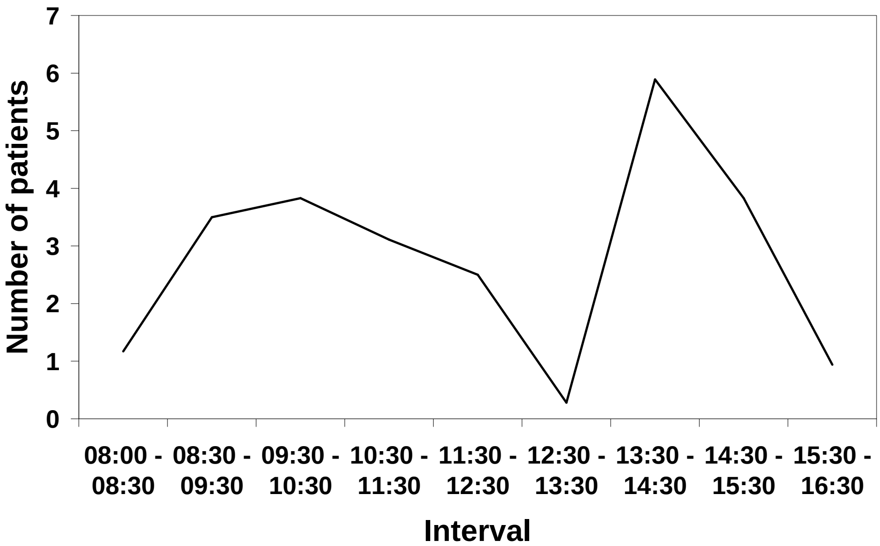

Figure 4: Mean aggregated arrival rate per interval

5.3.3 The Arrival Process used in the Model

The approximation model is used to identify critical factors influencing patient waiting time and staff workload. Prolonged patient waiting time and high staff workload occur roughly from 10:00 - 15:00 hrs. Therefore the arrival process during this time interval is considered in the approximation model. The Poisson process is a useful process to model arrival processes for queuing models [1]. To determine if the arrival process at the PAC can be modeled with a Poisson process, first the definition of the Poisson process as given in the lecture notes by Adan and Resing [1] is given. Next it is examined if the Poisson process provides a reasonable fit for the arrival process at the PAC.

Define $N(t)$ as the number of arrivals in $[0, t]$ for a Poisson process with rate γ. This means that the time between successive arrivals is exponentially distributed with parameter γ and is independent of the past. Then $N(t)$ has a Poisson distribution with parameter γt, so

$$P(N(t) = k) = \frac{(\gamma t)^k}{k} e^{-\gamma t} \quad \text{k=[0,1,2,..]} \tag{47}$$

In each small time interval of length Δt the probability of an arrival is equally likely and if Δt is chosen small enough, the probability of more than one arrival in this interval $\rightarrow 0$.

Adapting this to the arrival process at the clinic means that patients should arrive completely random in time, and that they should arrive one at a time. The latter is true since patients arrive individually. The first property is harder to establish. Because patients sent away with an appointment are not recorded in GPL, the arrival process of all patients had to be observed and could not be retrieved from the available data. With the observation it is determined that in the time interval 10:00 - 15:00 hrs patients arrive individually and completely random in time. Therefore the arrival process is modeled with a Poisson process, with estimated arrival rate γ equal to 5 patients per hour. Since a Poisson process remains Poisson under merging and splitting, the arrival processes for the four patient classes are also Poisson. These arrival rates are approximated with the following calculations:

$$\zeta_1 = \sum_{r=2}^{4} \frac{a_r n_r \gamma}{N} \tag{48}$$

$$\zeta_r = \frac{n_r \gamma}{N} \quad \text{for } r = [2..4] \quad \text{with} \tag{49}$$

$$\sum_{r=2}^{4} \zeta_r = \gamma \tag{50}$$

in which a_r is the fraction of patients of class r who is given an appointment, n_r is the number of patients of class r and N is the total number of patients. These calculations lead to the arrival rates stated in Table 8.

Patient class	ζ_r
S	1.50
W	3.61
A	0.43
K	0.95

Table 8: Arrival rates per patient class

5.4 Consultation Times

The procedures followed to determine the mean and standard deviation of the consultation times per employee are described in this paragraph.

5.4.1 The Secretary

The consultation time of the secretary is not separately monitored in GPL. Therefore she was observed to determine the distribution of her consultation time. It is estimated by observation that this consultation time is exponentially distributed with $E(S_{r,1})$ equal to 5:30 minutes for $r = [2..4]$, and $E(S_{1,1})$ equal to 2:30 minutes. The mean consultation time for patients that are sent away is lower because the secretary does not have to fill in PDMS for this patients. As mentioned before in Chapter 3, the secretary is disturbed a lot by patients, the phone and fellow workers. Observation showed that the effective capacity of the secretary (e_1) can be as low as $\frac{1}{2}$ of her regular capacity, but usually she has an effective capacity of about $\frac{2}{3}$.

5.4.2 The Nurses and the Anesthesiologists

A single procedure was followed to determine the distribution functions regarding the consultation times for the various patient classes at the nurses and the anesthesiologists. For the nurses, data from the period May 9, 2007 - May 31, 2007 was used. This period was chosen because on May 9, a new routine was introduced at the PAC. Previously, patients that needed to have blood drawn had to go back to the nurse after their visit to the anesthesiologist. This meant extra time in the waiting room. Since this was considered as not very patient friendly, it was decided that the nurses decide before the patient's visit to the anesthesiologist if blood has to be drawn and then do it immediately. For the anesthesiologists, data from the period November 1, 2006 - November 30, 2006 was used, for the same reason as mentioned in Subparagraph 5.3.2.

All histograms that were made for the five data sets regarding the consultation times for the various patient classes, showed a shape that indicated a lognormal distribution. Other distributions with similar shaped histograms are for example the Gamma and Weibull distribution, but since the lognormal distribution is a common used distribution to model durations of various phenomena in health care [37], this distribution was taken into account first.

For each data set separately, the following steps were executed:

- Convert the data from minutes into seconds to ease calculations
- Sort the data in ascending order
- Define H_0 as the hypothesis that the data follows a lognormal distribution
- Calculate $LN(X_i)$ for all i
- Calculate the maximum-likelihood estimators (MLE) for the lognormal distribution: $\hat{\mu}$ and $\hat{\sigma}$
- Use the MLE's to calculate the test statistic for the Kolmogorov-Smirnov test
- Decide if H_0 should be rejected or accepted

This procedure is extensively described in [32], pp. 363-367. Table 9 summarizes the outcomes for the five data sets. The specified level of the test α is equal to 0.10.

Data set	**n**	$\hat{\mu}$	$\hat{\sigma}$	Value test statistic	Result
Nurse/W	104*	6.24	0.83	0.8094	Accept H_0
Nurse/A	14	6.13	1.00	0.7922	Accept H_0
Anesthesiologist/W	267	7.25	0.56	0.7831	Accept H_0
Anesthesiologist/A	33	7.74	0.30	0.5565	Accept H_0
Anesthesiologist/K	69	7.01	0.61	0.8844	Accept H_0

Table 9: Outcomes for the separate data sets

* The data set Nurse/W was slightly adjusted. If the original data set was used, with $n = 208$, H_0 was rejected (the value of the test statistic equals 1.0868). The sensitivity of goodness of fit test increases with sample size, so stricter standards are applied to large samples [50], [52]. This may lead to an unnecessary rejection of H_0. To avoid this, the data set was first sorted in ascending order, and then every second data point was deleted so that 104 data points remained. This adjusted data set provided the result as stated in Table 9.

The lognormal distribution provides a reasonable fit for the data and therefore the consultation times are modeled with a lognormal distribution with parameters $\hat{\mu}$ and $\hat{\sigma}$, which results in $E(S_{r,i})$ and $SD(S_{r,i})$ as given in Table 10.

Employee	**Patient class**	$E(S_{r,i})$	$SD(S_{r,i})$	$SCV_{S,r,i}$
Nurse	W	12:04	12:01	1.00
Nurse	A	12:37	16:33	1.33
Anesthesiologist	W	27:27	16:40	0.61
Anesthesiologist	A	40:04	12:18	0.31
Anesthesiologist	K	22:14	14:58	0.68

Table 10: Consultation times of the nurses and anesthesiologists per patient class

As mentioned in Chapter 3, the anesthesiologist also spends time on activities not directly related to patients treated at the PAC that day. An effective capacity of $\frac{5}{8}$ was estimated. This number is based on the observation that at least one of the anesthesiologists (mostly the nurse practitioner or the senior physician) performs another tasks, and that anesthesiologists who are treating patients spend about five minutes an hour with other things like looking for lost medical records. This leads to $e_3 = (1 - \frac{1}{4})(1 - \frac{1}{12}) = \frac{11}{16}$.

6 Results for the Approximation Model

In this chapter the current design at the PAC is analyzed by using the approximation model described in Chapter 4 and the parameters defined in Chapter 5. With the insights provided by this analysis, alternative designs for the PAC and their influence on performance are discussed.

6.1 Analysis of the Current Design

In this paragraph the current design as described in Chapter 3 is analyzed.

6.1.1 Parameter Values

In Table 11 the arrival rate, mean service time in minutes and the squared coefficient of variance are given per patient class. This table is based on Table 8 and 10 from Chapter 5. In the current design there is one secretary, two nurses and four anesthesiologists available, so $s_1 = 1$, $s_2 = 2$, and $s_3 = 4$. Furthermore $e_1 = \frac{2}{3}$ and $e_3 = \frac{11}{16}$.

Patient class	ζ_r	$E(S_{r,1})$	$SCV_{S,r,1}$	$E(S_{r,2})$	$SCV_{S,r,2}$	$E(S_{r,3})$	$SCV_{S,r,3}$
S	1.50	2:30	1.00	-	-	-	-
W	3.61	5:30	1.00	12:04	1.00	27:27	0.61
A	0.43	5:30	1.00	12:37	1.33	40:04	0.31
K	0.95	5:30	1.00	-	-	22:14	0.68

Table 11: Parameter values for current the design

6.1.2 Results

The performance measures per station are given in Table 12, and the mean LOS per patient class is given in Table 13. The occupation rate of the anesthesiologists is very high, the senior physician has to assist the nurse practitioner and the resident physicians because three anesthesiologists is not enough for this design. The mean number of patients present in at the PAC is equal to 9.80. Notice the high LOS for all patient classes compared to their total mean service duration.

Station	ρ_i	$E(W_{Q,i})$	$E(L_{Q,i})$	$E(L_i)$
Secretary	0.78	0:27:36	2.95	3.73
Nurse	0.41	0:02:24	0.17	0.98
Anesthesiologist	0.84	0:33:36	2.79	5.09

Table 12: Performance measures per station for the current design

Patient class	$E(V_r)$
S	0:31:12
W	1:51:00
A	2:04:12
K	1:31:12

Table 13: Mean LOS per patient class for the current design

6.2 Alternative 1

In this alternative, the secretary only performs back-office activities like picking up the phone and preparing appointment patients. The secretary's tasks involving patients that have to be carried out immediately after arrival of the patient are taken over by one of the two nurses present. The nurse sitting behind the reception desk performs triage, instead of the secretary, and the other nurse is available for the examination of the patients. This alternative was proposed by the employees of the PAC.

6.2.1 Parameter Values

In this alternative $s_2 = 1$. Because the secretary picks up the phone it is assumed that the nurse sitting behind the reception desk is not disturbed, so $e_1 = 1$.

6.2.2 Results

The performance measures per station are given in Table 14, and the mean LOS per patient class is given in Table 15. The mean number of patients present at the PAC is equal to 10.63. Note that with 'secretary' the nurse sitting behind the reception desk is meant. The results show that the occupation rate and therefore the waiting time at the secretary decrease, while the occupation rate and waiting time at the nurse increases dramatically. With this alternative a new problem is created at the nurses station.

Station	ρ_i	$E(W_{Q,i})$	$E(L_{Q,i})$	$E(L_i)$
Secretary	0.52	0:05:24	0.60	1.12
Nurse	0.81	0:54:00	3.62	4.44
Anesthesiologist	0.84	0:33:36	2.79	5.09

Table 14: Performance measures per station for alternative 1

Patient class	$E(V_r)$
S	0:07:48
W	2:18:00
A	2:31:12
K	1:06:36

Table 15: Mean LOS per patient class for alternative 1

6.3 Alternative 2

Sometimes it is suggested by employees of the PAC that all patients should get an appointment. This would enable regulation of patient arrivals. In this alternative the effects of an appointment-only system are evaluated.

6.3.1 Parameter Values

The arrival rates for the patient classes were adjusted as follows. $\zeta_1 = \gamma$ because all walk-in patients are sent away with an appointment. During the day, there are six hours available in which appointments can be scheduled (due to lunch, start-up time and the closing in the afternoon, the other available two hours can not be used for appointments). This results in

$$\zeta_r = \frac{1}{6}\frac{n_r}{249} \quad \text{for } r = [2..4] \tag{51}$$

with n_r is again the number of patients of class r. 249 is the number of days the PAC was opened the previous year. Now $\zeta_1 = 5$, $\zeta_2 = 2.83$, $\zeta_3 = 0.34$ and $\zeta_4 = 0.75$. It is assumed that all appointment patients arrive on time, and therefore $SCV_{r,1} = 0$ for $r = [2..4]$. $E(S_{r,1})$ equals 2:30 minutes because for appointment patients, data is inserted in PDMS prior to their arrival.

6.3.2 Results

The performance measures per station are given in Table 16, and the mean LOS per patient class is given in Table 17. The mean number of patients present at the PAC is equal to 5.61. Patients that come back for their appointment have to wait on average twelve minutes for the secretary. In reality it is not always possible to see patients on appointment basis, this is mainly due to the emergency patients who have to be evaluated the same day they walk in. Also an appointment means an extra visit to the hospital for a patient. Staff of the PAC regards this as very patient unfriendly.

Station	ρ_i	$E(W_{Q,i})$	$E(L_{Q,i})$	$E(L_i)$
Secretary	0.74	0:12:00	1.80	2.55
Nurse	0.32	0:01:12	0.07	0.71
Anesthesiologist	0.66	0:08:24	0.55	2.36

Table 16: Performance measures per station for alternative 2

Patient class	$E(V_r)$
S	0:17:32
W	1:06:36
A	1:19:48
K	0:48:00

Table 17: Mean LOS per patient class for alternative 2

6.4 Alternative 3

Scheduling appointments during periods of low walk-in demand smooths the load on the employees and facilities of the PAC [46]. As mentioned be seen in Paragraph 5.3.1, the patient arrivals on Fridays are significantly lower than on other weekdays. This is caused by the closing of many referring surgeon outpatient clnics on Friday afternoon. In this alternative as many appointments as possible are scheduled on Friday afternoon. This increases patient arrivals on Friday which results in an increase of the utilization of available resources. The remaining appointments are scheduled in the early morning. Since walk-in patients are referred to the PAC by other outpatient clinics immediately after consultation, none of these patients will be present in the early morning. Currently patients arrivals in the early morning are due to appointment patients and patients told to come back the next day.

6.4.1 Parameter Values

The period considered for the model is interval 10:00 - 15:00, appointments are only scheduled outside this interval. Thus

$$\zeta_r = (1 - a_r)\zeta_r \quad \text{for } r = [2..4] \tag{52}$$

in which a_r is the fraction of appointments for patient class r. The parameter ζ_1 does not change and is equal to 1.50, $\zeta_2 = 2.53$, $\zeta_3 = 0.13$ and $\zeta_4 = 0.84$.

6.4.2 Results

The performance measures per station are given in Table 18, and the mean LOS per patient class is given in Table 19. The LOS for this alternative is lower than the LOS for the previous alternative, which might not seem logical at first. This result is caused by two factors: (1) in this alternative the arrival rate at the anesthesiologist is lower than in alternative 2, namely 3.50 patients per hour opposed to 3.92 patients per hour, and (2) the total patient arrival rate at the secretary is lower, resulting in lower patient waiting time at this station. The mean number of patients present at the PAC is equal to 3.84. Note the decrease in occupation rate of the employees and in the LOS for all patient classes. To make this new appointment system a success a proper appointment schedule has to be developed, and anesthesiologists have to be present at the PAC when they are scheduled for a shift. All patients sent away have to be scheduled for an appointment, and not told to come back early the next day. The latter may lead to more appointments for walk-in patients, but because there are no appointments scheduled in the interval 10:00 - 15:00, it is less likely that patients are sent away.

Station	ρ_i	$E(W_{Q,i})$	$E(L_{Q,i})$	$E(L_i)$
Secretary	0.57	0:10:12	0.86	1.43
Nurse	0.27	0:01:12	0.04	0.58
Anesthesiologist	0.57	0:04:48	0.27	1.83

Table 18: Performance measures per station for alternative 3

Patient class	$E(V_r)$
S	0:21:36
W	1:00:36
A	1:13:48
K	0:42:00

Table 19: Mean LOS per patient class for alternative 3

6.5 Alternative 4

In the current design, the secretary has to perform triage. Since she is not medically trained, the triage is not always performed correctly. In the design proposed by this alternative, the secretary only welcomes the patients, gives them the questionnaire needed for triage, and collects their medical record. She checks if all information is filled in on the form of the referring surgeon and sends the patient to the waiting room. She then puts the medical record on a pile, from which the nurses pick the records in a first come first serve order. The nurse collects the patient from the waiting room and performs triage. She inserts the patient's data into PDMS and perform an examination on the patient. All these activities are performed on each patient, regardless of his ASA Score and whether it is busy or not.

Once the nurse has finished her examination, she decides if the patient can go immediately to the anesthesiologist, or needs an appointment. If the patients is an adult with ASA Score 1 or 2 or a child, and it is not too busy, he can stay for instant evaluation by the anesthesiologist. If it is too busy the patient can choose to wait or make an appointment. Because the examination by the anesthesiologist needs preparation for adults with ASA Score 3 or 4, these patients get an appointment, unless they live far from the hospital or are emergency patients. The examination that is instantly performed by the nurse enables preparation of appointments for adults with ASA Score 3 or 4 such that approval for surgery can be given by the anesthesiologist immediately. The anesthesiologists appreciate it when they can approve a patient they examined themselves, since approving a patient seen by another anesthesiologist requires a lot of reading in the medical record. The secretary is responsible for collecting data from other doctors and/or other hospitals.

6.5.1 Parameter Values

Because all patients are evaluated instantly by the nurse, patient class S, and therefore ζ_1, disappears. The secretary is not responsible for inserting data in PDMS, so only the time she needs to welcome patients remains, which is exponentially distributed with mean 2.5 minutes for all patient classes. The nurse has to insert extra patient data in PDMS, namely the part the secretary did before. She also needs to carry out a thorough triage. therefore 3 minutes are added to the mean consultation time of the nurse for patient class W and A. For now it is assumed that the same fraction of patients as in the current design get an appointment. These patients do return later for an appointment, which results in three extra patient streams in the model. The arrival rate for the new patient classes $W2, A2$ and $K2$, corresponding to $r = [5, 6, 7]$ is equal to

$$\zeta_r = a_r \zeta_{r-3} \quad \text{for } r = [5..7] \tag{53}$$

with $SCV_{r,1} = 0$ because appointment patients are assumed to arrive on time. The formulas from the analytical model stated in Chapter 4 that were altered to model this alternative are listed in Appendix C.

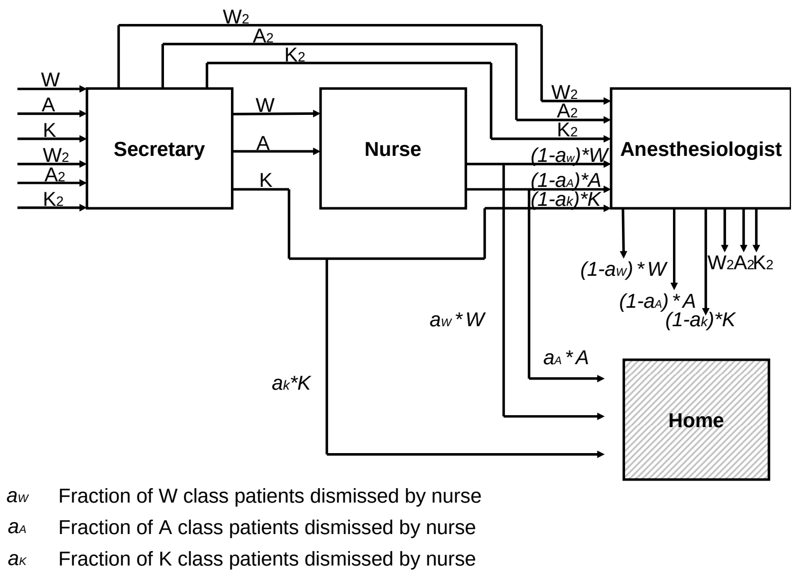

Figure 5: Patient flows for alternative 4

6.5.2 Results

The performance measures per station are given in Table 20, and the mean LOS per patient class is given in Table 21. The mean number of patients present at the PAC is equal to 7.46. In this design, the secretary's occupation rate decreases while the occupation rate of the nurse increase. The occupation rate of the anesthesiologists did not change, because there are still appointments scheduled.

Station	ρ_i	$E(W_{Q,i})$	$E(L_{Q,i})$	$E(L_i)$
Secretary	0.54	0:05:24	0.60	1.14
Nurse	0.51	0:05:24	0.35	1.36
Anesthesiologist	0.84	0:31:48	2.66	4.95

Table 20: Performance measures per station for alternative 4

Patient class	$E(V_r)$
W - instantly evaluated	1:30:36
W - dismissed by nurse	0:30:36
W - appointment	1:10:12
A - instantly evaluated	1:43:48
A - dismissed by nurse	0:31:12
A - appointment	1:22:48
K - instantly evaluated	1:04:48
K - dismissed by nurse	0:10:48
K - appointment	1:04:48

Table 21: Mean LOS per patient class for alternative 4

6.6 Alternative 5

In this alternative, alternatives 3 and 4 are combined. These combination was chosen because both alternatives turned out to have advantages. In alternative 3 the waiting time for patients decreased and occupation rate for staff decreased while alternative 4 allows for better preparation of appointment patients. Alternative 5 comes down to scheduling appointment patients during periods of low walk-in demand, namely in the early morning and on Friday afternoon, and to the nurse sending patients away with an appointment instead of the secretary. All patients go to the nurse during their first visit. If necessary, the nurse takes blood samples from the patient and decides if other measures should be taken prior to surgery. The examination performed by the nurse enables a better preparation of appointment patients with ASA Score 3 or 4, so that these patients can be approved by the anesthesiologist during their appointment, instead of a few days later. During an appointment, patients only have to consult the anesthesiologist, since they visited the nurse in their previous visit.

6.6.1 Parameter Values

To determine if combining this two alternatives also results in improvement, the model was adjusted as stated below. First, patient class S, and therefore ζ_1, is left out since all patients are instantly evaluated by the nurses. For now it is assumed that the same fraction of patients as in the current design get an appointment. The actual appointments are not taken into account in the model, since they do not occur in the interval 10:00 - 15:00. Patients dismissed by the nurse leave the system just before entering the queue at the anesthesiologists. The patients flows for alternative 5 are given in Figure 6.

As in alternative 4, the consultation time of the secretary is exponentially distributed with mean 2.5 minutes for all patient classes and the mean for the consultation time of the nurses

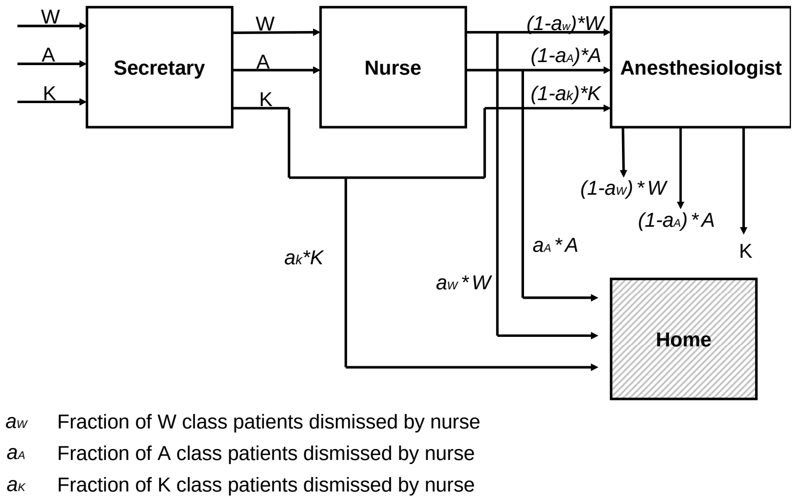

Figure 6: Patient flows for alternative 5

is increased with 3 minutes. The formulas from the analytical model stated in Chapter 4 that were altered to model this alternative are listed in Appendix C.

6.6.2 Results

The performance measures per station are given in Table 22, and the mean LOS per patient class is given in Table 23. The mean number of patients present at the PAC is equal to 3.90. During a staff meeting in June 2007, this alternative was unanimously chosen to be implemented at the PAC. The decrease in waiting times for patients, the more balanced workload over the staff members and the possibility for a better preparation and earlier approval of patients supported this decision. During this meeting it was also decided that to provide more continuity at the PAC, resident physicians work for three days in a row each six weeks instead of one day each two or three weeks. The new appointment schedule developed during the implementation of this alternative design is illustrated in Appendix D.

Station	ρ_i	$E(W_{Q,i})$	$E(L_{Q,i})$	$E(L_i)$
Secretary	0.42	0:03:36	0.30	0.71
Nurse	0.51	0:05:42	0.36	1.37
Anesthesiologist	0.57	0:04:12	0.26	1.82

Table 22: Performance measures per station for alternative 5

Patient class	$E(V_r)$
W - instantly evaluated	1:00:36
W - dismissed by nurse	0:28:48
A - instantly evaluated	1:14:24
A - dismissed by nurse	0:29:24
K - instantly evaluated	0:35:24
K - dismissed by nurse	0:08:24

Table 23: Mean LOS per patient class for alternative 5

7 Analytical Model for the Anesthesiologists

During the implementation of the alternative 5, which will be referred to as 'the new design' from now on, the question arised what would be a proper guideline for the number of patients allowed to wait for the anesthesiologist. This chapter provides a model to determine such a guideline.

7.1 Model Assumptions

To calculate the results for the new design it was assumed that the same fraction of patients as before would get an appointment. Since most of the adult ASA 1 or 2 and child appointments are unnecessary it is desirable to decrease the amount of these kind of appointments. Also a trade-off between the number of these patients dismissed by the nurse resulting in an appointment and the waiting time for patients at the anesthesiologist for patients who stay could be made. In Figure 7 a simplified routing scheme for the new design is given in which all patient classes are absorbed in the flow into the secretary station. After departing the secretary a fraction P_{13} of this stream jumps over the nurse's station to the anesthesiologist station. This stream represents children. The remaining stream with fraction P_{12} represents adults. After departing the nurse, a fraction P_{20} of adult patients leaves the system. These are adults with ASA Score 3 or 4 scheduled for an appointment. The stream with fraction P_{23} represents the remaining adult patients. Just after the streams with fractions P_{13} and P_{23} join, a part of the patients decides to depart before entering the queue at the anesthesiologists. This stream is depicted with *. Note that all fractions except * are known in advance.

7.2 The Model

To enable a separate analysis of the anesthesiologists station, the secretary and nurses station are represented by an M/M/1 and M/M/2 queue respectively. This results in a Poisson departure process at both stations which is also Poisson with rate λ_i, in which λ_i is the patient flow arriving at station i, $i = [1, 2]$. Define γ as the patient flow arriving at the PAC, then

$$\lambda_1 = \gamma \tag{54}$$
$$\lambda_2 = P_{12}\lambda_1 \tag{55}$$
$$\lambda_3 = P_{13}\lambda_1 + P_{23}\lambda_2 \tag{56}$$

The average service rate at station 3, $E(S_3)$, is defined as the weighted average of the mean service duration for the three patient classes at station 3:

$$E(S_3) = \frac{\sum_{r=2}^{4} n_r E(S_{r,3})}{N} \tag{57}$$

To model the stream * the function D_{n_3} is introduced. D_{n_3} represents the probability that an arriving patient decides to join the queue at station 3 if there are n_3 patients present at station 3 (i.e. in the queue and in service). $0 \leq D_{n_3} \leq 1$ for $n_3 = 0, 1, .., \infty$. This definition of D_{n_3} results in stream *. Again s_3 is the number of servers at station 3 and e_3

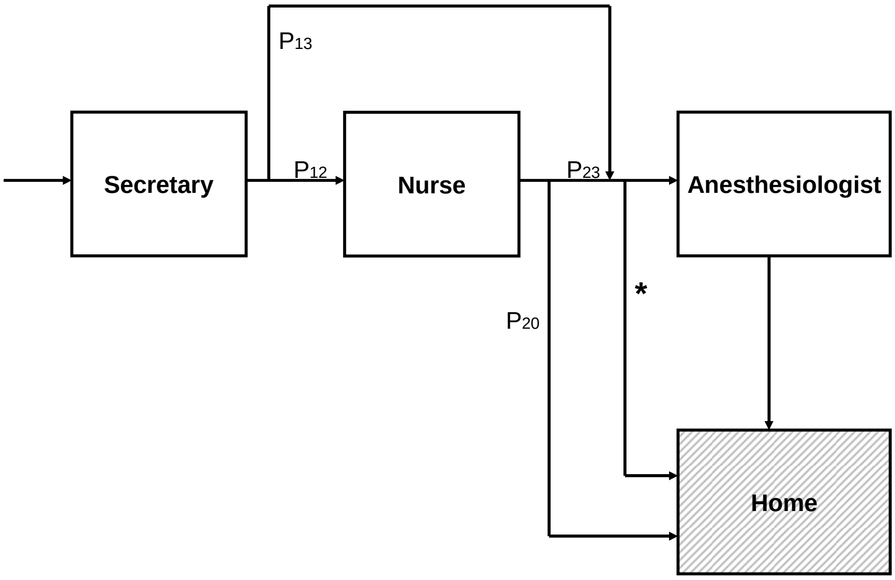

Figure 7: Simplified patient flows in the new design

is the effective capacity of station 3. The notion to introduce the function D_{n_3} comes from [60].

The stationary distribution for this model is given by [29]:

$$\pi_3(n_3) = Bc_{n_3}\pi_3(n_3) \quad \text{with} \tag{58}$$

$$c_{n_3} = \prod_{i=0}^{n_3-1} D_i \tag{59}$$

in which B is a normalization constant and $\pi_3(n_3)$ is the stationary distribution of the M/M/s queue. This results in the following stationary distribution, in which the normalization constant B is given by $\pi_3(0)$ and it is required that $\frac{\lambda_3 E(S_3)}{e_3} < 1$:

$$\pi_3(n_3) = \frac{1}{n_3!}\left(\frac{\lambda_3 E(S_3)}{e_3}\right)^{n_3} \prod_{i=0}^{n_3-1} D_i \quad \pi_3(0) \quad \text{for } n_3 = 1, 2, .., s_3 \tag{60}$$

$$\pi_3(n_3) = \frac{1}{s_3!}\left(\frac{\lambda_3 E(S_3)}{e_3}\right)^{s_3}\left(\frac{\lambda_3 E(S_3)}{s_3 e_3}\right)^{n_3-s_3} \prod_{i=0}^{n_3-1} D_i \quad \pi_3(0) \quad \text{for } n_3 > s_3 \tag{61}$$

$$\pi_3(0) = \left[1 + \sum_{n_3=1}^{s_3} \frac{1}{n_3!}\left(\frac{\lambda_3 E(S_3)}{e_3}\right)^{n_3} \prod_{i=0}^{n_3-1} D_i + \sum_{n_3=s_3+1}^{\infty} \frac{1}{s_3!}\left(\frac{\lambda_3 E(S_3)}{e_3}\right)^{s_3}\left(\frac{\lambda_3 E(S_3)}{s_3 e_3}\right)^{n_3-s_3} \prod_{i=0}^{n_3-1} D_i\right]^{-1} \tag{62}$$

7.3 Performance Measures

Define f_3^* as the fraction of patients that in equilibrium decides not to join the queue at station 3. f_3^* is given by

$$f_3^* = \sum_{n_3=0}^{\infty} (1 - D_{n3})\pi_3(n_3) \tag{63}$$

The number of patients dismissed by the nurses per hour (n_d) is equal to the arrival rate at station 3 multiplied by f_3^*:

$$n_d = f_3^* \lambda_3 \tag{64}$$

The mean queue length at station 3 is equal to

$$E(L_3^q) = \sum_{n_3=s_3+1}^{\infty} n_3 \pi_3(n_3) \tag{65}$$

By applying Little's law [1] the mean waiting time at station 3 is found:

$$E(W_3) = \frac{E(L_3^q)}{(1 - f_3^*)\lambda_3} = \frac{\sum_{n_3=s_3+1}^{\infty} n_3 \pi_3(n_3)}{(1 - f_3^*)\lambda_3} \tag{66}$$

8 Results for the Analytical Model for the Anesthesiologists

In this chapter the results for the analytical model described in the previous chapter are discussed. First the parameter values are given and the function D_{n_3} is defined. Next the results are stated and discussed.

8.1 Parameter values

As in the approximation model (Chapter 4) $\gamma = 5$. Furthermore $P_{12} = 0.81$, $P_{13} = 0.19$, $P_{20} = 0.07$ and $P_{23} = 0.93$. This results in $\lambda_3 = 4.70$. There are four anesthesiologists available, so $s_3 = 4$. The preparation of appointment patients has improved since the new design was implemented, anesthesiologists do not spend time anymore on looking for medical records anymore so e_3 is reduced to $(1-\frac{1}{4}) = \frac{3}{4}$. The mean service duration $E(S_r)$ equals 2.22. The current practice is that patients dismissed by the nurse if there are four or more patients waiting for the anesthesiologist. About 10% of these patients do stay, because they live far away or they are an emergency patient. If there are less than four patients waiting, about 90% of arriving patients stays for an instant evaluation by the anesthesiologist. The other 10% leaves, for instance because they have other obligations in the hospital or somewhere else. The parameter R_3 is the size of the waiting room for patients waiting for the anesthesiologist. By defining D_{n_3} as below, it is possible to investigate the effect of the size of the waiting room on the waiting times for patients and on the number of patients sent away per hour.

$$D_{n_3} = 0.90 \quad \text{for } n_3 < s_3 + R_3 \tag{67}$$

$$0.10 \quad \text{for } n_3 \geq s_3 + R_3 \tag{68}$$

8.2 Results

In Table 24 the mean waiting time for the anesthesiologist, the fraction of patients that decides not to join the queue (f_3^*) and the mean number of patients dismissed by the nurses per hour ($f_3^*\lambda_3$) are given for $R_3 = [0..7]$. For the staff of the clinic, a waiting room of size three, four

R_3	$E(W_3)$	$E(W_3)$ (min)	f_3^*	$f_3^*\lambda_3$
0	0.18	10:48	0.22	1.03
1	0.27	16:12	0.17	0.80
2	0.32	19:12	0.14	0.66
3	0.36	21:36	0.12	0.56
4	0.39	23:24	0.11	0.52
5	0.40	24:00	0.10	0.47
6	0.42	25:12	0.10	0.47
7	0.43	25:48	0.10	0.47

Table 24: Expected waiting time and number of patients dismissed by nurses for $R_3 = [0..7]$

or five patients is considered reasonable. There is not a big difference among the results for these values of R_3 and therefore it is decided to maintain the current size of the waiting room, which is equal to four patients.

9 Simulation Study

This chapter is organized as follows. First the simulation model built to perform the study is described. Next the verification and validation of this model, and the performance measures that can be calculated with the model are depicted. Finally alternative configurations for the organization of the lunch break are given. Results for this simulation study are in the next chapter.

The simulation study outlined in this chapter was carried out after the implementation of the new design. At this stage in the project, the first experiences with the new design were positive but the lunch break continued to cause long waiting times for patients who arrive during and around lunch. The simulation study is used to examine the effect of alternative configurations for the organization of the lunch break. The model was built with the the software package eM-Plant, version 7.0.6. eM-Plant is software for integrated, graphic and object oriented modeling, simulation and animation [56].

9.1 Description of the Simulation Model

This paragraph is divided into four parts: arrivals, routing of patients, service time distributions and opening hours. In figure 8 the lay-out of the model is shown for visual support.

9.1.1 Arrivals

With the new design, the effect of the secretary sending patients away previously became visible. Because in the new design all patients have to be evaluated by the nurse, there is no regulation on the walk-in arrivals until they depart from the nurses. An increase of arrivals during the morning with a peak around 11:00 was experienced by staff. After observation of the walk-in arrivals, the arrival process at the PAC is approximated with a non-homogeneous Poisson process with rates per interval as in Table 25. Upon arrival, an empirical distribution

Time	**Arrival rate**
08:00 - 09:30	2
09:30 - 10:30	5
10:30 - 11:30	10
11:30 - 15:00	5
15:00 - 16:30	2

Table 25: Arrival rates per interval

based on the ratio among adults walking in with ASA score 1 or 2 or 3 or 4 and children walking in is used. This ratio is deducted from Table 4 and 5 in Chapter 5. Appointment patients are scheduled in the morning, in the appointment intervals defined for the new design as outlined in Appendix D. An empirical distribution based on the proportion of adults with ASA score 1 or 2 and children that had appointments in the original design (Table 5 in Chapter 5) is used to determine whether a combined adult/child appointment slot is assigned

to a child or an adult. The amount of appointment slots per day in the new design is based on last year's demand for appointments and therefore it is assumed that all slots are used. It is also assumed that appointment patients arrive on time. The consultation by phone, which is an appointment but currently carried out by a anesthesiologist when he has time, is not considered in the model since it is completely unpredictable when the anesthesiologist will perform this consultation. Also making the phone call occurs at most once a day and takes at most ten minutes. Anesthesiologists do not wait for appointment patients, but keep on treating walk-in patients until an appointment patient is waiting for them. If an appointment patient is waiting, the anesthesiologist assigned to treat this appointment patient first finishes treating his current patient (if applicable).
During the opening hours of the PAC, the phone rings according to a Poisson process with rate $\lambda = 20$ per hour.

9.1.2 Routing of patients

For adults walking in with ASA score 1 or 2 , the routing is defined as follows:
ecretary → **Nurse** → **Anesthesiologist** → **Home** or
Secretary → **Nurse** → **Home**, if at departure from the nurse there are four or more walk-in patients waiting for one of the anesthesiologists. The patient gets an appointment.

For adults walking in with ASA score 3 or 4, the routing is defined as follows:
Secretary → **Nurse** → **Home**, these patients need extra preparation and come back later with an appointment, or they are routed
Secretary → **Nurse** → **Anesthesiologist** → **Home**, these patients need extra preparation too but live too far from the hospital to come back later. If an adult ASA 3 or 4 patient is scheduled for emergency surgery he is also seen immediately. An empirical distribution based on Table 5 in Chapter 5 is used to determine the routing for each adult ASA 3 or 4 patient.

For children walking in, the routing is defined as follows:
Secretary → **Anesthesiologist** → **Home** or
Secretary → **Home**, if at departure from the secretary, there are four or more walk-in patients waiting for one of the anesthesiologists. The child gets an appointment.

Since adults who come back for an appointment were treated by the nurse during their previous visit, their routing is equal to those of children coming back for an appointment:
Secretary → **Anesthesiologist** → **Home**

Patients dismissed by the nurse with an appointment leave the system and are not directly related to the appointment patients scheduled.

As can be seen in Figure 8, patients routed to the anesthesiologist first go to "Waitingroom2". There they are immediately distributed among four (virtual) waiting rooms, depending on their ASA score and whether they have an appointment or not. Children and adults with ASA score 1 or 2 are routed to waiting room "NonComplex" if they are walk-in patients, and to waiting room "AppNonComplex" if they have an appointment. The same procedure applies to adults with ASA score 3 or 4; they go either to waiting room “Complex” or to waiting room “AppComplex”. All of these waiting rooms have exit routes to the anesthesiologists who can treat the kind of patients present in the waiting room. Anesthesiologists pick patients from the waiting rooms assigned to them in a first come first serve manner, but appointment patients are prioritized over walk-in patients.

9.1.3 Service Time Distributions

The service time for the secretary is exponentially distributed with mean 2:30 minutes, because she is not responsible for entering patient data in PDMS anymore. The service time of both the nurses and the anesthesiologists is lognormal distributed with parameters as defined in Chapter 5. Because the nurses are now responsible for adding patient data in PDMS, 3:00 minutes are added to their mean service time. Again, the service time for walk-in and appointment patients is identical if they have the same ASA Score. Because different anesthesiologists work at the PAC each day it is not possible to make a well-based differentiation in service times regarding the three types of anesthesiologists. The duration of a phone call is modeled with an exponential distribution with mean 1 minute.

9.1.4 Assignment of Patients to the Nurses and Anesthesiologists

Patients arriving at the nurses’ station are treated by the nurse who is available first. If both nurses are available upon arrival, patients are assigned to them in turn.
Appointment patients are assigned in advance to one of the resident physicians, depending on the appointment agenda they are scheduled in.
Adults walking in with ASA Score 1 or 2 patients are treated by either the nurse practitioner or one of the resident physicians, depending on who is available first. Adults walking in with ASA Score 3 or 4 patients are treated by either the resident physician 2 or the senior physician, also depending on who is available first. If the senior physician is available when a child walks in, the child is immediately treated by him. Otherwise, the child joins the other walk-in patients and waits for either the nurse practitioner or one of the resident physicians to become available. This corresponds the current practice at the PAC; the secretary checks if the senior physician is available when a child walks in, and if not she sends the child to the waiting room. Walk-in patients are assigned to the anesthesiologists in a circulating manner if there is more than one anesthesiologist available upon arrival.

9.1.5 Opening hours

The reception opens at 08:00 when the first appointment patient arrives. It is closed during the lunch break, which is between 12:30 and 13:30. The nurses and anesthesiologists do not start treating a patient between 13:00 and 13:30, because in this interval they have lunch. Treatment of patients that started before 13:00 is finished. The PAC closes in the afternoon once all patients have left the system. The opening hours of the clinic specify the length of each replication so that the simulation is terminating [32]. Except during their lunch, all staff members are constantly available. Note that the reception closes for an hour but that staff has half an hour for lunch.

9.1.6 Remarks

The simulation model described here is, like any other simulation model, a simple representation of reality. Next to the to assumptions already mentioned in the text, it is important to remark that at the PAC treatment of a patient is not immediately started once treatment of the previous patient has finished. Furthermore there are not always four anesthesiologists available all the time, since they tend to perform other activities like making phone calls and visiting other departments in the hospital. The time the reception actually closes for lunch varies and depends on the staff members working.

9.2 Verification

Model verification is often defined as ensuring that the computer program of the computerized model and its implementation are correct [49]. To verify if this model was properly built in eM-Plant, the debugger functionality of the program was used. Also the animation of various replications was observed and the results provided by the model were analyzed for reasonableness.

9.3 Validation

Comparing simple cases of a simulation model to known results of an analytical model is a common used technique to validate simulation models [49]. The simulation model described in this chapter is simplified and compared to an analytical model of a network of M/M/c queues. In both models all patient classes as defined in Chapter 4 arrive according to a Poisson process with arrival rate ζ_r (Table 8) and have an exponential service time distribution with mean $E(S_{r,i})$ (Table 10).

The analytical model used for validation purposes is the approximation model (Chapter 4). $e_i = 1$ for all i, $s_1 = 1$, $s_2 = 2$, and $s_3 = 4$. In both models it is known in advance if a patient is sent away and patients follow the same routing in the simulation model as in the analytical model. In contrary to the simulation model described in the previous paragraphs of this chapter, patients are sent home by the secretary. This is because the analytical model used for validation was made in a previous stage of the project, in which the secretary was sending patients home. Results for this model were already available. Patients who arrive at the nurse or anesthesiologist station are treated by the nurse or anesthesiologist available first. If more than one nurse or anesthesiologist is available upon arrival, patients are assigned in a circulating manner. All patient types that visit the anesthesiologist can be treated by all three types of anesthesiologists.

To compare the two models a non-terminating simulation with a warm-up period was used, instead of the terminating simulation used for comparing the alternative configurations for the lunch break. This means that the PAC is open all day and patients arrive throughout the day. Many replications can be made with the simplified simulation model in a short period of time, so it was possible to check if the outcomes from the simulation model converge to those of the analytical model. After making 5,000 replications in which a warm-up period of 2,500 replications is included, the difference for all performance measures stated in Table

26 is less than 4%. The results for the simplified simulation model converge to those of the approximation model.

Performance measure	**Approximation model**	**Simulation model**	**Difference (%)**
ρ_1	0.52	0.52	0.00
ρ_2	0.41	0.41	0.00
ρ_3	0.58	0.58	0.00
$E(S_1)$	0:04:48	0:04:49	0.35
$E(S_2)$	0:12:04	0:12:03	-0.14
$E(S_3)$	0:27:40	0:27:40	0.00
$E(W_1)$	0:05:34	0:05:36	0.60
$E(W_2)$	0:02:25	0:02:20	-3.45
$E(W_3)$	0:04:18	0:04:15	-1.16
$E(V_1)$	0:08:04	0:08:03	-0.21
$E(V_2)$	0:57:23	0:57:19	-0.12
$E(V_3)$	1:10:35	1:10:38	0.07
$E(V_4)$	0:37:34	0:37:33	-0.04

Table 26: Difference per performance measure for the two models

9.4 Performance Measures

The performance measures stated below can be calculated with the simulation model and are used to compare alternative configurations for the organization of the lunch break.

- Occupation rates for the secretary, nurses and anesthesiologists per interval
- Waiting times for patients at the secretary nurses and anesthesiologists per interval of patient arrival time
- The number of adults with ASA score 1 or 2 that walk in and are dismissed by the nurse with an appointment per day

For a good comparison of the occupation rates of the different configurations, the occupation rate for the secretary only involves time spent with patient contact. Picking up the phone when there are no patients present is not taken into account. Picking up the phone when there are patients present is taken into account since it extends the time the secretary spends on serving the patient.

Due to a decrease in walk-in arrivals on Friday, long waiting times are exceptional on this day. Therefore in this simulation study only the appointment slots used on Monday to Thursday are defined. The arrival process is modeled such that the arrival rates used represent the average arrival rates per interval from Monday to Thursday.

To obtain approximate $100(1-\alpha)\%$ confidence intervals for performance measure μ with a relative precision of γ, the sequential procedure as described in [32], pp. 513-514 is used.

9.5 Alternative Configurations for the Lunch Break

After discussion with staff it was decided to re-consider the opening hours of the reception and the lunch time of the employees. This resulted in four possible configurations for the lunch break.

9.5.1 Configuration 1

In this configuration the reception remains closed between 12:30 and 13:30. Staff members have lunch in two shifts. The first group has lunch from 12:30 to 13:00 and consists of one nurse, the nurse practitioner and resident physician 2. The second group has lunch from 13:00 to 13:30 and consists of the other nurse, resident physician 1 and the senior physician. The secretary is free to choose which group she joins. The staff is grouped like this to ensure there is always one anesthesiologist available to treat complex patients.
It was decided not to simulate this configuration. Because of the shifts, there is half capacity during the interval 12:30 - 13:30 instead of full capacity during the interval 12:30 - 13:00 and no capacity during the interval 13:00 - 13:30. With the reception being closed, there is no supply of new patients between 12:30 and 13:30. This results in longer waiting times for patients who arrived just before 12:30 because there is only half the capacity available, and in a higher occupation rate for staff members working the first half hour. There is no supply of new arriving patients, while there are patients waiting at the reception desk when the reception opens again at 13:30. Summarized, this configuration will not result in an improvement and therefore it is not simulated.

9.5.2 Configuration 2

Now again the staff has lunch in two shifts, but the reception is opened during the interval 12:30 - 13:30. The first shift that has lunch consists of the secretary, one nurse and resident physician 2. The second shift consists of the other nurse, the nurse practitioner, resident physician 1 and the senior physician. When the secretary has lunch, the nurse practitioner manages the reception.

9.5.3 Configuration 3

In this configuration staff has lunch in two shifts, but now the shifts are based on profession. The reception remains closed between 12:30 and 13:30. The first shift that has lunch between 12:30 and 13:00 consists of the secretary and both nurses, while the second shift that has lunch between 13:00 and 13:30 consists of all four anesthesiologists. The idea of having lunch in shifts with staff members of the same profession is based on the observation that currently the anesthesiologists have to wait for new patients when they come back from lunch at 13:30. These ‘new’ patients first have to be treated by the nurses after the break and this results in anesthesiologists having nothing to do for a while.

9.5.4 Configuration 4

This configuration combines the lunch in shifts based on profession and the reception being opened during the interval 12:30 - 13:30. The shifts defined for lunch are identical to those of configuration 3. When the secretary has lunch, the nurse practitioner manages the reception.

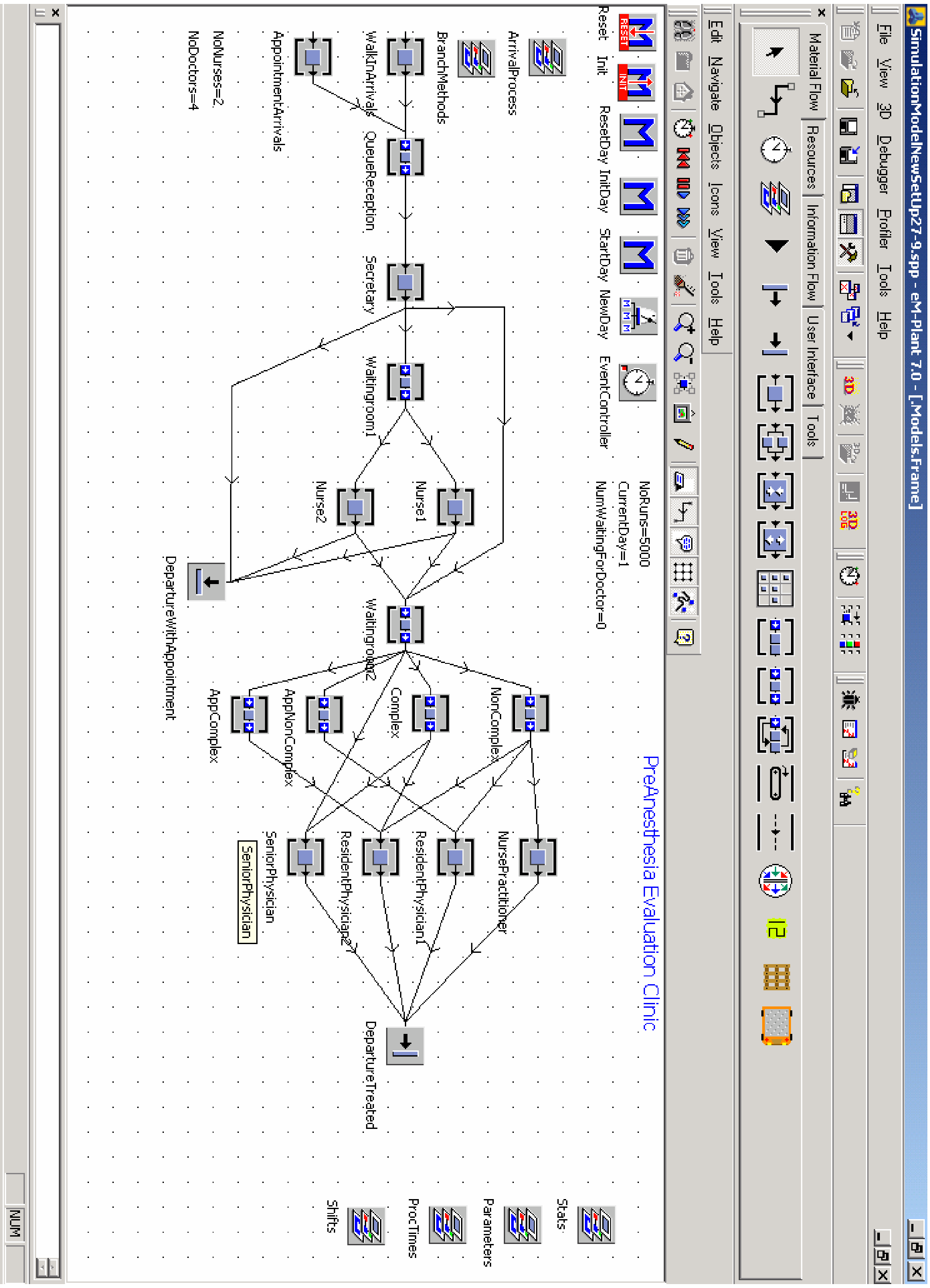

Figure 8: Lay-out of simulation model

10 Results for the Simulation Study

This chapter starts with the results for the new design which give an indication for the current performance of the PAC. Next this results are compared with the results for configuration 2, 3, and 4. Confidence intervals for the difference between the new design and the three configurations are calculated, again using the sequential procedure as described in [32]. For all approximate $100(1-\alpha)\%$ confidence intervals for performance measure μ with relative precision γ, $\alpha = 0.05$ and $\gamma = 0.10$ is used. Performance measures for which $\bar{X}(n) \approx 0$ are indicated with a *.

10.1 The new design

Results for the new design are given in Table 27 and 28. For all staff members, the occupation rates increase during the morning followed by a peak in the interval 11:00 - 12:00. Then a decrease toward and during the lunch break occurs, followed by another peak just after lunch. Subsequently, the occupation rates decrease again. The waiting times show the same pattern. The waiting times for the secretary and the nurses are very low in the early morning and late afternoon. The waiting time for the secretary is very high for patients that arrive during the lunch break, since they have to wait until 13:30 when the reception opens again. The confidence interval for the number of patients dismissed by the nurses per day is [1.35 , 1.63]. Unfortunately these results could not be compared to data available from the tracking system GPL. At the moment of writing, staff was still learning how to work with the new routines. Next to that not all nurses were able to work the hours assigned to them, which resulted in under-capacity. There was also a lot of discussion about the opening hours of the reception, resulting in the reception being closed around lunch for almost two hours one day and being closed for only half an hour the other day. These factors could not be accounted for in the simulation study and therefore a good comparison with GPL could not be made.

Interval	**Secretary**	**Nurse**	**Anesthesiologist**
08:00 - 09:00	[25.54 , 30.64]	[13.03 , 15.63]	[40.60 , 48.38]
09:00 - 10:00	[27.39 , 32.85]	[22.65 , 27.17]	[51.88 , 62.14]
10:00 - 11:00	[33.06 , 39.66]	[48.90 , 58.62]	[50.96 , 60.96]
11:00 - 12:00	[39.12 , 46.94]	[69.54 , 83.38]	[69.29 , 82.09]
12:00 - 12:30	[26.85 , 32.21]	[59.34 , 71.16]	[53.74 , 64.48]
12:30 - 13:30	*	[19.63 , 23.55]	[40.24 , 48.22]
13:30 - 14:00	[63.30 , 75.88]	[57.70 , 69.20]	[45.47 , 54.57]
14:00 - 15:00	[31.14 , 37.34]	[61.54 , 73.74]	[55.17 , 66.05]
15:00 - 16:00	[10.95 , 13.13]	[31.77 , 38.09]	[47.26 , 56.64]
16:00 - 16:30	[5.66 , 6.80]	[13.95 , 16.75]	[23.46 , 28.14]

Table 27: Confidence intervals for occupation rates per interval

10.2 Configuration 2

In the proceeding paragraphs confidence intervals are only given if there is a difference between the new design and the configuration under consideration. The relevant confidence intervals

Interval	Secretary	Nurse	Anesthesiologist
08:00 - 09:00	*	*	[04:44 , 05:40]
09:00 - 10:00	*	*	[10:36 , 12:44]
10:00 - 11:00	[02:08 , 02:35]	[03:29 , 04:25]	[07:20 , 08:48]
11:00 - 12:00	[02:57 , 03:33]	[10:07 , 12:09]	[13:57 , 16:43]
12:00 - 12:30	[03:06 , 03:44]	[06:13 , 07:27]	[11:31 , 13:49]
12:30 - 13:30	[34:23 , 41:11]	[04:11 , 05:01]	[05:31 , 06:37]
13:30 - 14:00	[07:11 , 08:37]	[09:13 , 11:03]	[07:38 , 09:10]
14:00 - 15:00	[01:39 , 01:59]	[08:12 , 09:50]	[08:32 , 10:28]
15:00 - 16:00	*	*	[04:01 , 04:49]
16:00 - 16:30	*	*	*

Table 28: Confidence intervals for waiting times per interval of patient arrival time

for configuration 2 are given in Table 29 and 30. The differences in occupation rates show that the workload is more balanced around lunch. The waiting time for patients arriving around lunch at the secretary decreases, but is partly relocated to the nurse and anesthesiologist station. The confidence interval for the difference in number of patients dismissed by the nurses per day is [1.28 , 1.54]. This increase is probably caused by only half the capacity being available during lunch combined with the constant supply of new patients to the nurses and anesthesiologists. Note that this configuration results in an increase in waiting times for the nurse and anesthesiologist station.

Interval	Secretary	Nurse	Anesthesiologist
12:30 - 13:30	[23.00 , 27.58]	[34.33 , 41.19]	[13.78 , 16.54]
13:30 - 14:00	[-45.92 , -38.28]	[-16.39 , -13.65]	*
14:00 - 15:00	[-5.32 , -4.44]	[-11.27 , -9.39]	*

Table 29: Confidence intervals for difference in occupation rates per interval

Interval	Secretary	Nurse	Anesthesiologist
11:00 - 12:00	*	*	[03:48 , 04:34]
12:00 - 12:30	[-02:25 , -02:01]	[02:58 , 03:34]	[12:52 , 15:26]
12:30 - 13:30	[-36:49 , -36:15]	[13:37 , 14:57]	[17:51 , 21:25]
13:30 - 14:00	[-07:25 , -06:11]	*	*

Table 30: Confidence intervals for difference in waiting times per interval of patient arrival time

10.3 Configuration 3

This configuration only results in a longer waiting time at the nurses for patients that enter the PAC in the interval 12:00 - 12:30, the confidence interval for this difference is [04:09 , 05:11]. The nurses have lunch half an hour earlier, but still have to treat the patients that were already waiting before lunch. Now they do this in the second half hour of the lunch break. The anesthesiologists do not have a higher occupation rate in the interval 13:30 - 14:00. Because new patients are admitted after 13:30, the anesthesiologists have to wait for this patients to be treated by the nurse first.

10.4 Configuration 4

The confidence intervals for the difference in the occupation rates and waiting times for the secretary are identical to those stated in Table 29 and 30 respectively. Configuration 4 results in a more balanced workload around lunch and lower waiting times at the secretary for patients that arrive during lunch. The waiting times of these patients are partly relocated to the nurse and anesthesiologist station. For patients that arrive around lunch, this configuration results in a decrease of their total waiting time. The difference in number of patients dismissed by the nurses per day ≈ 0. The current amount of patients that is dismissed by the nurses is considered acceptable. The reception being opened during lunch is regarded as being an advantage, since then the staff members do not have to negotiate about the closing times of the reception each day. The absence of a real lunch break makes it easier to take half an hour off for lunch, instead of treating patients during a supposed to be lunch break because these patients arrived before the lunch break. The results for this configuration were considered so positive by staff that it was chosen for implementation at a staff meeting in October 2007.

Interval	**Nurse**	**Anesthesiologist**
12:30 - 13:30	[20.80 , 24.97]	*
13:30 - 14:00	[-15.12 , -12.60]	[19.97 , 23.97]
14:00 - 15:00	[-14.85 , -12.37]	[-5.86 , -4.88]
15:00 - 16:00	[-5.50 , -4.58]	[-6.35 , -5.29]

Table 31: Confidence intervals for difference in occupation rates per interval

Interval	**Nurse**	**Anesthesiologist**
12:00 - 12:30	[-06:51 , -05:43]	*
12:30 - 13:30	[08:50 , 10:36]	[09:07 , 10:57]
13:30 - 14:00	[-05:58 , -04:58]	*
14:00 - 15:00	[-05:10 , -04:18]	*

Table 32: Confidence intervals for difference in waiting times per interval of patient arrival time

11 Conclusions and Recommendations

This chapter summarizes the conclusions that can be drawn from the study described in this report. The research question stated in the first chapter is subdivided into two separate questions: (1) *What causes the current waiting times for patients and the high workload experienced by staff* and (2) *Is it possible to decrease patient waiting times and workload experienced by staff by altering the design of the PAC*. In the following subparagraph each question will be answered separately. Subsequently recommendations are given for further improvement.

11.1 Conclusions

What causes the current waiting times for patients and the high workload experienced by staff?

Factors causing long patient waiting times and high workload for staff are identified in the previous chapters of this report. These factors are:

- The secretary has to perform three tasks simultaneously: (1) answer the phone, (2) welcome patients and decide if they can stay for instant evaluation, and (3) insert patient data into the computer system. The first and second task interrupt the third task.
- Anesthesiologists spend a part of their time with trivial tasks like looking for lost medical records.
- Appointments are ill prepared: medical history of the patient is not always available.
- Test results are not available when the patient visits the anesthesiologist, leading to a list of patients to be approved.
- Appointments are scheduled during periods of increased walk-in arrivals.

Is it possible to decrease patient waiting times and workload experienced by staff by altering the design of the PAC?

The outcomes of the multi class open queuing network model (Chapter 4) suggested measures to decrease patient waiting times and workload for staff, namely

- When welcoming patients, the secretary receives the patient's medical record, but does not decide on whether the patient can be evaluated immediately or not. She just puts the record on the nurse's pile.
- The nurse takes over a part of the activities of the secretary, and is now responsible for carrying out the triage. All patients are evaluated by the nurse and are dismissed by her if appropriate.
- The secretary prepares appointments by placing requests for the patient's medical history at other doctors and/or hospitals.

- Testing is now performed in advance, so test results are available during the appointment.
- Appointment patients are scheduled during periods of low walk-in demand.

After the introduction of these measures mid-2007 the workload experienced by the anesthesiologists decreased dramatically. The nurses experienced a higher workload than before, which was expected since they had to perform more tasks. The secretary's workload remained the same, which was unexpected. Apparently with her current tasks the secretary still experiences a high workload.

If there are four or more walk-in patients waiting for the anesthesiologist, the nurse dismisses patients with an appointment. With the model outlined in Chapter 7 it was attempted to make a trade-off between the number of patients dismissed by the nurse per hour and the average waiting time for patients who get instant evaluation by the anesthesiologist. Unfortunately the results from the model were inconclusive and therefore the current boundary of four patients is maintained.

Because patients arriving around lunch still experienced longer waiting times after the implementation of the re-design, a simulation study (Chapter 9) was used to evaluate alternative configurations for the lunch break. In the configuration that was chosen to be implemented, the clinic is opened from 12:30 to 13:30 and employees have lunch in two shifts based on profession.

Preliminary experiences with the new routine, appointment system and new set-up for the lunch break are positive, although there are still some issues to be taken care of. On the moment of writing, no suitable data was available to numerically compare the performance of the re-designed PAC with the performance of the old PAC.

11.2 Recommendations

First it is recommended to explore possibilities to decrease the workload of the secretary. For instance, the nurses could prepare appointments in the early morning when walk-in arrivals are low, and an attempt could be made to decrease the amount of phone calls to the clinic. The nurses experience a higher workload than before, so evaluating their situation should be considered. When suitable data becomes available, the performance of the re-designed PAC and the 'old' PAC should be compared.

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Appendices

A ASA Classification System

The text in this appendix is partly a summary of the first part of the Wikipedia lemma 'ASA Score' [4]. It explains the ASA classification system used at the PAC to characterize the physical condition of a patient.

In 1963 a five category physical status classification system for assessing a patient before surgery was adopted by the American Society of Anesthesiologists (ASA) [2]. A sixth category was added later. The six categories are:

1 A normal healthy patient

2 A patient with mild systemic disease[3]

3 A patient with severe systemic disease

4 A patient with severe systemic disease that is a constant threat to life

5 A moribund patient who is not expected to survive without the operation

6 A declared brain-dead patient whose organs are being removed for donor purposes

The physical status score is followed by "E" if the surgery is an emergency. An emergency is defined as existing when delay in treatment of the patient would lead to a significant increase in the threat to life or body part.

These definitions appear in each annual edition of the ASA Relative Value Guide, and there is no additional information that can be helpful to further define these categories. This results in many possible interpretations of the ASA score definitions.

Due to the nature of the ASA Classification System, patients with ASA Score 5 or 6 will not be present at the PAC.

[3] A disease that affects a number of organs and tissues or affects the body as a whole [55]

B Aggregated Patient Arrivals

In this appendix an overview of the aggregated patient arrivals per month and per weekday is given. With the abbreviation SD mentioned in the tables, the standard deviation is meant.

Month	**# of arrivals**	**# of days**	**Mean # arrivals/day**	**SD**
All	5857	249	23.60	7.11
June 2006	474	21	22.57	3.93
July 2006	427	21	20.33	5.89
August 2006	467	23	20.30	6.16
September 2006	498	21	23.71	7.27
October 2006	491	21	23.38	7.50
November 2006	518	22	23.55	6.17
December 2006	460	19	24.21	7.79
January 2007	531	22	24.14	8.32
February 2007	497	20	24.85	5.82
March 2007	556	22	25.27	6.92
April 2007	479	18	26.61	8.23
May 2007	459	19	24.16	9.38

Table B1: Aggregated patient arrivals per month

Day	**# of arrivals**	**# of days**	**Mean # arrivals/day**	**SD**
All	5857	249	23.60	7.11
Monday	1137	46	24.72	3.43
Tuesday	1344	50	26.88	4.45
Wednesday	1245	52	23.94	4.23
Thursday	1307	51	25.63	3.45
Friday	824	50	16.48	3.02

Table B2: Aggregated patient arrivals per weekday

C Adjustments for the Approximation Model

To calculate results for alternative 4 and 5, some formulas from the approximation model as described in Chapter 4 had to be adjusted. The adjusted formulas are stated in the next two sections.

C.1 Alternative 4

The index $r = [2, 3, 4, 5, 6, 7]$ corresponds to the patient classes $W, A, K, W2, A2$ and $K2$ respectively.

Formula (1) and (3):

$$\rho_1 = \sum_{r=2}^{7} \rho_{1,r} \tag{69}$$

$$\rho_3 = \sum_{r=2}^{7} \rho_{3,r} \tag{70}$$

Formula (4) and (6):

$$\rho_{1,r} = \zeta_r E(S_{r,1}) \frac{1}{e_1 s_1} \quad \text{for } r = [2..7] \tag{71}$$

$$\rho_{3,r} = \zeta_r E(S_{r,3}) \frac{1}{e_3 s_3} \quad \text{for } r = [2..4] \tag{72}$$

$$\rho_{3,r} = (1 - a_r)\zeta_r E(S_{r,3}) \frac{1}{e_3 s_3} \quad \text{for } r = [5..7] \tag{73}$$

Formula (7) and (9):

$$\lambda_1 = \sum_{r=2}^{7} \zeta_r \tag{74}$$

$$\lambda_3 = \sum_{r=2}^{4} (1 - a_r)\zeta_r + \sum_{r=5}^{7} \zeta_r \tag{75}$$

Formula (10) and (12):

$$SCV_{Ar,1} = w_1 \sum_{r=2}^{7} Q_{r,1} SCV_{r,1} + 1 - w_1 \tag{76}$$

$$v_1 = \frac{\lambda_1^2}{\sum_{r=2}^{7} \zeta_r^2} \tag{77}$$

Formula (14) and (15):

$$E(S_1) = \frac{1}{\lambda_1} \sum_{r=2}^{7} \zeta_r E(S_{r,1}) \tag{78}$$

$$SCV_{S,1} = \frac{1}{\lambda_1 E^2(S_1)} \sum_{r=2}^{7} \zeta_r E^2(S_{r,1})(SCV_{S,r,1} + 1) - 1 \tag{79}$$

Formula (24), (25), (27) and (28):

$$Q_{2,3} = \frac{(1 - a_2)\zeta_2 + (1 - a_3)\zeta_3}{\lambda_3} \tag{80}$$

$$Q_{1,3} = \frac{\sum_{r=4}^{7}(1 - a_r)\zeta_r}{\lambda_3} \tag{81}$$

$$P_{1,3} = \frac{\sum_{r=4}^{7}(1 - a_r)\zeta_r}{\lambda_1} \tag{82}$$

$$SCV_{2,3} = P_{2,3} SCV_{D,2} + 1 - P_{2,3} \quad \text{with} \tag{83}$$

$$P_{2,3} = \frac{(1 - a_2)\zeta_2 + (1 - a_3)\zeta_3}{\lambda_2} \tag{84}$$

Formula (30) and (31):

$$E(S_3) = \frac{1}{\lambda_3} \left(\sum_{r=2}^{4} (1 - a_r)\zeta_r E(S_{r,3}) + \sum_{r=5}^{7} \zeta_r E(S_{r,3}) \right) \tag{85}$$

$$SCV_{S,3} = \frac{1}{\lambda_3 E^2(S_3)} \left(\sum_{r=2}^{4} (1 - a_r)\zeta_r E^2(S_{r,3})(SCV_{S,r,3} + 1) \right. \tag{86}$$

$$\left. + \sum_{r=5}^{7} \zeta_r E^2(S_{r,3})(SCV_{S,r,3} + 1) \right) - 1 \tag{87}$$

The formulas for the performance measures also change. With patient route a, the route including a visit to the anesthesiologist is meant, with patient route b the route is meant in which patients are dismissed with an appointment by the nurse.

$$E(V_{2a}) = \sum_{i=1}^{3} E(W_{Q,i}) + \frac{E(S_{S,2,1})}{e_1} + E(S_{S,2,2}) + E(S_{S,2,3}) \tag{88}$$

$$E(V_{2b}) = \sum_{i=1}^{2} E(W_{Q,i}) + \frac{E(S_{S,2,1})}{e_1} + E(S_{S,2,2}) \tag{89}$$

$$E(V_{3a}) = \sum_{i=1}^{3} E(W_{Q,i}) + \frac{E(S_{S,3,1})}{e_1} + E(S_{S,3,2}) + E(S_{S,3,3}) \tag{90}$$

$$E(V_{3b}) = \sum_{i=1}^{2} E(W_{Q,i}) + \frac{E(S_{S,3,1})}{e_1} + E(S_{S,3,2}) \tag{91}$$

$$E(V_{4a}) = E(W_{Q,1}) + \frac{E(S_{S,4,1})}{e_1} + E(W_{Q,3}) + E(S_{S,4,3}) \quad (92)$$

$$E(V_{4b}) = E(W_{Q,1}) + \frac{E(S_{S,4,1})}{e_1} \quad (93)$$

$$E(V_5) = E(W_{Q,1}) + \frac{E(S_{S,5,1})}{e_1} + E(W_{Q,3}) + E(S_{S,5,3}) \quad (94)$$

$$E(V_6) = E(W_{Q,1}) + \frac{E(S_{S,6,1})}{e_1} + E(W_{Q,3}) + E(S_{S,6,3}) \quad (95)$$

$$E(V_7) = E(W_{Q,1}) + \frac{E(S_{S,7,1})}{e_1} + E(W_{Q,3}) + E(S_{S,7,3}) \quad (96)$$

Furthermore, all sums with index $\sum_{r=1}^{..}$ are changed to $\sum_{r=2}^{..}$ and formulas defined for $r = [1..n]$ are now defined for $r = [2..n]$.

C.2 Alternative 5

Formula (6):

$$\rho_{3,r} = (1 - a_r)\zeta_r E(S_{r,3}) \frac{1}{e_3 s_3} \quad \text{for } r = [2..4] \quad (97)$$

Formula (9):

$$\lambda_3 = \sum_{r=2}^{4} (1 - a_r)\zeta_r \quad (98)$$

Formula (24), (25), (27) and (28):

$$Q_{2,3} = \frac{(1 - a_2)\zeta_2 + (1 - a_3)\zeta_3}{\lambda_3} \quad (99)$$

$$Q_{1,3} = \frac{(1 - a_4)\zeta_4}{\lambda_3} \quad (100)$$

$$P_{1,3} = \frac{(1 - a_4)\zeta_4}{\lambda_1} \quad (101)$$

$$SCV_{2,3} = P_{2,3} SCV_{D,2} + 1 - P_{2,3} \quad \text{with} \quad (102)$$

$$P_{2,3} = \frac{(1 - a_2)\zeta_2 + (1 - a_3)\zeta_3}{\lambda_2} \quad (103)$$

Formula (30) and (31):

$$E(S_3) = \frac{1}{\lambda_3} \sum_{r=2}^{4} (1 - a_r)\zeta_r E(S_{r,3}) \quad (104)$$

$$SCV_{S,3} = \frac{1}{\lambda_3 E^2(S_3)} \sum_{r=2}^{4} (1 - a_r)\zeta_r E^2(S_{r,3})(SCV_{S,r,3} + 1) - 1 \quad (105)$$

The formulas for the performance measures also change. With patient route a, the route including a visit to the anesthesiologist is meant, with patient route b the route is meant in which patients are dismissed with an appointment by the nurse.

$$E(V_{2a}) = \sum_{i=1}^{3} E(W_{Q,i}) + \frac{E(S_{S,2,1})}{e_1} + E(S_{S,2,2}) + E(S_{S,2,3}) \tag{106}$$

$$E(V_{2b}) = \sum_{i=1}^{2} E(W_{Q,i}) + \frac{E(S_{S,2,1})}{e_1} + E(S_{S,2,2}) \tag{107}$$

$$E(V_{3a}) = \sum_{i=1}^{3} E(W_{Q,i}) + \frac{E(S_{S,3,1})}{e_1} + E(S_{S,3,2}) + E(S_{S,3,3}) \tag{108}$$

$$E(V_{3b}) = \sum_{i=1}^{2} E(W_{Q,i}) + \frac{E(S_{S,3,1})}{e_1} + E(S_{S,3,2}) \tag{109}$$

$$E(V_{4a}) = E(W_{Q,1}) + \frac{E(S_{S,4,1})}{e_1} + E(W_{Q,3}) + E(S_{S,4,3}) \tag{110}$$

$$E(V_{4b}) = E(W_{Q,1}) + \frac{E(S_{S,4,1})}{e_1} \tag{111}$$

D New Appointment Schedule

The appointment schedule that was developed to complement walk-in arrivals, involves two parallel agenda's. It is presumed that appointments in the first agenda are handled by the more experienced resident physician, while the less experienced resident physician is responsible for the appointments in the second agenda.

To ensure there are enough appointment slots available, data from the period June 2006 - May 2007 was used to determine the required number of appointments per week. As stated in Table 5 in Paragraph 5.2, the number of appointments in this period per patient class W, A, and K is equal to 1288, 352 and 133 respectively. Dividing these numbers by 249, the amount of working days in the investigated period, and then multiplying it by 5, leads to the required number of appointments per week. For class W patients this is equal to 26 appointments, class A patients need 7 appointments and class K patients need 3 appointments per week.

For class W and class K patients, the time scheduled for an appointment is equal to 30 minutes, and for class A patients time scheduled for an appointment is equal to 45 minutes. These are conservative estimates which provide some room for delay, furthermore 30 and 45 minute intervals are easy to work with.

The appointments are scheduled during intervals with less walk-in arrivals. This results in the appointment schedule shown in Table 33.

Agenda 1			**Agenda 2**		
Day	**Time**	**Patient class**	**Day**	**Time**	**Patient class**
Mon - Fri	08:00	A	Mon - Fri	08:00	W or K
Mon - Fri	08:45	W or K	Mon - Fri	08:30	W or K
Mon - Fri	09:15	Consultation per phone	Mon - Fri	09:00	W or K
Mon - Fri	09:30	Emergency	Mon - Fri	09:30	W, A or K
Fri	13:30	A	Fri	13:30	W or K
Fri	14:15	A	Fri	14:00	W or K
Fri	15:00	W or K	Fri	14:30	W or K
Fri	15:30	W or K	Fri	15:00	W or K
			Fri	15:30	W or K

Table 33: New appointment schedule

The 09:30 appointment in agenda 2 is twice a week assigned to a W/K appointment and three times a week there is extra capacity available in which any kind of appointment can be scheduled. If the patient scheduled for this appointment time is a class A patient, the senior physician can treat this patient instead of the resident physician.