A SIMULATION MODEL TO SUPPORT IMPLEMENTATION OF A COMBINED WALK-IN AND APPOINTMENT SYSTEM AT DIAGNOSTIC FACILITIES

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Management summary

Introduction and Problem description

If resources such as machines or personnel in a production or service process are scarce, they have to be allocated in such a way that the objectives of the organization can be realized. The manner in which this is done impacts the performance. At diagnostic facilities appointment systems are commonly used to organize these resources, where supply and demand are matched to avoid crowded waiting rooms and to create a leveled workload. Possible downsides of this system are that there can be several days between the appointment request and the actual moment of service (access time) and that the planning costs time and money.

Alternatively, if no schedule is used, patients can walk in without an appointment at any time the facility is open. This system potentially offers logistical benefits: utilization can be increased because no time has to be reserved for slack, no resources have to be used for scheduling and access time is reduced to zero. There are also benefits from the patient's perspective: less visits to the hospital and the potentially stressful period of awaiting the appointment is avoided. A possible drawback of the system is that the fluctuation in demand can cause peaks in the workload and long waiting time for patients.

There are also situations in which a walk-in system is not possible or desired. For this situation a combination between an appointment and walk-in system can be constructed. In this combined system time is reserved for appointments while the remaining time is open for walk-in patients. The challenge in this combination is to balance the pros and cons of both systems and to minimize the number of walk-in patients who is not allowed to walk-in because it is too busy at the diagnostic facility (a deferral).

Research objective and approach

The objective of this research is to develop a simulation model that can be used to support decision makers at a diagnostic facility with choices regarding the combination of a walk-in and appointment system. To this extent we created the Walk-in and Appointment Simulation Model (WAPSIM), that consists of four elements: (i) the core system with a planner, a choice to accept or defer a walk-in patient and one server, (ii) a preparation component, (iii) a test component and (iv) extra server components. These elements can then be combined to represent real world diagnostic facilities. By adding design choices corresponding to when walk-in is possible, how appointments are scheduled and who gets priority in the waiting room, there is a broad range of functionalities to experiment with. We used the model to analyze a case of the radiology department of the Academic Medical Centre Amsterdam, who are considering to implement a combined walk-in and appointment system for the regular CT-scans and are currently working with an appointment system.

Results and recommendations

After validation of WAPSIM for the CT-scan case we simulated the situation in which walk-in and appointments are combined. The results show that a combined walk-in and appointment system is a viable option:

- Most walk-in patients can be served on the day of the request;
- Decrease in the number of no shows, as there are fewer appointments;
- Waiting time of appointments decreases compared to the current situation;
- Waiting time of walk-in patients is higher than that of appointments;
- More patients incur waiting time than in the current situation;
- Access time for patients who require an appointment as soon as possible does not change;
- The amount of work done outside of office hours increases (overtime).

Furthermore we experimented with five design choices, the experimental factors. Three of these factors allow the decision makers to make trade-offs between the performance indicators:

- Increasing the allowed waiting time for walk-in patients reduces the fraction of walk-in patients who is deferred, but also leads to higher waiting time for walk-in patients;

- By changing the priority in the waiting room from '*Appointments first*' to '*Appointments first, unless a walk-in patient is waiting more than an hour*' the waiting time of appointments rises, but the waiting time for walk-in patients decreases.
- Introducing a closing time of one hour for walk-in patients (meaning that walk-in patients who arrive one hour before the end of the day are deferred for walk-in), increases the number of deferred walk-in patients increases while the percentage of work done out of office hours decreases.

These primary trade-offs give an indication of the effects but may miss important dynamics. For a more extensive analysis we studied the dynamics between the experimental factors, which can be used to explain unexpected outcomes or to make interdependence between several factors apparent. Based on this extensive analysis we can conclude that the used schedules are too restrictive because of agreements with other departments and the underestimation of the processing time of some patient types. Through sensitivity analysis we showed that three small changes in the schedule could improve overall performance.

Some of the results of the simulation study can be used to give practical advice, such as the improvement of the schedule. However, there is not a best practice that can be advised. The power of WAPSIM is that all effects can be mapped to aid the decision makers. To make full use of this power we suggest a method in which the main effects from the experimental factors are used to start a discussion between decision makers, and the analysis of the dynamics between factors can be used as catalyst to come to a consensus. We also note that the factors that can be experimented with WAPSIM are only part of the considerations related to the implementation of a combined walk-in and appointment system. There are internal and external organizational changes, such as changes in information requirements and responsibilities, which need to be mapped if a department decides to implement a combined walk-in and appointment system.

Conclusion

We developed a reusable simulation model that can be used to analyze the combination of walk-in and appointments to organize diagnostic facilities. There are many factors that can be experimented with, but it is important to note that the model should be calibrated and validated whenever it is used. We think that WAPSIM can be used for a broad range of cases, however at this point we cannot claim that the model is truly generic because it has only been tested extensively on the CT-case of the AMC. Based on this research the radiology department decided to implement a combined walk-in and appointment system, and the results of the WAPMSIM-analysis will be used to support decision makers with design choices.

Preface

In 2007 I started with the bachelor Industrial Engineering & Management at the University of Twente, as a freshmen I was looking forward to being a student, while ambition and motivation to study were not as high on my priority list. However, throughout the years my ambition and motivation grew and in 2013 I came in contact with the department for Quality Assurance and Process Innovation (KPI) at the Academic Medical Centre (AMC) in Amsterdam for a graduation project. A department with members who are inspiring, their hard work and devotion to make the AMC a better hospital are not always appreciated, but the members of KPI are determined to keep coming up with good ideas and doing solid research.

This was the first time that I conducted a research over a period of more than six months and even though being independent, planning and project management are things you learn during your studies, graduating is truly a new experience. I think that without the changes in course based on discussions with my supervisors the sailing would have been stormier. For this I want to thank my supervisors Maartje Zonderland, Nikky Kortbeek and Delphine Constant. Also, extra thanks to my supervisor Aleida Braaksma, who has made the reading and correcting of reports into a form of art.

During my graduation project I was part of a research group of the radiology department of the AMC, the members of the research group were very open from the start and as a result it was possible to have short lines when I had questions or things were unclear. I would like to thank Marieke Sprengers, Ludo Beenen, Maaike Vogel, Martin Poulus and Nick Lobe for their time and commitment, without the individual/group meetings and discussions this research would not have been possible.

I would also like to thank my colleagues at KPI and the fellow interns who were also working on their graduation projects. Sanne, Ingeborg, Lieke, Astrid and Dianne, having other students around was really great (to take extra coffee breaks or to share the pains of graduating).

When I started graduating in Amsterdam I also started another project, I moved to Utrecht to live with my girlfriend. Both graduating and living together for the first time can sometimes be stressful, and stressful persons are not the most fun to be around and I'm no exception. So lastly I would like to thank Justa for being a great girlfriend and supporting me all the way.

Now it remains for me to say: I hope you enjoy reading the rest of my report.

Greetings,

Kees Smid

CONTENTS

1. Introduction

Worldwide on average seven percent of gross domestic product (GDP) is spent on health care, the expenditures of many western countries have grown to somewhere between ten and fifteen percent of GDP and America leads the charts with almost eighteen percent of GDP [1]. In times of global crisis many governments are looking to reduce these expenses while maintaining or even improving the quality of care. In response to this challenging goal there is increasing attention from operations research professionals who can help to develop innovations that can contribute to these objectives, however traditional business sectors still receive much more attention [2]. The combined objective of decreasing costs and improving quality is not always possible, however there are many opportunities that take the preferences of patients into account through patient-centered research [3].

In this research we follow this patient-centered philosophy and explore one such opportunity for logistical improvements: the use of a combined walk-in and appointment systems for diagnostic facilities. In this chapter we will give an introduction on the problem (§1.1), the objective of the research (§1.2) and the organization of the project and report (§1.3).

1.1 Problem description

If a resource in a production or service process is scarce, it has to be allocated in such a way that the objectives of the organization can be realized. This is referred to as planning and scheduling [4]. The manner in which this is done can have big impact on the performance of an organization. In this research we look at a more specific application of planning and scheduling, the diagnostic facilities of a hospital. There can be multiple scarce resources such as staff and machines of which the time has to be aptly scheduled throughout the workweek.

In the case of a diagnostic facility appointment systems are commonly used to organize this process. An appointment with the desired diagnostic department is scheduled when a specialist requires additional information to assess the condition of a patient. When the test results are available a follow-up appointment with the specialist is planned to finish the triage and start treatment if needed. Appointment systems are used to match supply and demand, avoid packed waiting rooms and create a leveled workload while delivering timely care [5]. A downside of appointment systems is that there can be several days between the appointment request and the actual moment of service (access time). In anticipation of the diagnostic results the patients remain in uncertainty about their state of health, which in the worst case could deteriorate [6].

An alternative to the traditional appointment system is an advanced access system, which can be considered as a more patient-centered approach to the scheduling problem [7]. With advanced access patients can choose their moment of service and are preferably scheduled on the day of their request. The literature review by Rose et al. [8] shows that the use of an advanced access system reduces access time, has a positive effect on the no-show rate and can be good for productivity. Rose et al. conclude that there is also disagreement: supporters of advanced access argue that it improves continuity and patient satisfaction, while others state that it is hard to implement, can lead to worse continuity of care and emphasize that there are patients who value the scheduling of an appointment at a time of their choice.

Taken one step further, patients do not make an appointment at all, but are served as they arrive. This is referred to as a walk-in system, in which no schedule is used. Theoretically the walk-in system offers logistical benefits: utilization can be increased because no time has to be reserved for slack, no resources have to be used for scheduling and access time is reduced to zero [5]. In an appointment system, slack is time that is planned to avoid overtime as the result of deviations in the schedule such as delays, tardiness of patients and emergencies. A possible downside of a walk-in system is that the fluctuation in demand can cause peaks in the workload and long waiting time for patients.

There are also situations in which a walk-in system is not possible or desired. Possible reasons are: there are patients who must be planned (for example because the patient has to use medicine for a certain time before further diagnosis is possible), not all demand can be met on the walk-in day, or there is a desire to confirm to the patient's wish for an appointment. For this situation a combination between an appointment and walk-in system can be constructed, in this combined system there are time blocks that are reserved for appointments while the remaining time is left open for walk-in patients. The combined system can be and is used beyond diagnostic facilities at a hospital, for example: restaurants, municipal offices and call-centers. This system gives rise to two central questions: (1) how much time should be reserved for appointments and (2) how this time should be distributed over a workweek. The manner in which these questions are answered influences key performance indicators, some of which were mentioned in this section: access time, waiting time and utilization. Kortbeek et al. [9] developed a methodology to generate an empty appointment schedule where the number of walk-in patients who cannot be served on the same day is minimized, while satisfying the restriction of a maximum access time for scheduled patients. In [10] a heuristic is developed to solve large problem instances.

1.2 Research objective

The objective of this research is to:

> *Develop a simulation model that can be used to support decision makers at a diagnostic facility with choices concerning resource and capacity planning when combining a walk-in and appointment system.*

Hans et al. [11] developed a framework for planning and control in healthcare that can be used to establish the scope of an intervention and to position managerial problems. The framework covers four managerial areas: medical, resource capacity, materials and financial planning. Also, each of the managerial areas is decomposed in four hierarchical levels: strategic, tactical, offline operational and online operational. The managerial areas and hierarchical levels are combined in a four-by-four framework that, when filled, maps all planning and control functions. In this research we focus on the managerial area of resource capacity planning, more specifically on the lower three hierarchical levels. The scope could be extended by including strategic choices such as the extension of capacity, but this will not be the primary aim of this research. In Figure 1 we show an example of the framework applied to a general hospital; the scope of this research is marked in the figure.

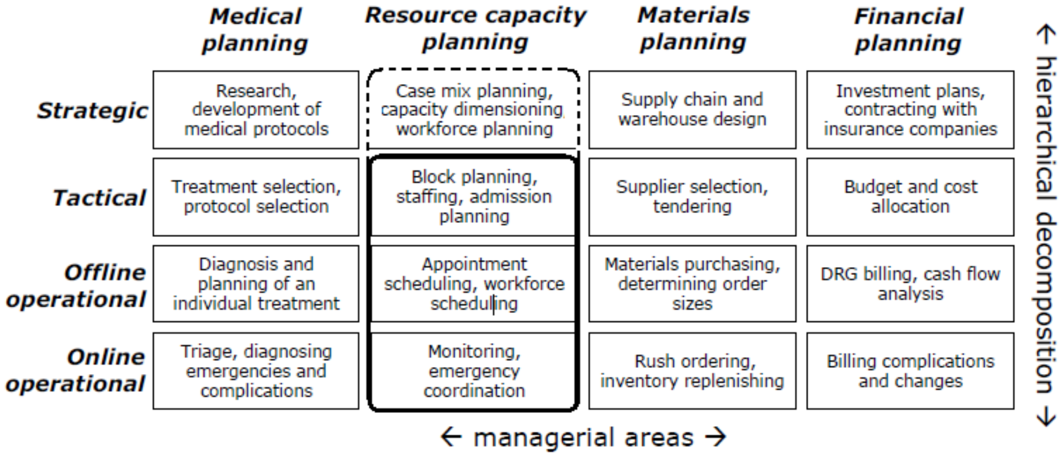

Figure 1 - Example of the planning and control framework in a general hospital [11]**.**

When a diagnostic facility considers the use of a system that combines walk-in and appointments, there are many decisions regarding resource capacity planning that need to be made. The decisions vary from tactical decisions such as how many blocks have to be reserved for scheduled patients to online operational decisions such as which patient in the waiting room should get priority. Decisions on higher levels restrict those of lower levels, and the combination of decisions lead to scenarios that can be considered for implementation. This means there are countless settings, but it is uncertain how each scenario will perform. Also, the solution that performs best for one instance of the problem rarely can be used one-on-one on the next instance of the problem. For these reasons it would be valuable to have a simulation model that can help test and evaluate different scenarios without actually having to implement them or organizing a pilot.

1.3 Case study

The combined system is used at two radiology departments in the Netherlands, more specifically for the computed tomography (CT)-scans, and received positive reactions from all stakeholders: patients, radiology and other departments [12, 13]. The Tweesteden hospital Tilburg started the project in 2007 and the Rijnstate hospital Arnhem in 2010. We will study a case of the radiology department of the Academic Medical Centre (AMC) Amsterdam, one of the eight academic hospitals in the Netherlands. Two studies [14, 15] at the AMC showed both the quantitative and qualitative potential of organizing CT-scans on a walk-in basis at the radiology department of the AMC (opposed to the current practice, an appointment system).

The first research, a questionnaire combined with an Analytical Hierarchy Process (AHP) analysis [14], concluded that patients value an 'one-stop-shop' the most, minimizing the number of hospital visits, followed by a short access time and waiting time. These results are in line with the conclusions of Elkhuizen [3] and the experience of the other two hospitals [12, 13]. The second research, a simulation study by Kranenburg [15], showed that a walk-in system could reduce the number of hospital visits and access time. It also became evident that a system with only walk-in is not possible: some patients need to be planned because other resources are required (for example other specialists), and the radiology department wants to offer patients the possibility to plan an appointment.

The Radiology department is now considering to implement a combined walk-in and appointment system to organize the CT-scans and is at the brink of making the mentioned decisions on how to realize it.

1.4 Research questions and structure

To achieve the research objective we formulated several research questions leading to an outline of the structure of the remainder of the report. In Chapter 2 we review literature that can be categorized into two major subjects: the walk-in and appointment system and generic simulation modeling and implementation.

1. How do a walk-in and appointment system work and how can they be combined efficiently in one system?
2. What are the characteristics of a simulation model that can be reused and how can it be developed?

With the building blocks offered by the literature study and an analysis of the CT-scan case of the radiology department at the AMC, we sketch the context in which the model will have to function in Chapter 3.

3. What are the elements of a diagnostic facility's service process that is organized through a combined system and how can this be conceptualized?

These efforts will lead to the conceptual simulation model in chapter 4, in Chapter 5 we describe the technical design and validation of the simulation model and the experimental design in Chapter 6. We analyze the results and we make suggestions for implementation in Chapter 7 and 8. In Chapter 9 we draw conclusions and make recommendations for further research.

4. Can the developed simulation model be used to represent the current system with sufficient accuracy?
5. Which experiments are useful for implementation of a combined system at the radiology department of the AMC and how can the results of the experiments be interpreted?
6. Which recommendations can be made to support decision making during the implementation of a combined walk-in and appointment system at the radiology department of the AMC?
7. What are the possible implications of the research for other diagnostic facilities?

2. THEORY

In this chapter we will look at the first two research questions and how they relate to the rest of this research. In the first section we look at appointment systems, walk-in, the possibility of combining both systems effectively and the related performance indicators (§2.1), followed by an overview of how simulation is being used in healthcare, what common problem areas are and how reusability of models could be an opportunity of how to overcome these problems (§2.2). In the concluding section we link the theory to practice (§2.3).

2.1 WALK-IN AND APPOINTMENT SYSTEMS AND THEIR EFFICIENT COMBINATION

The way a healthcare service (such as a diagnostic facility) organizes the flow of patients through the system influences the access time and direct waiting time for that service. In turn, timely access to health services can influence the health of a patient and is an important factor for patient satisfaction [5]. One way to organize a health service is by using an appointment system to schedule patients. There are also services that do not use an appointment system but only serve walk-in or emergency patients. We discuss the separate walk-in and appointment systems in Subsection 2.1.1 and their performance indicators in Subsection 2.1.2. There are also services that use an appointment system, at the same time also serving walk-in and/or emergency patients who do not have an appointment. This combined system is treated in Subsection 2.1.3. The goal of this section is to answer the first research question:

> *"How do a walk-in and appointment system work and how can they be combined efficiently in one system?"*

In this section we will see that the definition of 'efficient combination' is case dependent, so the answer to the research question is also case dependent. However, there are several characteristics of a combined walk-in and appointment system that should always be considered. Through this section we mean to give an overview of these characteristics, as is out of the scope of this research to give an in-depth analysis of all the theories related to the topics discussed.

2.1.1 APPOINTMENT SYSTEM AND WALK-IN SYSTEM

An appointment scheduling system is often used to manage the access to service providers efficiently and conveniently. Scheduling in healthcare has received considerable attention of the operations research (OR) community, Cayirli and Veral [16] reviewed literature on outpatient clinics and identified a variety of factors that influence appointment scheduling: the number of services, the number of doctors, the number of appointments per clinic sessions, the arrival process of patients, service times, lateness and interruptions level of doctor and the queue discipline. It can be concluded that each health service has its own characteristics that determine how difficult it is to come up with a good appointment schedule. Based on these characteristics the complexity of developing an empty appointment schedule can vary from hard to easy. For example, when planning surgeries the scheduler has to take into account high treatment time variability, necessary preparation and the availability of surgeons and equipment [5]. When the mean time needed to help the patient is known and there is little variability, the scheduling problem can be reduced to finding a suitable appointment slot. In diagnostic facilities this is sometimes the case, however making an appointment schedule can be complicated by the other factors identified by Cayirli and Veral in [17], for example when there are different types of patients who each have their own process time and there is the possibility that patients do not show up for their appointment.

A system where the patient only visits a diagnostic facility without an appointment is called a walk-in system. Suppose patients arrive according to a Poisson process, the service time is exponentially distributed and there are *c* servers, then the system can be considered to be an M/M/c queue. The system can be extended by adding a maximum number of waiting patients, k. Formulas to calculate average waiting time and idle time of servers for the stationary system are relatively simple [18]. However, the math rapidly becomes more complicated as assumptions are adapted to suite real world problems [19]:

- Arrival rate of patients can vary over the day, days of the week and even season;
- Patients might not be willing to wait limitless and abandon the queue;
- Processing time can be distributed differently than exponentially, for example deterministically;
- Machine breakdown or tardiness of personnel;
- There are several types of patients and servers.

Literature shows us that working with the separate systems analytically can be complex. For more extensive information about these systems the reader is referred to the mentioned sources. Moreover, literature argues that, because of the diversity and complexity in health care processes, existing models from other sectors cannot readily be adapted [5]. Regardless of the complexity of the system one would like to evaluate, we need a means to compare the performance of walk-in and appointment systems. Defining the performance measures is the goal of the following subsection.

2.1.2 Performance indicators

There are several performance indicators for the service process which are mostly independent of the system that is used [8, 9, 20, 21]. Different stakeholders can value the performance indicators differently, so we present them in a random order here:

- Waiting time is the number of minutes that is spent involuntary in the waiting room, if a patient shows up early for an appointment this waiting time is not considered, while waiting time for a walk-in patient starts at arrival;
- Access time is the number of days between the request for an appointment and the actual appointment. In the Netherlands there are service specific norms for the access of diagnostic facilities. These norms for non-urgent patients are made by all related stakeholders and are called the Treeknorms. For diagnostic facilities the norm is that 80% of patients should be served within three weeks after the request and there is a maximum access time of four weeks [22];
- Time to third available appointment is a measure that is sometimes preferred over access time when looking at the performance of an appointment system. It gives a better indication of the actual availability of appointments and can be determined prospectively;
- Utilization is the percentage of available time that a server is busy. The reverse measure, *idle time* of important resources, is also a common performance indicator;
- Overtime is the amount of time worked outside the appointment schedule;
- Deferral is the fraction of walk-in patients who is rejected for direct service, but will get an appointment for a later date.

The walk-in and appointment systems perform different on each indicator, the overall effect of both systems on the performance indicators is summarized in Table 1. Patients who can walk-in always have an access time of zero days. However, in general patients in a walk-in system will experience more waiting time, because the arrival of new patients is not coordinated through a schedule. In an appointment system slack is scheduled to avoid overtime and waiting time as the result of deviations to the schedule, this can result in lower utilization of servers. In a walk-in system this planned slack is not needed, patients from the queue are served as soon as possible up to a set time. However, no general comment can be made about the utilization or overtime of a walk-in system because it depends on how the arrival of patients is dispersed over the day.

Table 1 - Overall effect of walk-in and appointment systems on performance indicators

	Walk-in system	Appointment system
Waiting time	↑	↓
Access time	0	↑
Time to third available appointment	0	↑
Utilization	-	-
Overtime	-	-
Deferrals	↑	-

2.1.3 Combining appointment and walk-in in one system

In this study we focus on the combination of walk-in and appointments in one system, the health service has an appointment system but time is reserved to serve the walk-in and/or emergency patients, in order to avoid a clogged system. Even though it is not the goal of this study to create an optimal appointment schedule, we want to emphasize the importance of a good appointment schedule and its impact on performance. By categorizing the patient types that can be identified in literature and summarizing a selection of existing scheduling approaches we want to enable users of the model to make informed choices when making an appointment schedule.

When reviewing literature from the first decade of this century we can identify three patient types: (1) the outpatient, does not have a bed at the hospital and is only there for a part of the day; (2) the inpatient, has a bed in a ward of the hospital; and (3) the emergency patient, arrives at the hospital with an urgent demand for care. Inpatients and emergency patients share characteristics of the walk-in patient, as their demand is not scheduled, but there are differences. Inpatients wait at the ward, changing the perception of the incurred waiting time. In most situations emergency patients get priority over the other patients. An actual walk-in patient is an outpatient who arrives at a health service without an appointment, has no priority and might not be willing to wait very long. In the remainder of this section we will study several theories that have been developed to generate an empty appointment schedule, as each theory takes different patient categories into account.

Cayirli and Veral [16] suggest that when designing an appointment system one can go through a series of three steps. First the appointment rules are determined which include: choices about block size, the number of patients in the beginning block and the interval between patients. Secondly patient groups are classified, an example for the CT-scan case would be to make a distinction between patients who need contrast fluid and those who do not. Lastly the appointment system is adjusted for no-shows and walk-ins. The first step has received more attention in literature and there is no general appointment rule that works for all health services. No-shows and walk-ins are considered to be incidental events, and it is suggested to overbook sessions to take no-shows into account and leave slots open to account for walk-in. In later research Cayirli et al. [20] developed a universal web based appointment tool that allows the user to obtain a daily schedule, based on a set of input parameters: target number of patients per session, average service time, standard deviation of service time, probability of no-show and walk-in and the cost ratio. Based on these parameters the model also gives a suggestion on how many patients should be planned ideally.

Sickinger and Kolish [23] use a generalized Bailey-Welch (GBW) rule to create an initial schedule, for a system that has outpatients, inpatients and emergency patients. For example if ten patients have to be planned in four timeslots: the GBW rule fills the first slot with two patients and consecutively adds a patient to the following slots, starting at the first slot again if there are still patients left after the last block. The initial schedule would be {3, 3, 2, 2} and is further improved, based on a reward-system for the different patient types, using a neighbourhood search heuristic.

Kortbeek et al. [9] developed two analytical models to generate a schedule that first finds a balance between time reserved for planned patients and time reserved for walk-in patients throughout a workweek and secondly shows how to distribute the time blocks over the workday. These two models are linked through an iterative algorithm that finds the appointment schedule that minimizes the number of unscheduled patients who cannot be helped on the day of arrival. Finding the optimal solution for problems of realistic size proved to be an issue, as the runtime for complete enumeration gets too high. To resolve this, Veldwijk [10] created a heuristic that is based on the algorithm of Kortbeek et al., the heuristic starts by creating a feasible schedule followed by a local search that looks for a better performing schedule. The heuristic finds similar solutions within a minute for the small problems that were solved exactly by the algorithm of Kortbeek et al. in over eight hours. When applied to a larger instance of the scheduling problem, the CT-scan case, the heuristic showed positive results as most walk-in patients could be helped on the day of arrival while the access time for planned patients was less than ten days. Note that neither the heuristic nor algorithm include emergency patients.

There are many more examples of patient scheduling that include other factors, but do not include walk-in or emergency patients. Patrick and Puterman [24,25] evaluated the situation in which inpatient service requests should be handled on the day of the request and different levels of priority existist. Kaandorp and Koole [26] include patients who show up early, however walk-in is not included.

An appointment is made for a later day, any day after the request. In advanced access scheduling patients are offered an appointment on the same day as the request or at a later date if desired by the patient (desirably within a day to reduce the number of no-shows) [8]. In an advanced access system there is no walk-in, but there can be slots that are reserved in the schedule for this purpose.

Based on the selection of literature we presented in this section, we can see that there is a multitude of factors and patient characteristics that can be included when making an appointment schedule. Ideally all these factors are considered when making a schedule, as this reflects reality the best. However this would make patient scheduling overly complex while it is an activity that is done regularly at most health care facilities. For the development of a reusable model it is important to take the diversity of schedules into account Also, when to model is used for analysis an appointment schedule that fits the case should be used.

2.2 Simulation Modeling

Simulation is a means to evaluate anything that can be modeled, and is considered cheaper, faster, safer than real world experimentation and can be valuable even if the model is not completely valid [27]. In health care the systems are often complex, there can be many factors influencing the performance (see §2.1) and direct implementation is often not desirable. There are several kinds of computer simulation; when we say simulation in the remainder of this study we refer to discrete-event-simulation. As stated in the research objective, the goal of this research is to develop a model that can be used to support decision makers of diagnostic facilities with choices regarding the combination of walk-in and appointments in one system. In other words, the model should be reusable for different cases (not only the CT-scan case of the AMC). With this objective in mind we study the following research question in this section:

> *"What are the characteristics of a simulation model that can be reused and how can it be developed?"*

In Subsection 2.2.1 we study how simulation models have been used in healthcare and what success factors and challenges there are in the sector. In Subsection 2.2.2 we study simulation modeling and several theories related to the reuse of simulation models.

2.2.1 SIMULATION MODELS IN HEALTHCARE

The literature review of Günal and Pidd [28] shows that the use of simulation in healthcare has increased in the past decades. The studies of Seila and Brailsford [29] and Virtue et al. [30] underline that the performance of healthcare systems can have direct influence on the quality of care, that care processes are stochastic by nature and that often there are conflicting goals because of the presence of multiple stakeholders. For the analysis of a system with these characteristics a simulation model is an appropriate tool. In healthcare simulation is used on several levels: body system or organ level, operational or tactical level and the strategic level. Note that the body level does not concern computer simulation. Most computer simulation studies are focused on the modeling of tactical and operational level problems of easily containable parts of a hospital such as the emergency department or in- and out-patient clinics [28]. In other words, the problems that are studied have similar characteristics. A point of critique is that the remodeling of these similar (but different) situations was not always necessary and that case studies seldom lead to generalizable insights or to general theory. Günal and Pidd [28] argue that it would be valuable if researchers learned more from other studies and provide general and conceptual descriptions with sufficient detail. This will enhance the reuse of approaches if model reuse is not possible or desirable. It is mentioned in [31] that according to literature many simulation studies are not actually used by decision makers, only about 18% of the models are actually used for implementation. The survey by Van Lent et al. [31] shows that the actual implementation rate might be higher, about 44%, as academic papers are published before complete validation and implementation due to time pressure.

SIMULATION AT DIAGNOSTIC FACILITIES

There are fewer simulation studies focusing on diagnostic facilities than on other departments [32]. However in this paragraph we will give some examples of studies done at diagnostic facilities, mostly of radiology departments. Couchman et al. [33] used a simulation model to predict the effect of increased workload at a biochemistry laboratory, showing that new equipment, extra capacity or a new way of processing was needed to keep the time between arrival of the sample at the reception and production of the report acceptable. Beside a specific simulation study on the staffing capacity and utilization of a radiology department Centeno et al. [34] provided recommendations to improve operational performance and the quality of the service: provide a waiting area for patients, lunch area for staff and add an emergency column in the information system. Another specific study at a radiology department by Ramakrishnan et al. [35] quantified the benefits of the to-be implemented digitized archiving method at the CT scan area on patient throughput and report generation time. O'Kane [36] developed a more generic simulation model that can be used to study several factors like the availability of staffing resources and priority in the waiting room and could be easily adapted to different radiology departments. [36] also describes the minimum required input data, system events and output data. All studies included a process description, the first two included an extensive statistical analysis, but none of these studies discussed implementation of the recommendations.

SUCCESS OF SIMULATION STUDIES

Through a literature study and survey, Fletcher and Worthington [32] identified twenty four dimensions that are important for the success of simulation studies in healthcare. The dimensions that are extra relevant for generic simulation models are identified per stage of the study:

- During project initiation the purpose and target level of use must be clearly defined by stakeholders (see [37]);
- In model design and build, for generic design the additional dimension of assessing the appropriateness for central use should be added. Also, the key common processes should be modeled, avoiding too detailed local issues;
- For the data it might be useful to make a distinction between types of data, as there can be local data and generic data based on global averages for example;
- When validating a generic model for central use average data will be used, for more specific use more accurate validation is needed;

- At the implementation stage, user capability and support are required. In the case of generic models that can be used on multiple instances the user interface and documentation are extra important.

Jahangirian et al. [38] review why the simulation studies conducted in the healthcare sector are behind on other sectors even though simulation has been so widely applied for several decades. The main conclusion is that there is a lack of stakeholder involvement and therefore implementation. Based on the cross-sector study [38], three discussion points were formulated that are relevant when a simulation study is conducted:

- Organizational structure, opposed to the agile structure many companies have adapted that accepts the improvements offered by simulation, hospitals are often very slow hierarchical organizations that are more resistant to organizational change;
- Competitive structure*,* hospitals in general lack the incentive to adopt drastic changes;
- Data capture*,* the gathering of data can be restricted in hospitals for several reasons, while simulation studies are data intensive. This can make stakeholders reluctant to participate; data is also often not available.

In earlier work Seila and Brailsford [29] identified some more practical challenges that should be considered and are related to these discussion points: management of knowledge and support, team management, selecting performance measures, modeling of human behaviour, rapid modeling, lack of data, lack of standardization and highly complex systems.

There is also other work on how stakeholders can be engaged in the simulation process. In [39] Fackler and Spaeder argue that the adoption of simulation solutions would be enhanced if healthcare professionals had a rudimentary understanding of mathematics and statistics that are used. The math that is used should be explained so that the user is able to understand it or hidden when this is not possible. Fackler et al. [40] suggest to start with a simple model that represents the current way of working, to prove the concept of simulation before it is used to analyze new and possibly more complex situations. Baldwin et al. [41] state that a strength of simulation in healthcare can be to enrich communication with different stakeholders to increase mutual understanding of the problem. This understanding can be used to improve the model and leads to commitment. These results are confirmed by Elkhuizen [3], who experienced that the visualization that is offered by simulation proved to be very helpful to get the commitment needed for implementation. Lastly, Brailsford et al. [42] argue that research should be pull driven, meaning that the healthcare organization or department requests the expertise of a modeler and that the presence of a local champion who appreciates the potential value of simulation modeling is considered to be a key success factor to realize this pull.

2.2.2 Simulation Modeling and reuse

Within simulation there are several types of models: throwaway, on-going use, regular use, generic and reusable [43]. As suggested in section 0, it is be desirable to create simulation models that are not only useable for a single healthcare case. In this research we focus on models that can be used in more than one situation, so the first three types of simulation studies will not be evaluated further. Generic simulation models are a specific type of reusable models. A reusable model can be used easily in another context and purpose than originally intended, while a generic model should work in another context but only for the same purpose.

In any simulation study there are several steps: problem analysis, data collection, conceptual modeling, technical modeling, validating, experimenting and analysing the results [44]. As the objective of this research is to develop a simulation model that can be (partly) reused, mainly the conceptual and technical modeling will change compared to single use models, as the model will have to cover a wider range of situations. To make it easier to specify a simulation model to a situation Daum and Sargant suggest three modeling techniques [45]:

1. Hierarchical model specification, gives the modeler the ability to move between levels of the model which enhances the manageability of a complex model and allows specification at each level;
2. The scaling of model elements, is the combination of similar model elements into an array;
3. Reuse of model elements, makes it possible to repeatedly use specifications of existing model elements.

Daum and Sargant [45] argue that using the first two techniques is necessary to model complex systems and that the reuse is needed to realize a development process that is quicker, easier and less expensive. In the following paragraphs we will go more into depth about how reusability can be accomplished, what possible downsides there are and what terminology is suggested in literature.

A REUSE SPECTRUM

Reuse is a broad term, as reuse can happen on different scales. Pidd [27] defined a spectrum, depicted in Figure 2, for the reusability of software that takes into account two facets of reuse. On the one side is the complexity of the form of reuse and on the other side is the frequency at which it is done. The framework covers the spectrum of the relatively easy scavenging of code, this is the common activity of programmers who reuse parts of code that others have produced, to the modeling and reusing of a complete system which is rarely done or realizable because of its complexity. Code scavenging has also been termed pragmatic use by Holmes and Walker [46], who want to remove the negative suggestion and emphasize the value that can be gained by this type of reuse. Pidd emphasizes the importance of reuse strategies to benefit from the potential values of reuse, also because there are always multiple groups of people involved. A reuse strategy should cover four aspects: (1) a comprehensible level of abstraction, (2) selection on what can be reused, (3) a way to specialize the reuse to a situation and (4) an integration mechanism.

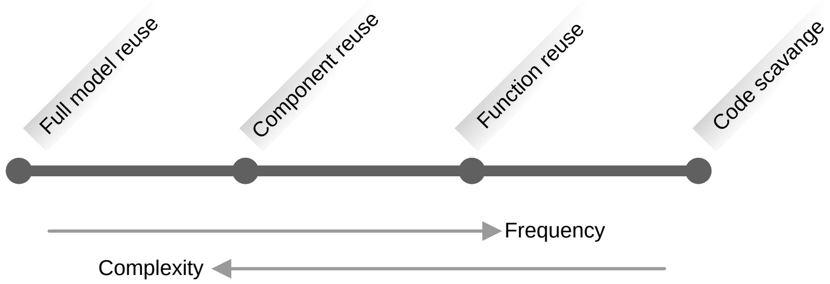

Figure 2 -A Reuse Spectrum [27]**.**

Paul and Taylor [47] focus on reuse of models/components in simulation studies and are more skeptical about the value of reuse, especially full model reuse. Paul and Taylor argue that as conceptual simulation modeling is iterative in nature, the modeler is constantly changing the model so that it fits the needs and wants of different stakeholders and the dynamics of the real world. While the reuse of (parts of) models is a promising concept, as it could save time and money in the modeling process, it is often the case that the reusable part cannot be applied to a next case directly. In this case the testing and reworking of the component can be more time consuming than building it from scratch. Reuse also requires a high degree of trust in the work of other coders. New users might feel they have more control over their own code and there may be undetected bugs in the component [48]. Additionally, Paul and Taylor underline that simulation is a decision aiding technique and that the processes of developing the model can be as valuable as the numerical output. To tackle the issues of losing time and a declined learning experience Paul and Taylor suggest a simulation process that does use reusable components, but in a more pragmatic manner. This approach is depicted in Figure 3, it starts with a process of grabbing and gluing together reusable components, followed by a running, rejecting and retrying cycle until the model can be used for experimentation. Abbreviated as G^2R^3, this process of simulating stimulates the quick development of a practical, rather than a complete/correct model. Giving the foundations for an intellectual process, this is where the potential value of reusable simulation modeling lies according to Paul and Taylor [47].

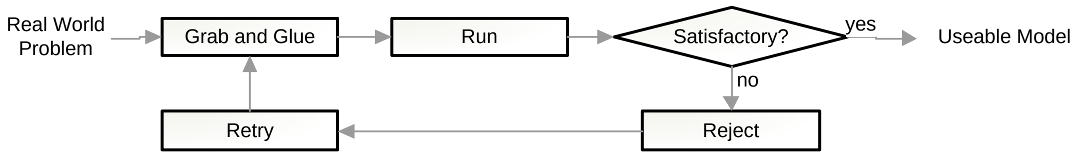

Figure 3- The G^2R^3 process [47]

COMPONENT BASED SIMULATION

An approach as suggested by Paul and Taylor needs components that fit this working method and fit a reuse strategy like suggested by Pidd. In this subsection we describe a ontology for component-based simulation (CBS) developed by Teo and Szabo [49] that is part of a framework developed by Szabo [50]. Szabo states that current approaches fail to offer an integrated framework for CBS model development. The ontology is used to enhance unambiguous communication by capturing and explaining the vocabulary that is used in CBS modeling. The aim of the ontology is to let components be reused in breadth and depth. Breadth refers to the coverage across domains and depth to the use of a component for specific applications. Before we continue, note that Szabo addresses reuse of simulation components at the highest level, proposing the foundations for a framework that can support a marketplace for components. As stated before in terminology of [43], developing a generic simulation that can be reused for the same purpose but in different situations is a distinct type of reuse that does not focus on reuse in the breadth. The ontology offers valuable insights and definitions for the development of generic simulation models and promotes the use of the three modeling techniques suggested by Daum and Sargant [45,50].

Szabo [49] developed the Component Simulation and Modeling Ontology (COSMO) to realize meaningful communication between components. COSMO consists of sets of classes to describe simulation components and their composition, and can be used to structure the development process of components and their interaction with other components. A component is modeled as a finite state machine and a transition from one state to another can happen when the component receives input and after processing it gives output. To ensure that the component's communication is useful, constraints can be set on the input that is accepted and the output that is sent. Teo and Szabo formalize the COSMO structure in the tuple:

$$C_i = < R, A_i, B_i >$$

- R are the mandatory attributes that are common to all components.
- A_i are component specific attributes.
- B_i is the behaviour of the component which is represented as follows:

$$[I_l]S_p[\Delta t] \xrightarrow{Cond_m} S_t[O_l][A_m]$$

I_l is the set of input data, S_p the current state and Δt the processing duration. $Cond_m$ defines the condition(s) for the state transition. S_t is the next state, O_l the set of outputs and A_m is the set of attributes that are involved in the state changes.

If components are defined using the COSMO ontology the syntactic composability can be easily verified, which means that the components can be connected and communicate on a technical level. This is also referred to as verification of the connections. As in any simulation study, the validation of the composition needs to be assessed to see if the exchange between components is meaningful and can be used for the objective of the simulation study. Turnitsa et al. [37] argue that COSMO is useful for model description, capturing functional utility, but does not capture modeling decisions and assumptions.

2.3 CONCLUSION

The main challenge in combining walk-in and appointments in one system is to find the balance between waiting time of walk-in patients and access time of appointments. For this purpose an empty appointment schedule that fits the characteristics of the analyzed system. From literature we can see that there is a multitude of factors that can be included when making an appointment schedule, one of the important factors is the types of patients who are present in the system. The more of these factors will be included, the more complex the scheduling problem becomes. Several combinations of factors have been analyzed, and have led to algorithms that find optimal schedules for those combinations. Literature also shows us that there is no universal planning rule for health care facilities that can be used to create the best possible appointment schedule. Moreover, the algorithms/heuristics that are developed are often too complex for daily use either because of computational performance or the lack of a useable tool.

Corresponding to the challenges of patient scheduling is the rising popularity of computer simulation in health care, as simulation offers a tool to do experiments with different schedules in a close-to-reality model. Furthermore, scheduling and simulation in health care show the same trend: problems are diverse and are often tackled on a case-by-case basis or not all factors are included. The use of more generic simulation models useable for comparable but different cases is possible and could reduce time and money spent on modeling. The development of a fully reusable model is considered to be (too) complex and is rarely done, while a more pragmatic re-use of model-components is considered to be a viable option. For this research we should take the flexibility required to cooperate with the diversity of patient types and appointment schedules into account. We will also take a component based perspective on simulation modeling.

3. Diagnostic facilities and the CT-scan case

This chapter has two central sections that we use to answer the first part of the third research question. In the first section we briefly describe diagnostic facilities and their characteristics (§3.1), in the second section we will conduct an in-depth process analysis of the CT-scan case at the AMC (§3.2). In the concluding section we reflect on the research question and see how we can make the next step, to a combined walk-in and appointment system (§3.3).

> *"What are the elements of a diagnostic facility's service process (that is organized through a combined system and how can this be conceptualized)?"*

3.1 Diagnostic facilities

When we look at a hospital, the role of diagnostic facilities is different from other parts of the hospital. Where most other departments focus on the treatment of patients, diagnostic facilities supply the other departments with more information about the patient. This means that the place of a diagnostic facility in the whole care trajectory of a patient is never isolated from the rest of the hospital; there is always a department (or external party like a general practitioner) that sends the patient to the diagnostic facility, afterwards the patient will receive the diagnosis from his/her doctor and if needed continues to receive more care. In other words, the diagnostic facility does not directly contribute to the wellbeing of the patient but is often an essential link in the chain.

The stream of patients at a diagnostic facility can be very inhomogeneous (as described in Section 2.1), varying from emergency patients who must be served immediately to patients who visit the diagnostic for a yearly check-up. The definition of performance may vary among patient groups. For the check-up patients access time is not very important, while an emergency patient who needs additional diagnostic information to receive treatment at the emergency department must be served within minutes. Between these two extremes there are the regular patients who might be allowed to wait up to several weeks. However, a lower access time is in most cases desirable, as the time to diagnosis can be stressful for a patient and can even lead to deterioration of health in some cases [6].

3.2 AMC CT-scan case

We conduct this study at one of the eight academic hospitals in the Netherlands, the Academic Medical Center Amsterdam (AMC). More specifically, it is a study done for the radiology department, conducted at the department for Quality Assurance and Process Innovation (KPI in Dutch). The vision of KPI is to work in a businesslike fashion through four organizational areas that can help improve the quality of care at the AMC: patient logistics, patient centeredness, patient safety and evidence-based practice [51]. In this research we will focus on the former two. Through the consulting activities the department supports the three strategic areas of the AMC: education, research and patient care [52]. The development of a simulation model is a part of a project that is evaluating the possible implementation of a combined walk-in and appointment system for the CT-scans. The research team consists of members of KPI and the radiology department.

3.2.1 Process description

The process description in the simulation study conducted by Kranenburg in 2009 [15] forms the base for this section, through interviews with members of the radiology department and observing the daily process we verified the overall process and identified recent developments. We study four elements of the current process: the resources, the patient types, the planning process and the CT-scan process.

Resources

There are five machines in the AMC that can be used for CT-scans: two of the machines are located at the radiology department, one at the emergency department, one at the radiotherapy department, and lastly there is a pet-CT that combines two imaging techniques but is rarely used for regular CT-scans. Only the two machines located at the radiology department are used for the regular stream of patients. In practice the CT-scan at the emergency department is sometimes used for the imaging of regular patients on very busy days to avoid overtime. However, in this case study we focus on the stream of regular patients who are treated by the first two machines, the Phillips Brilliance and Phillips MX8000, respectively CT1 and CT2.

Patient types

There are two main streams of patients who form the demand for the regular CT-scans: outpatients (86%) and inpatients (14%). For each patient a radiologist determines the imaging protocol that is required, based on a request sent by the specialist. The requests are reviewed about two times a day and over 95 percent is accepted. Overall, the imaging protocols can be categorized in four groups:

1) Protocols that need contrast fluid that is administered intravenously (IV);
2) Protocols that need contrast fluid that is administered orally, the patient should arrive sober;
3) Protocols that need both IV and oral contrast fluids;
4) Protocols that need no contrast fluids.

There are also some protocols that require the availability of other resources of the hospital, for example a specialist from another department needs to be present during or before the CT-scan. With the prospect of a combined walk-in and appointment system, the patients who need an additional resource present will always need an appointment. The last exception is that there are some patients who cannot be scanned by the older machine CT2 and are thus restricted to CT1. In Table 2 the nine patient categories and the composition of production in the period May 2012 - April 2013 is shown.

Table 2 – Distribution of patient categories for 5/2012 to 5/2013 (RIS)

Category	Number	Percentage
Oral+IV+CT1	2580	22.9%
Oral+IV	878	7.8%
IV+CT1	606	5.4%
Oral	38	0.3%
IV	1149	10.2%
CT1	1566	13.9%
Other resource needed	1120	10.0%
Scan on CT1 or CT2	3314	29.5%
Total production	11251	100.0%

The planning process

The CT-scans are organized through an appointment system and are open for service five days in the week from 8:30 to 16:45. Days are divided in slots of 15 minutes. Not all slots can be used for regular patients by the scheduler: certain slots are reserved for inpatient emergencies, daily breaks and weekly calibration of CT1. There also are emergency slots that are left open as long as possible, but can be used by the scheduler if there is a real capacity shortage. The largest part (279 slots of 330 slots per week) of the schedule is open for scheduling. There also are guidelines on where in the week different patient types should be scheduled, for example all the cardiac-scans are scheduled on Tuesday or Thursday afternoon. Most protocols require a block of 15 minutes in the schedule, but there are some that need 30 minutes and there are exceptions where up to several hours are scheduled for one patient.

The planning process is shown in Figure 4. Once the request for a CT-scan is processed and a protocol is determined for the patient, the planners of the radiology department can schedule an appointment for the patient.

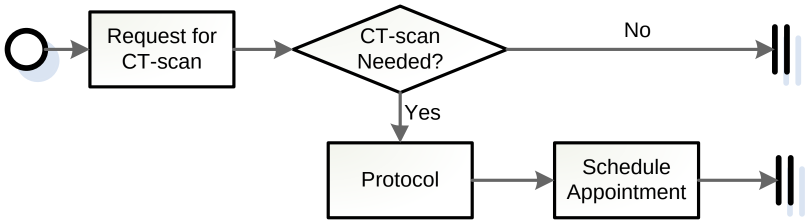

Figure 4 - Processing of Request for CT-scan

After the on-paper request has been protocolled, outpatients are scheduled using X-care (the appointment information system of the AMC). For inpatients a paper request is also filed and protocolled. However, most inpatients are not scheduled in X-care but handled in a more pragmatic manner. If the inpatient can be fitted between scheduled appointments the patient is called from the clinic, otherwise the patient is sent to the CT-scan at the emergency department.

An example of how the schedule is seen by the planner in X-care is given in Figure 5. The light green slots have been used for a patient, red it cannot be used for a patient, and the text in each yellow slot indicates for what patient type the slot can be used.

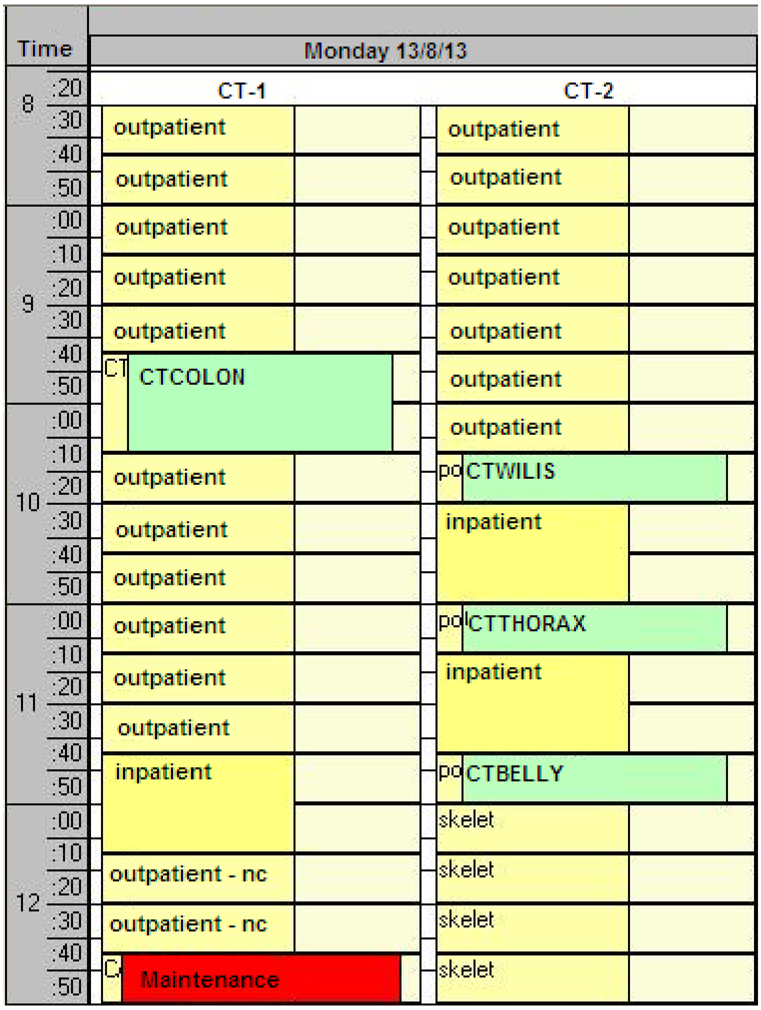

Figure 5 - Example of active X-care roster

The CT-Scan process

Once the patient arrives the preparation and scan can start. In Figure 6 we show schematically how the patients flow through the CT-scan system. The patient arrives at the reception. Based on the protocol that the patient was planned for the receptionist knows whether the patient needs to drink contrast fluid or not. Also, if IV-contrast fluid is required, an IV access line is placed in a room dedicated to this purpose. After required preparation steps are completed the patient is scanned on the scheduled CT-scan.

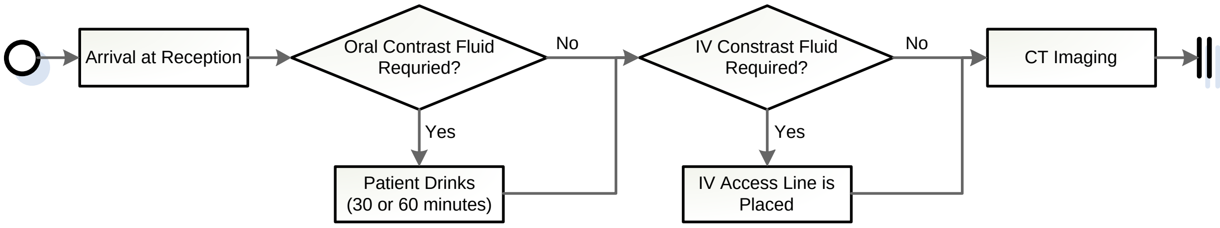

Figure 6 - Patient flow through CT-scan system

Note that the flow through the system is not dependent on the machine that the patient is scheduled for and that before the start of each process there can be some waiting time. There are also some exceptions result in deviations of the standard process, in a combined walk-in and appointment system these patients will need to get an appointment:

1) Before contrast fluids are used a test is done to ensure that the kidney is strong enough to handle the fluids. If the kidney is not strong enough, which is the case with 6% of all patients who need contrast fluid, the patient is admitted in the hospital for a short time to go through further preparation steps.
2) 2.7% of all patients is are allergic to the IV contrast fluid that is used, these patients also need additional attention before and after the CT-scan.

3.2.2 Performance

In this subsection we analyze the performance indicators that we introduced in Subsection 2.1.2 for the current situation, using the data in the period May 2012 to April 2013 and a measurement month (September 2013). For the analysis we used data from the Radiology Information System (RIS), the hospital's scheduling system (X-care), and a monthly analysis of radiology's head of planning.

Waiting Time

Patients who require preparation time are required to show up early for their appointment, to ensure that the scan can start at the planned time. It is important to note that waiting time for the individual steps between the reception and the start of the scan are not registered in RIS. To compute the estimated waiting time of a patient at the CT-scan we use four times: (i) the preparation time, (ii) the appointment time, (iii) the registration time upon arrival of the patient, and (iv) the start time of the scan. For the computation we first determine if a patient is early or late for their appointment. Patients who have no preparation time we compare the arrival time with the appointment time. For patients who do have preparation time we compare arrival time with (the appointment time – the preparation time). We can then compute the waiting time:

- For patients who are late it is equal to, start time of the scan - arrival time;
- For patients who are early it is equal to, start time of the scan - appointment time;
- For patients who are early and the scan starts before the appointment time, there is no waiting time.

For this computation it is important that the times (iii) and (iv) are registered accurately, however for the period May 2012 to April 2013 there were a lot of irregularities. To ensure the quality of the data we asked the employees of the radiology department to pay extra attention when registering these times in a measurement month. The information about the waiting time in the measurement month, September 2013 is shown in Table 3.

Table 3 - Waiting time information (measurement month September 2013)

	Information
Patients incurring waiting time	42.0%
Average waiting time (mm:ss)	11:53
50th percentile of waiting time (mm:ss)	07:27
80th percentile of waiting time (mm:ss)	17:42

Access Time

The access time at the radiology department can be viewed in two ways: (i) the retrospective way in which historic data is used and (ii) the prospective way in which we study future availability of appointment slots.

Retrospective

When we study the access time in RIS, the average time between request and appointment is 24 days. However when we exclude the upper 10% of patients (with an access time of more than 60 days and up to 358 days), the average access time is 14 days. In many of these cases the high-access time appointments are patients who come back for a check-up and thus distort our image of the access time. Another possible reason for the realized access times could be that some appointments are scheduled as close as possible to a follow-up meeting with another specialty.

In Figure 2 we show a boxplot of the access time of appointments in the period May 2012 to April 2013, the whisker that ends at 60 days is the 90th percentile. In the boxplot we see that the main group of patients falls between 5 and 27 days and that there is a long tail to the right.

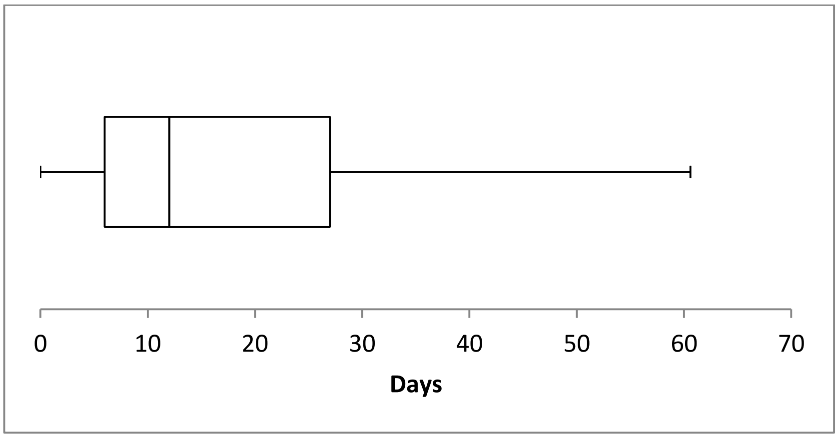

Figure 7 - Boxplot of access time, outliers ommited, May 2012 to April 2013 (RIS)

Prospective

The radiology department also keeps track of the third available appointment slot manually for the largest group of patients, outpatients. The time to third available appointment is shown in Figure 8, we can see a large fluctuation for patients who need a CT-scan with contrast fluids in the months June to August. There is a difference between patients who do need contrast fluid and patients who do not because of the number of slots that is marked 'with contrast' and 'without contrast' in the schedule (this is done to help the planners with clustering the appointment types). We should also take into account that the data is a monthly sample, which could misrepresent the actual fluctuations because it is a random indication. Another possible operational explanation for the fluctuation is that outpatients with contrast are not planned during the absence of radiologists, lunch hours and at the end of the day, while outpatients without contrast can be planned throughout the whole day. In other words there are fewer slots in which the contrast patients may be planned.

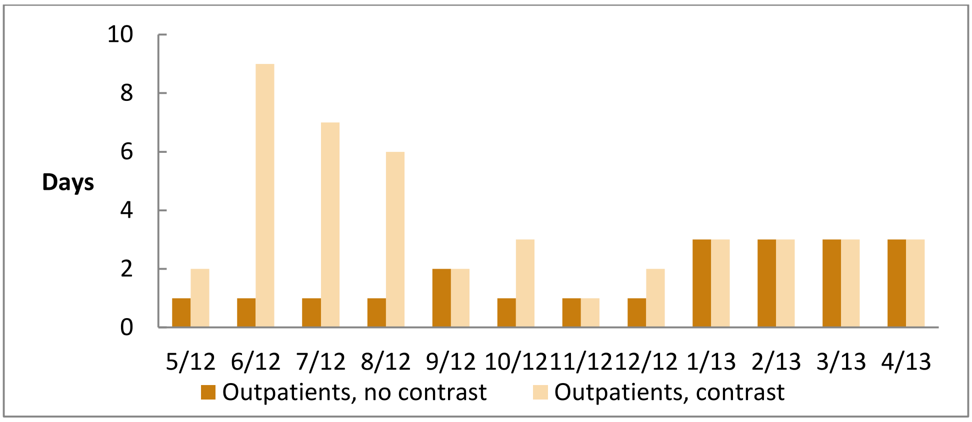

Figure 8 - Time to third available appointment registered manually by planner

Remarkable is the difference between access time and time to third available appointment, which can be explained by the manner in which new appointments are scheduled. The planner takes into account other appointments in the AMC and patient preferences. Also, some patients get an appointment as close as possible to a future date because the scan results are needed at that date (which can be months away).

Utilization

During the measurement month both CT scans were available for 21 working days, each day having 33 slots of 15 minutes, which means that the total time available for scanning patients was 346 hours and 30 minutes. In this month there were 908 patients, the average scanning time for 97.3% of all patients was 12m22s, about half of the remaining patients are colon patients who required 26m48s on average and the remaining part are punction patients who required 1h20m27s on average.

In Table 4 the utilization for the measurement month is computed (time used/time available). As expected, the utilization of CT1 is higher than that of CT2. There are two reasons for this difference: (i) not all patients can be served on CT2 and (ii) there is a preference to help patients on CT1 because of lower radiation dosage and higher quality images.

Table 4 - Utilization during measurement month 9/13 (RIS)

	CT-1	CT-2	Overall
Time used (hhh:mm:ss)	109:04:37	96:58:54	206:03:31
Time available (hhh:mm:ss)	173:15:00	173:15:00	346:30:00
Utilization (%)	63.0	56.0	59.5

In the measurement month the no-show rate was 1.4%, while the yearly no-show rate is 2.6% (May 2012 – April 2013).

Overtime

During the month September there were 2 hours and 53 minutes of overtime, this is 1.4% of total scanning time. A reason for the low overtime is that scans that would have to start after closing time of CT1 and CT2 are deferred to the CT-scan at the emergency department.

3.3 Conclusion

Based on an analysis of the current planning and CT-scan process we see that the CT-scans of the radiology department is organized by an appointment system. However, there is a hidden way to deal with patients who need service on the day of the request. Registry of these patients happens outside the official planning system of the AMC (X-care) because only the planners can access this system.

The historic data we reviewed, as summarized in Table 5, gives a clear image of most of the current performance indicators. For access time there is a large discrepancy between retrospective (historic data) and prospective (time-to-third available slot) information, this is an indication that access time could be lower. From the utilization we can see that there should be enough space to further reduce access time and/or help more patients.

Table 5 - Summarized performance

Performance indicator	Data	Source
Patients incurring waiting time	42.0%	RIS: September 2013.
Average waiting time (mm:ss)	11:53	
50th percentile of waiting time (mm:ss)	07:27	
80th percentile of waiting time (mm:ss)	17:42	
Retrospective access time	24 days	RIS: May 2012 – April 2013.
90th percentile of retrospective access time	14 days	
Prospective access time without contrast	1.8 days	Monthly samples: May 2012 – April 2013.
Prospective access time with contrast	3.7 days	
Utilization CT1	63.0%	RIS: September 2013.
Utilization CT2	56.0%	
Overall Utilization	59.5%	
Overtime as percentage of time worked	1.4 %	RIS: September 2013.
No-shows	2.6%	RIS: May 2012 – April 2013.
	1.4%	RIS: September 2013.

Strictly speaking only 10% of all patients must be scheduled to be served on a later date, and 14% of the remaining patients should get an appointment on the same day for organizational reasons, for example the clinical patient has to be transferred to radiology from the ward. Like described in Chapter 2 this group of patients can be referred to as advanced access patients. The relatively small processing time for 97.3% of all patients is an indication that the CT-scans could be organized through a combined walk-in and appointment system. In this new system we will have to keep in mind that there are possibly extra steps in the process, like a visit to the lab to test the kidney strength of a patient who needs contrast fluids through IV.

4. CONCEPTUAL MODEL: ELEMENTS OF THE DIAGNOSTIC SERVICE PROCESS

In the previous chapter we analyzed the elements of a diagnostic facility, in this chapter we use a pyramid structure with four layers to conceptualize these elements so we can use them for the model. The fundament of the pyramid is the core system that is central to the model (§4.1). The middle part of the pyramid consists of additional components (§4.2), which can be used to extend the core model to match a real world system (§4.3). Lastly, the peak of the pyramid gives the model direction through design choices that have to be made within the combined system (§4.4), we summarize the assumptions linked to the model (§4.5) and have some concluding remarks (§4.6). Through these sections we can answer the second part of the third research question:

"What are the elements of a diagnostic facility's service process that is organized through a combined system and how can this be conceptualized?"

4.1 THE CORE SYSTEM: COMBINING WALK-IN AND APPOINTMENTS

In the hearth of the system we are evaluating there are some key elements, these elements are schematically shown in Figure 9. At the start of the system there is a stream of patients, some of these patients will receive an appointment and the rest is eligible for walk-in. The patients who require an appointment will go to the planner and will then wait to get access to the rest of the system. The walk-in patients do not need an appointment so they can enter the Waiting Room right away before they receive the health service. Altogether, we can identify two main components: (i) the Planner with related access time and (ii) the Server with the corresponding waiting room.

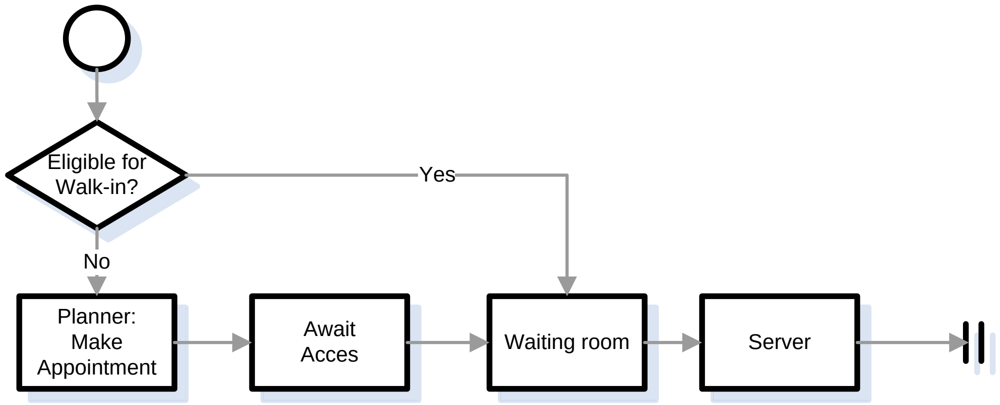

Figure 9- Essence of evaluated system

This core system will not suffice to capture how most real world health services look, except maybe for the general practitioner's consultation hours. However, from this system we can already see the basic in- and output that we identified in Chapter 2. The planner needs a schedule that shows when to plan the appointments. This empty schedule should be based on the arrival rate of walk-in patients throughout the days of the week, so that appointments will not be planned during walk-in peaks [9,10]. The model also needs the distribution, and its parameters, of the processing time for the server. The seven performance indicators we discussed in Section 2.1 can all be used to evaluate the system, but not all indicators will apply to walk-in and appointments, and some indicators will be interesting to track separately for both groups. For example access time will not apply to the walk-in patients, but it is useful to register waiting of walk-in patients separately. In this core system the performance indicator 'deferral of walk-in patients' can be omitted. This will be discussed in more detail in Section 4.4.

4.2 Defining Additional components

In the core system we only have the essential distinction between walk-in and appointment patients. When more process components are added a more detailed description of patient groups is probably necessary (as not all patients need to go through all processes). In this section we define three of these additions, processes that are common in a diagnostic facility's service system. In the next section we discuss the combination of all additions with the core-system.

4.2.1 Preparation process

Some patients might need some preparation before they can be helped by the server. The preparation process is straight forward, as shown in Figure 10. The patient goes in, is prepared for the next step, and goes out. In An example of a preparation process from the CT-scan case is the placing of the IV line that is needed to administer contrast fluids. For this component the distribution of the processing time and capacity information are required by the model. The waiting times of preparation processes are registered separately from the server.

Figure 10 - Basic Concept of Preparation Process

Note that an important distinction is that, unlike the server, the preparation component is not considered to be the bottleneck in the system. If this would be the case analyzing a walk-in/appointment system for the servers has no point, in this case the preparation components should be considered for further analysis. For example if a preparation process is constantly busy and has very high utilization, while the servers are idle most of the time, this is reason to look into better organization of the preparation station (rather than to improve how the servers are organized).

4.2.2 Test process

The route a patient takes through the system is not always known exactly on arrival, it can depend on unknown characteristics of the patient. Also, it might not be possible to decide if a patient is eligible for walk-in based only on the request of the specialist. In other words, additional information might be needed to determine the route of the patient, this information is acquired through a *test* process. Examples of possible tests are: heart rate, blood-values, and allergies. Based on the test results it is then decided what route the patient should take. Schematically the test process is shown in Figure 11. A small example of how the test component would work: if the kidney of a patient is not strong enough to process the contrast fluids the patient cannot be treated on that same day so an appointment is needed (Test: kidney strength, Route 1: to planner, Route 2: to CT).

Adding a test process requires new input for the model, the distribution of the particular test and the range for which the patient is sent to Route 1 or Route 2. Also, for each test process the model needs the processing time distribution and their parameters. The test component can have a capacity of more than one. The empty appointment schedule of the server should also be adjusted to accommodate the extra appointment requests that result from the declined walk-in patients due to a test component. For the output the waiting time for the test processes is recorded separately from the waiting time for the other processes, the times can be added up to determine total waiting time.

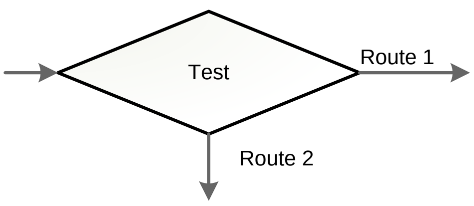

Figure 11 - Basic Concept of Test Process

Note that the model assumes that the test is available on a walk-in basis, either at the diagnostic facility or an external department. If the patient needs to make an appointment for the test, walk-in at the evaluated diagnostic facility is obviously not possible.

4.2.3 MULTIPLE SERVERS

There could be multiple servers of different types, extra servers is the last additional process for the model. For each server component that is added, the model will need an empty appointment schedule so that the planner can keep track of all separate servers. Unlike the other components, all servers share one central waiting room because in most cases there are patient groups that can be served on more than one server. Also, servers are seen as the last step in the diagnostic system, after the service the patient leaves the system we analyze. As every component, for each additional server the model needs distribution information about the processing time.

This addition allows the model to be used for analysis of problems of the strategic level, deciding on how many servers of what type are used in the system, but as stated in Chapter 1 this will not be a primary goal of the model.

4.3 COMBINING THE CORE SYSTEM AND COMPONENTS

The core system, individual components, input and output are simple when considered in isolation. However, the core system can be combined with all three additions to match the system that is being analyzed. In the example in Figure 12 the core system is marked with thick dotted lines and the additional components are labelled descriptively.

In the core system we only had two groups of patients, walk-in and appointments. When we study the example it becomes clear that there are numerous possible routes through the system, these routes are dependent on the type of patient who is served by the health service. The model allows the user to add patient types and specify their walk-in eligibility and route through the system.

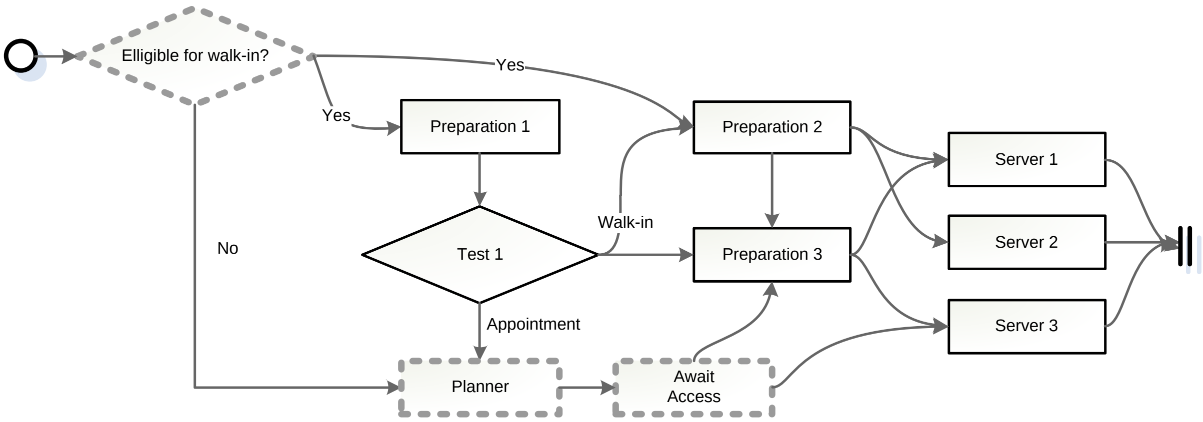

Figure 12 - Combining Core System and Components

With the addition of patient types, it might be desirable to cluster the appointments of each group (in the case, some patient groups need an external specialist present). To accommodate this, the model allows the individual schedules of the servers to be enriched to match this functionality.

4.4 DESIGN CHOICES

After patient types have been identified, processing times were analyzed and schedules for the servers have been made there are three design choices on how everyday decisions will have to be made. These design choices will determine the final performance of the combined walk-in and appointment system. In this section we describe the three design choices which will be elaborated on in Chapter 6.

4.4.1 Allowing walk-in: access choice

Some patient groups may not be eligible for walk-in by default, those patients will always get an appointment. In the core system, the walk-in eligible patients are always allowed to walk (none are deferred). However, when a walk-in eligible patient arrives at the reception desk of the diagnostic facility there are other factors that can influence the decision whether walk-in is actually possible at that point. For example:

- it might not be good for the overall performance to allow walk-in patients very close to the end of a working day because this will inevitably lead to overtime;
- if the expected waiting time is high, the walk-in patient can prefer to come back for an appointment;
- if the new arrival causes higher waiting time for existing patients, walk-in might be undesirable. For example: when a server is idle and a walk-in patient with a processing time of two hours arrives, this patient could be served right away. However, if in fifteen minutes the appointment schedule shows that several patients will arrive for the server, these appointments would incur high waiting times because of the walk-in patient.

If, based on the access choice, a patient is not allowed to walk-in, the patient is sent to the planner for an appointment. These patients are registered as deferred walk-in patients, one of the performance indicators described in Section 2.1.

4.4.2 Scheduling appointments: Sequence choice and planning horizon

When a patient requests an appointment, the scheduler has to decide which slot in the appointment schedule has to be scheduled. Per patient group the user can set the horizon in which the planner may search for an appointment, and if the first available or last available slot in this horizon should be used. For example some patients need an appointment as soon as possible to determine what care is needed, while other patients need an appointment to keep track of their health status each year. We refer to this choice as the sequencing choice, which can influence the performance of the whole system.

4.4.3 Serving Patients: Priority choice

When a process-component becomes idle and the corresponding waiting room has multiple patients waiting, the decision on which patient gets served next will have to be made. In other words, which patient group has what level of priority? For example the first-come-first-serve principle will be easy to use in practice, but it could be considered unfair to let patients who arrive in time for an appointment wait just as long as walk-in patients.

4.5 Assumptions and additional functionalities

In the previous sections we have described the fundamental functionalities of the model. The model replicates (a part of) the real world and, as any model, is bound by a set of assumptions to keep it controllable and transparent. In this section we list the assumptions that are relevant for the simulation model.

- Patients do not visit a component more than once;
- Patients who have an appointment do not get a new appointment. For example if a walk-in patient is deferred because it is too busy at that time, due to a test component this patient could then get another appointment (the patients skips the test component in this situation);
- Patients can only be at one component at a time, meaning that the process is a series of components (so parallel processing is not possible);
- Patient type is determined at arrival and does not change;
- Each test and preparation component has an individual waiting room. Servers share a central waiting room;
- Servers are considered to be the last stop in the system;
- Servers always have capacity one (since each server has its individual schedule). Also, appointments are only made for servers, so not for test and preparation components;
- For non-clinical patients, the planner starts searching for an appointment slot one day after the appointment request. For clinical patients an appointment can be searched on the same day.

- If an appointment is not found in the set planning horizon, the planning horizon is extended once by the length of the planning horizon. If this extension is not enough, the simulation stops and sends a message;
- If the planner can realize the same access time with different servers, the patient's preferred server is selected for the appointment.
- When evaluating if a walk-in patient is allowed the preferred server is selected if possible (even if other servers are expected to be less busy).
- If multiple servers are viable for walk-in, the patient will initially go to the server with the least expected arrivals (to ensure that capacity is reserved to serve the patient). The server on which the patient is served can change if the patient is in the waiting room and can be served earlier on another server;
- Arrival of patients happens according to a non-stationary Poisson process;
- Appointments are scheduled directly when an appointment request arrives;
- Once an appointment is made it is not changed, unless it is rescheduled due to a shutdown;
- Queue dodging does not happen, patients will always wait until they are served;
- Overtime is allowed, but if more than one slot overtime is expected a walk-in patient will be deferred.
- Only server components break down. So test and preparation components do not break down;
- At the start of each day there is a chance a server breaks down and server breakdown time is deterministic with a length of one or more days.
- On server breakdown cancelled appointments are recorded as failed appointment and rescheduled as soon as possible.

4.6 Conclusion

In Chapter 1 we stated the purpose of the simulation model: *"support decision makers at a diagnostic facility with choices about resource and capacity planning regarding the combination of a walk-in and appointment system"*.

In this chapter we have described the conceptual elements that are required to develop a model that can be used to achieve this purpose: (i) the core system with a planner, a choice to accept or defer a walk-in patient and one server, (ii) a preparation component, (iii) a test component and (iv) more server components. When we look at each individual element and component, the model will not be very complex. When all elements are combined to match a real world system, the created model becomes as complex as needed. By adding the design choices corresponding to walk-in, scheduling of appointments and priority in the waiting room, the user has a broad range of functionalities to experiment with. A model remains a restricted representation of reality; as long as it is clear to the user what these restrictions are this does not have to be a problem. For this reason we have formulated a list of assumptions that have to be considered by the user when using the model.

5. Technical design, verification and validation

In the previous chapter we have described the conceptual system, its components and how all elements can be combined to simulate the system of a diagnostic facility. In this chapter we give more formal definitions of parameters and variables of the combined walk-in and appointment simulation model (WAPSIM) (§5.1). We also discuss the data requirements (§5.2), verification (§5.3) and validation of the model (§5.4). The goal of this chapter is to answer the fourth research question:

> *"Can the developed simulation model be used to represent the current system with sufficient accuracy?"*

5.1 Formal description of the model

Listing all the parameters and variables in one table would lead to a cumbersome list. Therefore, we have categorized the parameters and variables in five categories. For each of the five categories we give a brief introduction and table with the parameters and variables. The model as described in this section is implemented in a simulation package developed by Siemens, PlantSim (v10.1).

5.1.1 Organization

For the overall structure of the system that is being simulated there are several organizational parameters related to the scheduling horizon, arrival rate, number and length of slots that are shown in Table 6.

Table 6 - Organizational parameters

Symbol	Description	Range
R	the number of replicated planning cycles.	r = 1,…, R
W	the number of weeks in a planning cycle.	w = 1,…, W
$D_{c,w,d}$	day d, in week w of cycle r. True if facility is open, false if closed.	
B	the number of slots in a day the facility is open.	b = 1,.., B
B_{length}	the length of a slot in minutes.	
$\lambda_{w,d,b}$	the arrival rate of patients in slot b, on day d of week w.	
Open	the opening time of the facility on an open day.	
Close	the closing time of the facility on an open day.	

5.1.2 Components

More process specific parameters are required to make the model match the system that is being simulated, for each of the components we described in Chapter 4 we formulated the parameters shown in Table 7.

Table 7 - Component specific parameters

Symbol	Description	Range
T	the number of test components in the facility.	t = 0,…, T
t_{cap}	the capacity of test component t.	
t_{dist}	the distribution of the test result of test t.	
t_{value}	the threshold value of test t.	
t_{route1}	Route 1 is chosen when test result is equal to or below t_{value}, can be any component or the planner.	
t_{route2}	Route 2 is chosen when test result is above t_{value}, can be any component or the planner.	
P	the number of preparation components in the facility.	p = 0,…, P
p_{cap}	the capacity of preparation component p.	
S	the number of servers in the facility.	s = 1,…, S
$s_{breakdown}$	the breakdown probability of server s	
$s_{downtime}$	the number of days server s breaks down on a break down	

$SR_{d,w,b}$	a server can be available for an appointment on in slot b, day d of week w. Void if no appointment can be planned. In this array A is used to mark a generic appointment slot, and C is used to mark a clinical slot.	sr= A,C, 1,…,T

5.1.3 Patient types

Most healthcare facilities will have more than one group of patients who is served. Each of these patient types have characteristics that make them different from the other types, these characteristics are captured by the parameters in Table 8.

Table 8 – Patient-type specific parameters

Symbol	Description	Range
N	the number of patient types.	n = 1,…, N
n_{frac}	the fraction of total number of patients who is of type n.	
n_{walkin}	true if patient type n is eligible for walk-in, false if not.	
$n_{clinical}$	true if patient type n is a clinical patient, false if not	
n_{Prep}	the number of expected preparation slots for a patient of type n.	
n_{slots}	the number of expected slots required for serving a patient of type n.	
n_{pref}	the preferred server for a patient of type n (blank if none).	Pref = {void; S_1; …; S_S}
$n_{horizon}$	the horizon in number of days in which an appointment is searched for a patient of type n.	
$n_{sequence}$	the manner in which an appointment is searched for a patient of type n.	Sequence = {First; Last}

For each of the added components c (= the number of Test, Preparation and Server components = T+P+S), the different patient types can have their own processing time distributions and priority rule. These parameters are shown in Table 9.

Table 9 - Patient specific parameters per component

Symbol	Description
$c_{n,procdist}$	the distribution of the processing time of component c for patient of type n.
$c_{priority}$	the priority rule that is used when the component c becomes idle.
n_{route}	the sequence of components visited by patients of type n, an array of length c, step one in the route is marked 1 and each consecutive step in the route is marked by the next integer. Components that are not visited remain void.

5.1.4 Appointments and Walk-In

Lastly we have defined several parameters in Table 10 that are required to deal with appointments (denoted A) and walk-in patients (denoted WI).

Table 10 - Parameters related to appointments and walk-in

Symbol	Description
A_{noshow}	the fraction of appointments that does not show up.
$A_{reschedule}$	the planning horizon in days that is used when rescheduling a patient due to breakdown
WI_{close}	the time at which the facility stops to allow walk-in patients.
$WI_{allowedwait}$	the number of slots a walk-in patient is allowed to wait.
WI_{delay}	the number of slots a walk-in patient is allowed to delay other patients.
CT	the check-up threshold, patient types with a planning horizon higher than CT are considered to be check-up patients. The access time for check-up and regular patients is aggregated separately.

5.2 Data requirements and reuse strategy

The quality of simulation studies is for a large part dependent on the quality of the input data. With a reusable model this is no less true and there is the additional challenge of making use of the flexibility of the model while respecting its boundaries. As stated in Chapter 2, Pidd [27] argues that a reuse strategy is needed to reap the benefits from reuse and should include four aspects:

- *Abstraction*, we attained this by describing the conceptual model in Chapter 4. The high level descriptions of the separate components, functionalities and assumptions allow the user to get a clear idea of how the model works and what its purpose is.
- *Selection*, is a technical aspect we have not implemented. It would allow the user to search and compare artefacts through a search directory. However, we argue that this becomes necessary when there is a large number of artefacts or functions to be used by the user, which does not hold for our project.
- *Specialization*, we have made an Excel front end for the simulation model that incorporates the parameters of the formal description and allows customization of all components to the user's problem.
- *Integration*, the simulation model reads the Excel files that were filled in by the user. To ensure that the Excel input can be filled in easily and accurately we have written a guide that can be followed by the user, after following the guide the simulation package can read the input and WAPSIM gives feedback for common errors in the input structure. The WAPSIM user guide can be found in Appendix A.

5.3 Verification

Verification is the process of assuring the technical functioning of the programmed model. Verification involves the debugging of unexpected mishaps in the code through statistical and logical tests. Law [44] suggests eight techniques that can help with verification: (i) write and debug in components or sub methods, (ii) let more than one person review the computer program, (iii) use different parameters, (iv) trace the state of the simulated system, (v) run the model under simplified assumptions, (vi) compute the sample mean and sample variance and compare to desired values, (vii) use a commercial simulation package and (viii) observe animations. Each of these techniques was used. For details and examples about the verification process we refer to Appendix B.

5.4 Validation

As for any simulation model, the issue of validity is no less important for a reusable model. Full validation for a one-use model is not possible, it is argued that through verification and validation tests a model gets increased credibility. A credible model can be used for the purpose that was defined. For a reusable full model validation is never done, for each new problem the model is used for the user will have to go through validation tests to ensure that the model is credible to use for the situation at hand. Pidd [27] notes that the first step before reuse will always be to check if the model is used for its intended purpose. Validation tests that we used to improve credibility are comparison with expert opinion and the existing system.

5.4.1 Comparison with expert opinion and existing system

During numerous individual and group meetings with different stakeholders we discussed the current system, possibilities and pitfalls of a combined walk-in and appointment system. Experts who were consulted to ensure the quality of the model input:

- The research group, consisting of two radiologists, two laboratory assistants, a team leader of radiology, two advisors of the department for process and quality innovation and myself as the simulator and data analist;
- The administrator of the radiology information system;
- Administration and planning employees of the radiology department;
- Technical maintenance of the radiology department;
- A work visit to the radiology department of the Arnhem Rijnstate hospital, which implemented a combined walk-in and appointment system in 2010.

5.4.2 Performance indicators

Using the input data from the data analysis and expert opinions we simulated the current system, in which there are only appointments. Note that the purpose of WAPSIM is not to simulate a 100% appointment system, but to experiment with the combination of walk-in and appointments and its various settings. Because of the flexibility of WAPSIM we should be capable of simulating the system accurately. The performance indicators time-to-third-available appointment and the number of deferred walk-in patients have been omitted from the comparison, the former is not tracked in WAPSIM and the latter is not an indicator in an appointment system.

Utilization

The utilization of the system is a verification issue, as it is influenced by three factors that were verified individually: (i) the number of patients arriving at the system, (ii) the processing time of patients and (iii) the number of patients dropping out of the system due to no show. It is not possible to calculate a confidence interval for the difference in utilization, as we only have one observation from historic data.

There is a slight overestimation of the utilization of CT1 and underestimation of CT2. For the overall utilization there is low relative difference of -1.5%. This is an indication that WAPSIM is able to simulate the workload of the current system, but needs an explanation. The underestimation of the utilization is caused by the lower no-show rate of 1.4% in the measurement month than the no-show rate of 2.6% that was observed over the period 5/2012-5/2013. This argument is verified by a relative error of -0.2% when the no-show rate from the measurement month was used. The overall utilization is 59.5% in both WAPSIM and the current situation.

Access time and time to third appointment

WAPSIM does not capture the access times of the current system. As we concluded in Chapter 3, the access times are a rough indication of what access times could be realized. For example the time to-third appointment is between one and three days most of the time, indicating that patients could get appointments fast if this would be desirable. The difference between WAPSIM and the historic data has three main reasons: (i) the manner in which appointments are planned in practice and (ii) the typology of patient types in WAPSIM and (iii) in WAPSIM clinical patients get an advanced access appointment.

i. Planning at radiology happens in a pragmatic manner, meaning that the planner keeps track of all kinds of variables such as: patient preference and appointments with other specialists. When the planner finds no dedicated slot in the desired horizon, the planner has the option to open up another slot or switch appointments (as long as other people who are involved are consulted). Also, it varies when a patient is planned: it could be the day of the request, but it is not uncommon that it takes up to several days. This results in the fact that 86% of all patients is planned within 40 days, only 27% gets an appointment within a week. In WAPSIM these patients are always planned as-soon-as-possible and the WAPSIM-planner starts searching the day after the request. Although it might not be realistic to plan like this in practice, all patients can be served within two weeks in this manner.
ii. The WAPSIM-planner has two logical heuristics (first slot or last slot in a given horizon) and directly schedules every patient as the appointment request arrives. In WAPSIM the planning horizon and heuristic is given per patient type, while in practice this is not patient type dependent but patient dependent. Check-up patients in WAPSIM get an appointment as late as possible in an 80 day horizon (this is average access time of patients who got an appointment more than a month after the appointment request). In practice this horizon may vary from a month to over a year.
iii. Clinical patients in the current situation are not given an appointment in the information system because the employees of the department are not able to use X-care. The inpatients are treated between appointments when it is possible. WAPSIM does give clinical patients an appointment (as would be desired in practice), preferably on the same day. WAPSIM registers this access time of zero days, while in reality no access time is registered.

The access time distribution in WAPSIM could be tweaked to match the historical data better by adapting the schedule for the CT-scans to match the actual results better and by fine tuning the planning horizon of each patient type. However, we argue that there is no heavy weighing reason to do so, as the other performance indicators that cannot be influenced as easily do match the existing system. These arguments in combination with the fact that WAPSIM was not developed to evaluate an appointment only system, is reason to argue that the not-matching access time is no reason to doubt the validity of the model.

Waiting time

The waiting time of WAPSIM has a good match with the data of the measurement month. To test this we computed the Welch Confidence Interval [-1m32s; 1m22s], this method is used because the number of observations in WAPSIM is not equal to that of the historic data [44]. There is no reason to assume that the two datasets have a different distribution, as the confidence interval contains zero. The number of waiting patients is overestimated by 4.5%, in WAPSIM 43.9% of all patients incurred waiting time when simulating the current system, while in the measurement month this was 42.0%.

Overtime

For the distribution of the amount of overtime the confidence interval [-8m04s; 1m47s] contains zero, so there is no reason to assume that the distribution of overtime in WAPSIM and the historic data are different. In WAPSIM overtime occurred 24.2% of the time, while it occurred 30.8% of the time in the measurement month (relative error of -21.3%). From the measurement month we have a limited amount of data on overtime (n=16), which is an explanation for the large relative error and wide confidence interval. A more practical explanation for the difference is that the planner in WAPSIM always selects the earliest possible slot in a day when planning a patient, while in reality the planner will also plan patients at the end of the day to confirm to patient preferences.

5.5 Conclusion

Based on the extensive verification steps we are confident that WAPSIM is technically solid and able to capture a broad range of systems. Due to the broad range of settings and functionalities there is a lot of flexibility, due to this flexibility the model has also become complex. The Excel front-end supported by a guide, allows a user with minimal simulation experience to adhere to the structure of the model. Because this structure is needed for WAPSIM to work correctly, the structure of the Excel-input is verified when it is loaded into WAPSIM. Because of the flexibility experimental ease remains an issue, and has two sides: (i) there are a lot of factors that can be experimented with (this number increases as the number of components increases) and (ii) the data can be aggregated to a multitude of levels (for example day-, week-, run-, patient-type and/or patient group level).

Because a combined walk-in and appointment system is not yet implemented at the AMC, WAPSIM was validated through historic data of a 100% appointment system. Almost all performance indicators have a good match with the current system. The only exception is the access time for appointments, for which there are two possible reasons:

1. WAPSIM was not designed with the purpose to simulate a 100% appointment system, when a patient is scheduled in reality the planner can consider patient preferences and for example other appointments in the hospital. These are nuances the planner in WAPSIM was not developed to capture.
2. The other possible reason for the mismatch is the doubt about registered access time, as stated in Chapter 3 there is reason to assume that the access time could be much lower.

Based on expert opinions and simulation of the current system we are confident that WAPSIM is able to simulate the current system and can be used for further experimentation.

6. Experimental design

In this chapter we study the first half of the fifth research question by describing the experimental factors and settings in detail (§6.1), define the simulated system according to the WAPSIM components of Chapter 4 and show the experimental design that will be used (§6.2), and determine the run length and number of required replications (§6.3). In the final section we summarize the chapter (§6.4).

> *"Which experiments are useful for implementation of a combined system at the radiology department of the AMC and how can the results of the experiments be assessed?"*

6.1 Experimental factors and settings

WAPSIM is a simulation model that allows the user to experiment with a broad range of experimental factors and settings. In this section we describe these factors and settings in more detail.

Allowing walk-in: access choice

There are three variables that influence if a walk-in patient may enter the system, or should get an appointment:

- Closing time for walk-in: the user can decide that after a certain time walk-in is no longer allowed. For example if the facility closes at 17:00, and the closing time for walk-in is set on one hour, walk-in patients arriving after 16:00 will not be allowed.
- Allowed waiting time: the number of slots that a walk-in patient is assumed to be willing to wait. If the service of the walk-in patient cannot start within this number of slots, the walk-in patient is deferred and is sent to the planner for an appointment.
- Allowed delay for other patients: the number of slots a walk-in patient may delay other work in the system. For example, a patient who needs 4 slots for service arrives at the facility. Service could start right away because the server is idle. However, from the next slot on there are 8 consecutive appointments. These appointments would be delayed by at least 3 slots. So if the 'allowed delay' factor would be set to 2, this walk-in patient would be deferred and is sent to the planner for an appointment.

Note that shut-down of servers will also influence the access choice, as patients who walk-in for the shut-down server will automatically be deferred. However, this is not a factor that is considered for experimentation as it is assumed that it cannot be influenced.

Serving Patients: Priority choice

The priority handling mechanism can be set per processing component. Because servers are considered to be the bottlenecks of the system, it will most likely be most valuable to experiment on the priority choice for the servers. There are three possibilities when considering the priority choice:

- First Come First Served (FCFS): patients are served as they arrive. In other words, all patients have equal priority. Possible downside is that scheduled patients, who arrive in time, still have to wait for a significant time (like the walk-in patients).
- Always prioritize appointments: if there are no more appointment patients in the waiting room, the walk-in patients are served FCFS. A possible downside is that the difference in waiting times between walk-in and scheduled patients becomes big.
- Combination of the two rules: appointments are prioritized unless there is a walk-in patient who has already been waiting more than a set number of minutes.

Opening of dedicated slots

In the schedule for each server, slots can be reserved for specific patient types. This enables the user to cluster patients of the same type. When the slots are not used for an appointment they will be open for walk-in. However, appointments are generally made in slots where the arrival rate is low, so there is a possibility that the slots will not be used at all. This is the reason we introduced the experimental factor of opening these dedicated slots for all appointment requests. At the end of a day the dedicated slots are opened a set number of days ahead in the schedule. Slots that are reserved for advanced access are not opened for general use, as it often is the case that these slots are required on the day the patient arrives.

Uncontrollable factors

There are also experimental factors that are mainly interesting for sensitivity analysis. In reality we might not be able to influence these factors. However, because we are simulating reality through WAPSIM we can influence all factors to analyze their potential effect on the system. These factors include: no-show rate, service times of components, shutdown-rate and the arrival rate of patients.

Excluded factors for the CT-scan case

The main purpose of the WAPSIM model is to effectively combine walk-in and appointments in one system, this means that the experimentation is on the operational level. It is possible to extend experimentation to the strategic level by considering experimental factors such as:

- Capacity of test and preparation components;
- The number of servers;
- The case-mix of patient types.

6.2 The simulated system and experiments

In this section we describe the system we will simulate, the input that we use, as well as the experimental design and the computation of the number of required runs and the warm-up period. The distributions of the processing times for the different components are determined using Datafit software from the Siemens PlantSim package.

6.2.1 Components

In Figure 13 the complete system that is simulated is shown, components are named descriptively to match this subsection and the typology of Chapter 4. The◇'s in the figure are added to show the different routes that patients can take through the system. As an example we added the dotted line, the patient following this route is eligible for walk-in and can go straight to CT1. The route a patient takes depends on his/her patient type, this is described in the next subsection.

In the system we are simulating there are six components, as shown in Figure 13. First we have two server components that are not interchangeable. Some patient types cannot be served at CT2 and for all patient types there is a preference to use CT1 because it produces better pictures and uses a lower radioactive dose. The processing times of the CT-scans are distributed log normally with different parameters depending on the patient types. Also, we assume that a scan requires at least 4.5 minutes, as each patient needs to be called from the waiting room and receives instructions on how to take position during the CT-scan.

Secondly there are three different preparation components: (i) the lab, (ii) the IV preparation and (iii) the oral components. The lab has virtually unbound capacity and needs 60 minutes to process a patient (deterministic). The capacity of the oral preparation component is set to 10, if this appears to be a bottleneck it would be easy to increase this capacity by letting more patients drink their contrast fluid in the waiting room. Processing time of oral preparation is deterministic and differs between patient types. There is one room dedicated to IV preparation, meaning the capacity of this component is one. For the IV preparation no significant match was found for the processing time, therefore an empirical distribution based on measurement weeks conducted by Kranenburg [15] was used.

Lastly there is one test component. Patients who require IV contrast fluid need to have an up-to-date test value of their kidney strength (eGFR) to be eligible for walk-in (this eGFR value can be obtain from the lab). For 6% of all these patients walk-in is not possible, the patient is then sent to Route 1 (the planner), otherwise the patient can continue to Route 2 (preparation component 2: place IV line). The processing time of the test station is zero, as it is a decision based on the test value: when it is too high the patient gets an appointment and when it is low enough the patient can continue to IV preparation.

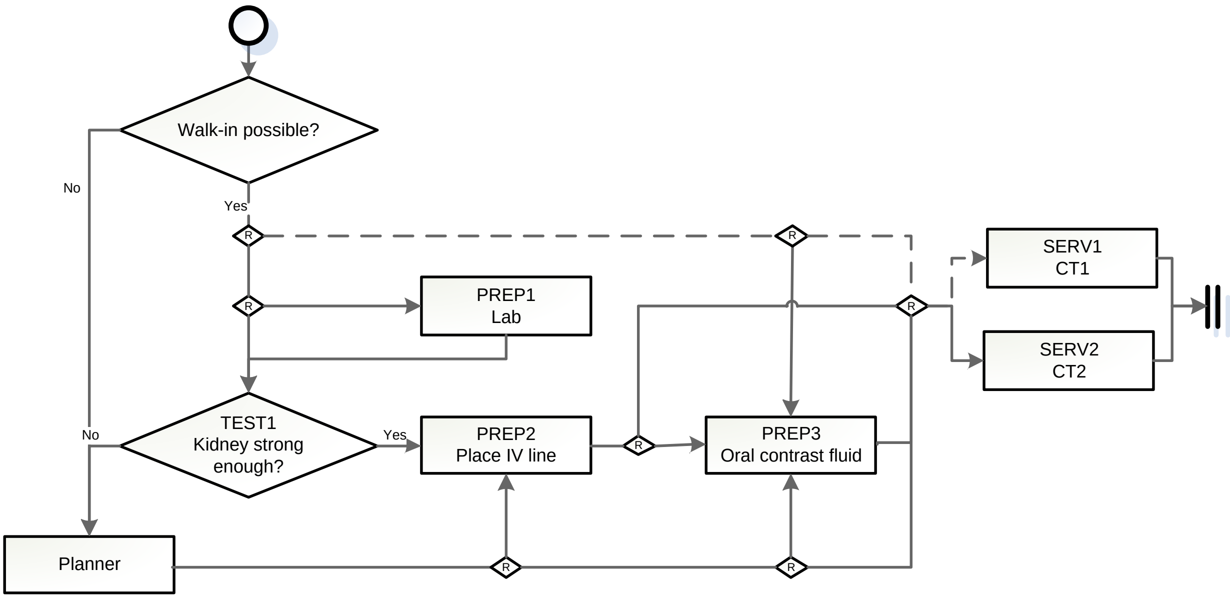

Figure 13 - The simulated system formulated through WAPSIM typology

6.2.2 Patient types

In Chapter 0 we identified 9 categories of patients according to their process characteristics. For the simulation model there are 30 patient types to account for several distinctions within the previously defined categories:

- Walk-in patients, advanced access and appointments. There are three types of patients who require an appointment for medical reasons (cardiac, colon and puncture patients). This group is 10% of all production. Of all production 12.5% is in-patient, who can get an appointment on the same day and the remaining 77.5% of production consists of out-patients.
- Planning rules. 16.5% of all out-patients are scanned for a check-up. This means the check-up patients can return for a CT-scan somewhere in the next year.
- Processing times of preparation components. For the oral preparation, some patients have to drink water for 30 minutes, while others drink contrast fluid for 60 minutes.
- Additional preparation step. Of all patients who require IV preparation, 6% does not have an up-to-date eGFR value. So all patient types that are eligible for walk-in and require IV are split into two types, as the patients who already have an eGFR value have a different route through the system.

Based on the 30 patient types we have defined two scenarios. In scenario one (S1) the check-up patient is considered to be eligible for walk-in. In scenario two (S2), the planning rule of these patient types will be changed, giving the check-in a patient an appointment as late as possible in an 80 day horizon. In Table 11 the summarized patient categories are shown. The complete list of patient types used for the simulation and the categorization of each type per experiment is shown in Appendix C.

Table 11 - Scenarios as used for the simulation

	S1	S2
Advanced access (%)	12.5	12.5
Appointment (%)	10.0	22.7
Walk-in (%)	77.5	64.8
Total	100.0	100.0

6.2.3 Interventions

For both scenarios S1 and S2 we will simulate sixteen interventions by changing four experimental factors:

- The allowed number of waiting slots in the access choice will be set to 6 and 10 slots. In other words 1.5 hours and 2.5 hours;
- The priority choice for when a server becomes idle will be set to appointments prioritized (=AP) and appointments prioritized unless the waiting threshold of one hour is exceeded for a walk-in patient (=APT).
- The closing time for walk-in patients is set to 0 and 1 hour;
- The opening of dedicated slots will be set to 0 days and 3 days.

The interventions are shown in Table 12, this experimental design is referred to as a 2^k factorial design. Through this design we can compute the expected effect of individual factors and the combined effect of multiple factors.

Table 12 - Factorial experimental design

Factor combination	(2) Number of allowed waiting blocks	(3) Priority Rule	(4) Closing time for walk-in	(5) Opening of dedicated slots	Response
1	6 (-)	AP (-)	0 (-)	0 (-)	R_1
2	6 (-)	AP (-)	0 (-)	3 days (+)	R_2
3	6 (-)	AP (-)	1 hour (+)	0 (-)	R_3
4	6 (-)	AP (-)	1 hour (+)	3 days (+)	R_4
5	6 (-)	APT (+)	0 (-)	0 (-)	R_5
6	6 (-)	APT (+)	0 (-)	3 days (+)	R_6
7	6 (-)	APT (+)	1 hour (+)	0 (-)	R_7
8	6 (-)	APT (+)	1 hour (+)	3 days (+)	R_8
9	10 (+)	AP (-)	0 (-)	0 (-)	R_9
10	10 (+)	AP (-)	0 (-)	3 days (+)	R_{10}
11	10 (+)	AP (-)	1 hour (+)	0 (-)	R_{11}
12	10 (+)	AP (-)	1 hour (+)	3 days (+)	R_{12}
13	10 (+)	APT (+)	0 (-)	0 (-)	R_{13}
14	10 (+)	APT (+)	0 (-)	3 days (+)	R_{14}
15	10 (+)	APT (+)	1 hour (+)	0 (-)	R_{15}
16	10 (+)	APT (+)	1 hour (+)	3 days (+)	R_{16}

Note that the scenarios S1 and S2 are defined as the first factor, this factor has been left out of the table to maintain readability. For this experimental design we have k=5, meaning there is a total of 32 experiments (2^5=32) and 32 responses. The priority rule FCFS will be evaluated for a limited number of interventions, to save computation time.

Other factors

The remaining factors are constant for all interventions, matching the data analysis:

- Allowed delay on other patients is set to 1 slot. In the CT-scan case all walk-in patients have an expected processing time of 1 slot. This means that if the patient can be served within the allowed waiting slots, the patient enters the facility for service;
- No-show rate for appointments is 2.6%, as observed in RIS for the period May 2012 to April 2013. This data is preferred over the no-show rate of 1.4% during the measurement month, as the no-show data is registered correctly throughout the year;
- Server shutdown rate is 8 days per year for CT1 and CT2, when a shutdown occurs this will be for the duration of one day, appointments that need to be rescheduled in case of a shutdown are planned as soon as possible regardless of patient type.

Note that all the parameters described in Section 5.1 could be adapted for further analysis, for the scope of this research these are also kept constant.

Appointment Schedule

For the different experimental settings and interventions we need a fitting appointment schedule. For the initial schedule we will use the algorithm of Kortbeek et al. [9] as adapted into a faster heuristic for larger cases by Veldwijk [10]. Within WAPSIM there are several assumptions that do not match with the algorithm, for example service time of servers is not deterministically distributed, service can take more than one slot and there are advanced access patients present. Several manual adaptions have been made to the roster generated by the heuristic to ensure that the schedules used for the simulation match the CT-scan case. The biggest changes in the schedule are the addition of fixed slots for cardiac patients on Tuesday and Thursday afternoon and the addition of slots for advanced access patients. An example of the initial schedule as generated by the heuristic of a Tuesday is given in Figure 14.

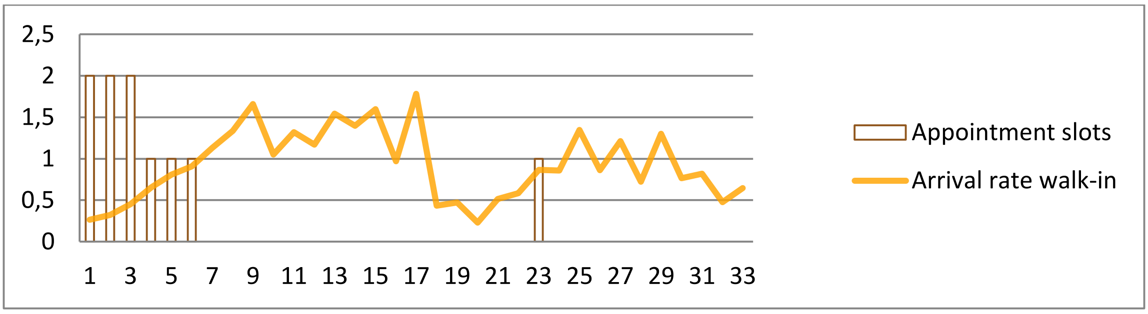

Figure 14 - Initial roster as generated by the heuristic of Veldwijk [10]

The schedule for the same Tuesday after adaption, as used for the WAPSIM simulation is shown in Figure 15. We dedicated slots in the morning and at the end of the day to accommodate for clinical patients, eight slots in the afternoon for the cardiac patients, and the appointment slots are dedicated to specific CT's. Advanced access slots are placed before regular slots in the morning, as the preparation of clinical patients can happen before the patient is brought to the radiology department, while regular patients who need preparation cannot be planned in the first slot. Note that both unused dedicated and advanced access slots, as with all appointment slots, are available for walk-in. The colon and punction patients also got dedicated slots throughout the week.

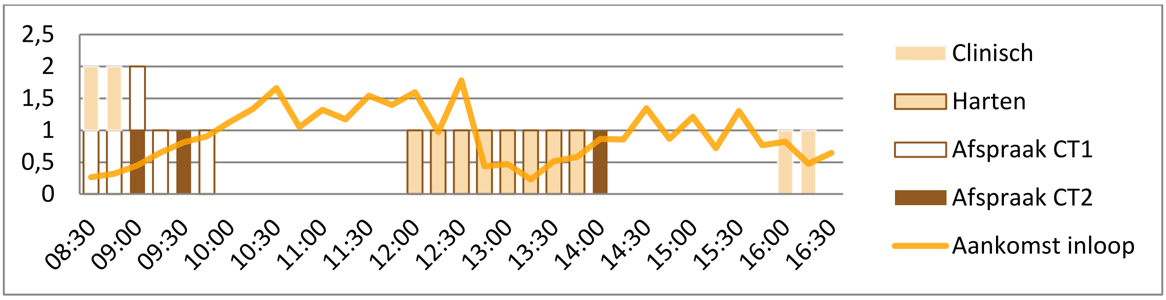

Figure 15 - Roster adapted to CT-scan case

In total we made four different schedules, for each combination a scenario and number of allowed waiting slots (2^2=4). The adaptions of the roster made by the heuristic were done in a structured manner, but it is not scientific. We chose for this pragmatic approach, as there is no method to construct an optimal schedule for this specific case, in which walk-in, appointments and advanced access are combined and there is a the possibility that walk-in patients get an appointment after they were allowed to walk-in (this can happen due to the test component).

6.3 Run length and number of replications

To determine the number of replications and run length that is required to get statistically significant results we take a short look into the type of simulation model WAPSIM is. The main purpose of WAPSIM is to evaluate a combined walk-in and appointment system, with the addition of advanced access patients. We study the daily elements of the system such as waiting time and the amount of overtime on a specific day, these are terminating elements of WAPSIM as they are known at the end of each day. Another important performance indicator is the access time of patients, it spans a larger time horizon and the arrival of patients on one day can influence how busy the system is on a day in the future, as there is no logical endpoint to the cycle of patients arriving and their appointments taking place, this is a non-terminating element of the model.

Non-terminating simulation models need a time to warm-up and reach the steady state. The reason for a warm-up period is that the systems starts without any patients in the schedule. Using the visual method of Welch we determined that the warm-up period takes about 7000 patients, or 28 weeks [44]. To ensure the model is warmed up, in each run the first 30 weeks are deleted from the output data before aggregation. For thoroughness we also remove the same amount of data at the end of each run, the end of the run consists of patients who do have an appointment but have not yet been served.

To determine the number of required replications to get statistically significant results we simulated a large number of two year runs. With the warm-up and cool-down period deleted, each replication can be considered to be a terminating simulation. This means we can use the confidence interval (CI) half width to determine the minimum number of replications required. We evaluated the different performance indicators and their CI using the following formula:

$$n^*(\gamma) = \min\left\{ i \leq n : \frac{t_{i-1,1-\frac{\alpha}{2}}\sqrt{\frac{S_n^2}{i}}}{|\bar{X}_n|} \leq \frac{\gamma}{1+\gamma} \right\}$$

With a relative error (γ) of 2% and a confidence level (α) of 95%, we found n^* = 45 for the experimental setting (this is notably more than the 20 replications that would suffice for the current system). Since runtime performance is not an issue for the WAPSIM model when considering the CT-scan case we rounded the number up to 50 runs.

A system with a quad core i5 3.4 GHz processor, 8GB of RAM and PlantSim installed on a solid state drive (SSD), requires 9 minutes and 22 seconds to simulate one experiment in the chosen set-up of 50 replications with a length of 2 years and a warm-up period of 30 weeks. Also, WAPSIM needs 40 seconds to load and verify a new set of input data for the CT-scan case. Performance wise it is worth noting that on a dual core E6750 2.66GHz processor, with 2GB of RAM and no SSD, the same experiment requires 32 minutes and 17 seconds.

6.4 Conclusion

In this chapter we described two scenarios that form the first experimental factor (i). In Scenario 1 the largest possible group of patients is allowed to walk-in, including check-up patients that need a CT-scan in a couple of months. In Scenario 2 these check-up patients are not allowed to walk in, they get an appointment. In addition to the scenarios we defined four experimental factors:

- ii. Number of allowed waiting blocks for walk-in patients;
- iii. The priority rule used for the central waiting room of the servers;
- iv. A closing time for walk-in patients;
- v. The opening of dedicated slots for general use.

The five experimental factors are combined in a 2^k factorial experimental design with the goal to study combination of walk-in and appointments in one system for the CT-scan case of the radiology department of the AMC. Following the concepts that we introduced in Chapter 4, we have a total of five components in that are combined with the core system: one test component, three preparation components and one extra server.

We generated initial appointment schedules using the heuristic of [10], these appointment schedules were then adapted to meet the requirements of the CT-scan case (for example reserved slots for cardiac patients). All other parameters that we described in Chapter 5 are kept constant for all experiments.

7. Results

In this chapter we will study the results of the experimental design that we presented in Chapter 6 to answer the second part of the fifth research question. In the first section we describe the type of output analysis that is used (§7.1), followed by an extensive analysis of the performance indicators (§7.2), sensitivity analysis of several input parameters (§7.3), and a concluding section (§7.4).

> *"Which experiments are useful for implementation of a combined system at the radiology department of the AMC and how can the results of the experiments be assessed?"*

7.1 Output analysis

Based on the 2^k factorial design that we presented in Chapter 6 we can calculate the main effect of the five factors that we changed, this main effect is denoted by e_j. For example we can study the main effect of Factor 3, changing the priority rule from AP to APT, on the waiting time of walk-in patients. The formula we use for computing the main effect of Factor 3 is:

$$e_3 = \frac{(R_5 - R_1) + (R_6 - R_2) + (R_7 - R_3) + (R_8 - R_4) + (R_{13} - R_9) + (R_{14} - R_{10}) + (R_{15} - R_{11}) + (R_{16} - R_{12})}{8}$$

The R_i in this formula are the responses as defined in Subsection 6.2.3, Table 11. Note that the formulas we used are actually twice as long to account for Factor 1, the two different scenarios. For readability we restricted the examples to the responses that are shown in Table 12.

The computation works as follows: the responses in which Factor 3 is changed to APT are deducted by the response of the experiment in which Factor 3 is set to AP, keeping all other factors constant. In the example R_5 is the experimental settings {- - + - -} after deducting R_1 that is caused by the experimental setting {- - - - -}, we have one of the eight parts of the effect that is caused by changing Factor 3 from AP to APT. In Table 13 we give the specification of all responses used for the computation of the main effect of Factor 3.

Table 13 - Specifcation of responses used for computation of the main effect of Factor 3

$(\mathbf{R_5} - \mathbf{R_1}) = \{- - + - -\} - \{- - - - -\}$	$(\mathbf{R_{13}} - \mathbf{R_9}) = \{- + + - -\} - \{- + - - -\}$
$(\mathbf{R_6} - \mathbf{R_2}) = \{- - + - +\} - \{- - - - +\}$	$(R_{14} - R_{10}) = \{- + + - +\} - \{- + - - +\}$
$(\mathbf{R_7} - \mathbf{R_3}) = \{- - + + -\} - \{- - - + -\}$	$(R_{15} - R_{11}) = \{- + + + -\} - \{- + - + -\}$
$(\mathbf{R_8} - \mathbf{R_4}) = \{- - + + +\} - \{- - - + +\}$	$(R_{16} - R_{12}) = \{- + + + +\} - \{- + - + +\}$

It is also possible that some factor is dependent on other factors to have an effect on the performance indicators. To this extent we can use the two-factor interaction effect (or j_1xj_2 interaction), which is denoted by $e_{j_1j_2}$ [44]. The formula we use for computing the interaction effect between Factor 2 and Factor 3 is:

$$e_{23} = \frac{1}{2}\left[\frac{(R_{13} - R_5) + (R_{14} - R_6) + (R_{15} - R_7) + (R_{16} - R_8)}{4} - \frac{(R_9 - R_1) + (R_{10} - R_2) + (R_{11} - R_3) + (R_{12} - R_4)}{4}\right]$$

The computation of an interaction effect is slightly more complicated than that of a main effect. In the first tem of the formula we see the responses in which only Factor 2 is changed, keeping Factor 3 on the active setting {+} and all other factors kept constant. In the second term of the formula we do the same but keep Factor 3 in its passive setting {−}. By deducting the effects on the second term from of first term, we find to what extent one factor depends on the presence of the other factor. In Table 14 we give the specification of all combinations of responses used for the computation of the interaction effect between Factor 2 and 3.

Table 14 - Specifcation of responses used for computation of the interaction effect between Factor 2 and Factor 3

First term	Second term
$(\mathbf{R_{13}} - \mathbf{R_5}) = \{- + + - -\} - \{- - + - -\}$	$(R_9 - R_1) = \{- + - - -\} - \{- - - - -\}$
$(\mathbf{R_{14}} - \mathbf{R_6}) = \{- + + - +\} - \{- - + - +\}$	$(R_{10} - R_2) = \{- + - - +\} - \{- - - - +\}$
$(\mathbf{R_{15}} - \mathbf{R_7}) = \{- + + + -\} - \{- - + + -\}$	$(R_{11} - R_3) = \{- + - + -\} - \{- - - + -\}$
$(\mathbf{R_{16}} - \mathbf{R_8}) = \{- + + + +\} - \{- - + + +\}$	$(R_{12} - R_4) = \{- + - + +\} - \{- - - + +\}$

Through these formulas we can analyze the responses of all individual performance indicators, so R_n can be read as any of the performance indicators (like in the example the average waiting time of walk-in patients). For each of the 50 replications the main and interaction effects are calculated, based on the computation of the mean effects and variance in these effects the confidence interval of each (interaction) effect can be computed. An oversight of the means of all main effects can be found in Appendix D, in Section 7.2 we will use the confidence intervals for an in-depth analysis of all performance indicators.

7.2 Performance indicators

Before we study the main and interaction effects as described in the previous section, we will study the primary effects that are caused by the experimental factors to get an impression of the system performance and the trade-offs that occur by introducing experimental factors. A primary effect occurs when only one factor is changed, for example the primary effect of Factor 2 is the difference between {- - - - -} and {- + - - -}. The significant primary effects are shown in Table 15. For Factors 2 to 4 we see expected trade-offs:

- Factor 2: increasing the allowed waiting time for walk-in patients reduces the fraction of walk-in patients who is deferred, but also leads to higher waiting time for walk-in patients;
- Factor 3: by changing the priority rule from 'Appointments first' to 'Appointments first, unless a walk-in patient is waiting more than an hour the waiting time of appointments increases, but the waiting time for walk-in patients decreases.
- Factor 4: when a closing time of one hour for walk-in was introduced (at the end of every working day), the number of deferred walk-in patients increases while the percentage of work done out of office hours decreases.

The effect of changing from Scenario 1 to 2 is not marked by a specific trade off. Also, the effect of opening dedicated appointment blocks for general use (Factor 5) is different than expected. The access time for appointment patients increases, while the goal of the intervention is to improve access time through more flexibility. In Subsection 7.2.3 we will study this exception in more detail.

Table 15 - Primary responses of four experimental factors

	All -	F2 +	F3 +	F4 +	F5 +	Current
Walk-in (%)	77.4					0.0
Deferred walk-in (%)	9.6	7.8		14.9		n/a
Utilization (%)	59.6					58.6
Waiting time appointments (mm:ss)	10:13		11:48			11:28
Fraction of appointments with waiting time (%)	56.8					43.9
50th percentile waiting time appointments (mm:ss)	07:07		07:35			7:39
80th percentile waiting time appointments (mm:ss)	15:02		16:40			18:02
Waiting time walk-in (mm:ss)	16:12	19:57	15:37			n/a
Fraction of walk-in with waiting time (%)	65.5	66.7				n/a
50th percentile waiting time walk-in (mm:ss)	06:22	07:03				n/a
80th percentile waiting time walk-in (mm:ss)	19:30	23:00				n/a
Access time non-checkup patients (d)	4.9				5.2	5.0
Overtime as percentage of total working time (%)	3.3			1.8		0.7

These primary effects are interesting and easy to comprehend, however for a more thorough analysis we will analyze confidence intervals of the main and interaction effects per performance indicator in the next subsections. Through this analysis we can explain the dynamics between experimental factors, why some experimental factors have another effect than expected, and why some trade-offs are stronger or weaker than expected.

7.2.1 Walk-in patients and deferrals

In all the figures in the remainder of this section the confidence intervals we have plotted the main and interaction effects above the corresponding description. Figure 16 serves as an example of how the figures in this section can be read. In this example only the change between scenario one and two should have an effect on the fraction of patients who are eligible for walk-in. On average 77.4% of all patients is eligible for walk-in in Scenario 1 and 64.8% in Scenario 2. This difference is verified by the figure, as Factor 1 has a significant expected effect of about -12.4%. If the confidence interval of an effect does not cover zero, the effect is statistically significant. Not every effect that is significant is of practical relevance, for example if the effect is very close to zero.

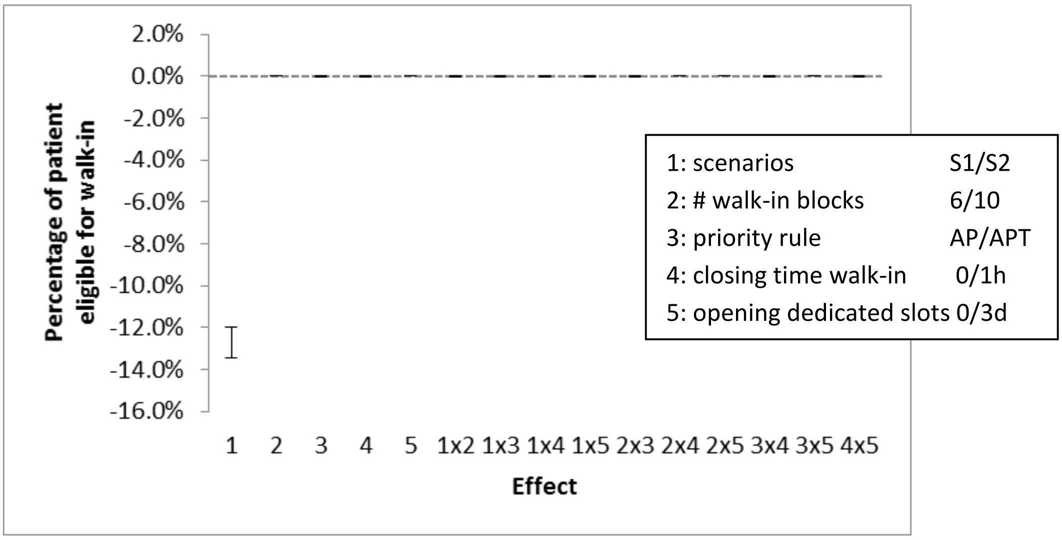

Figure 16 – Confidence intervals of main and interaction effects on the fraction of walk-in patients

In Figure 17 we see that there are four significant effects on the percentage of walk-in patients who is deferred, of which two are of practical relevance:

- Factor 2: with an allowed waiting time of 6 slots there is an average deferral rate of 12.0%, this includes both scenarios with and without closing time. By increasing the number of allowed waiting slots for walk-in patients to 10, the number of deferred walk-in patients decreases.
- Factor 4: without closing time the average deferral rate is 8.4%. By introducing the one hour closing time the number of deferred walk-in patients increases drastically.

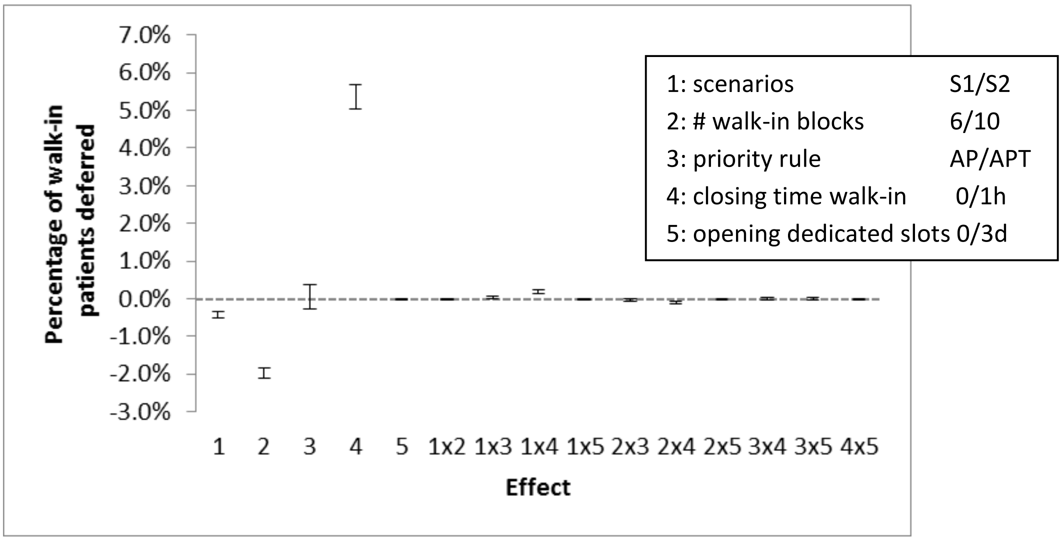

Figure 17 - Confidence intervals of main and interaction effects on deferral of walk-in patients

A source for the high deferral rate, as seen in Table 15, is the manner in which the rosters have been made. The large dedicated blocks on Tuesday and Thursday for cardiac patients and some of the advanced access slots are placed on moments of the day where a large stream of walk-in patients is expected to arrive, most of these patients are deferred and given an appointment. To get a better understanding of the impact of the roster on these effects we have added a sensitivity analysis with a less restricted roster in Section 7.3.

7.2.2 UTILIZATION

In comparison to the current system, utilization of the combined walk-in and appointment system is higher due to a decline in no-shows. In Figure 18 we can see that in the combined walk-in and appointment system there are two significant effects on the overall utilization:

- Factor 1: in Scenario 1 the average utilization is 59.6%. The increased number of patients who get an appointment in Scenario 2 reduces utilization, as a larger number of appointments also leads to more no-shows;
- Factor 4: without closing time the average utilization is 59.5%. By introducing a closing time of one hour for walk-in, utilization also slightly drops as more walk-in patients will be deferred. The deferred patients in turn result in more appointments, which result in more no-shows.

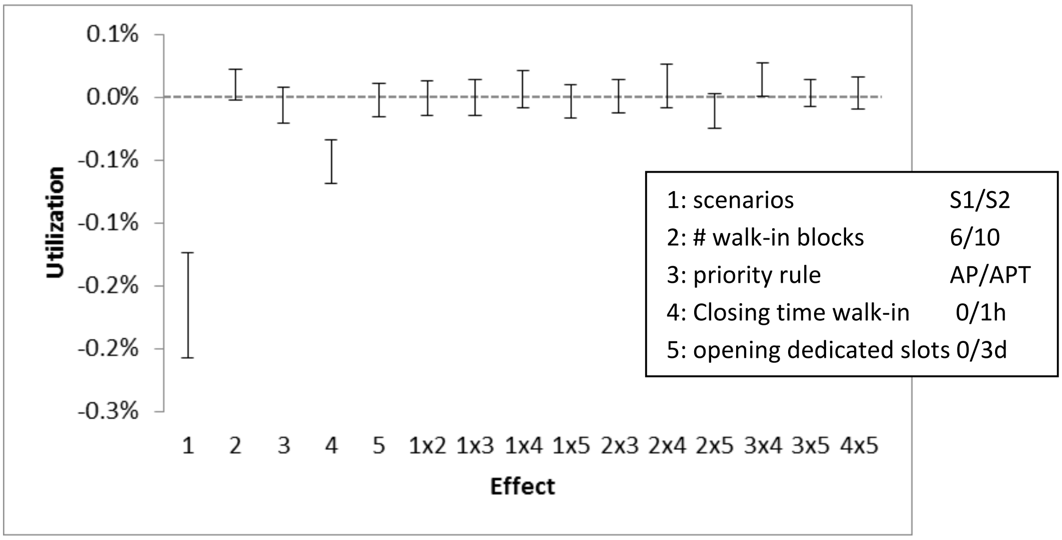

Figure 18 - Confidence intervals of main and interaction effects on utilization

It is also noteworthy that through the introduction of the combined walk-in and appointment system, the utilization difference between CT1 and CT2 gets larger. The number of patients who can be scanned on CT1 is larger and there is the preference to scan as many patients as possible on CT1, this leads to an average utilization of CT1 of 75.8% while the utilization of CT2 declines to 43.3%.

7.2.3 Access time

In Figure 19 we see that all factors that are related to the patient streams or scheduling of appointments have a significant effect on the average access time of regular patients (who are scheduled as soon as possible):

- Factor 1: in Scenario 1 the average access time is 4.9 days. When we introduce Scenario 2 the largest effect occurs. This can be explained by the generated rosters, as the amount of appointments increased by 56.6%, while the increase in total appointments slots suggested by the heuristic was only 46.8%. From the interactions effects e_{12} and e_{14} we see that this main effect is dependent on the number of allowed waiting slots and closing time for walk-in, which cause a bigger strain on the schedule (as they lead to more deferrals). The interaction can also be explained by the fact that Factors 1 and 2 are the input that is used to generate the appointment schedules.
- Factor 2 and 4: as these factors influence the fraction of deferred walk-in patients there is also influence on the number of appointments. More deferrals lead to more appointments, in the same schedule we expected to see a higher access time. In the same manner we expected that allowing more walk-in patients would lead to less appointments and thus a lower access time. The effects of Factor 2 and 4 are the opposite of what we expected. The deferred walk-in patient gets an appointment so fast, that it takes the average access time down. This is an indication that there might be too many appointment blocks for general use in the appointment schedule, as patient types that do have dedicated slots have an above average access time.
- Factor 5: this is the most remarkable effect, as the opening of dedicated slots has the goal of improving access time through a more flexible schedule. The result is the opposite effect, overall access time slightly increased due to the opening of dedicated slots. The reason for this increase can be found in the manner in which the planner finds a suitable appointment block. The planner first searches the planning horizon for a dedicated block, if there is none the planner will search for a general appointment block. By opening the dedicated blocks for general use, the patients who could use these dedicated slots got a higher access time while the increased number of general appointment slots had little effect on the other appointment requests. From the interactions e_{15} and e_{45} we see that this main effect is reduced when scenario two is introduced and when there is a closing time.

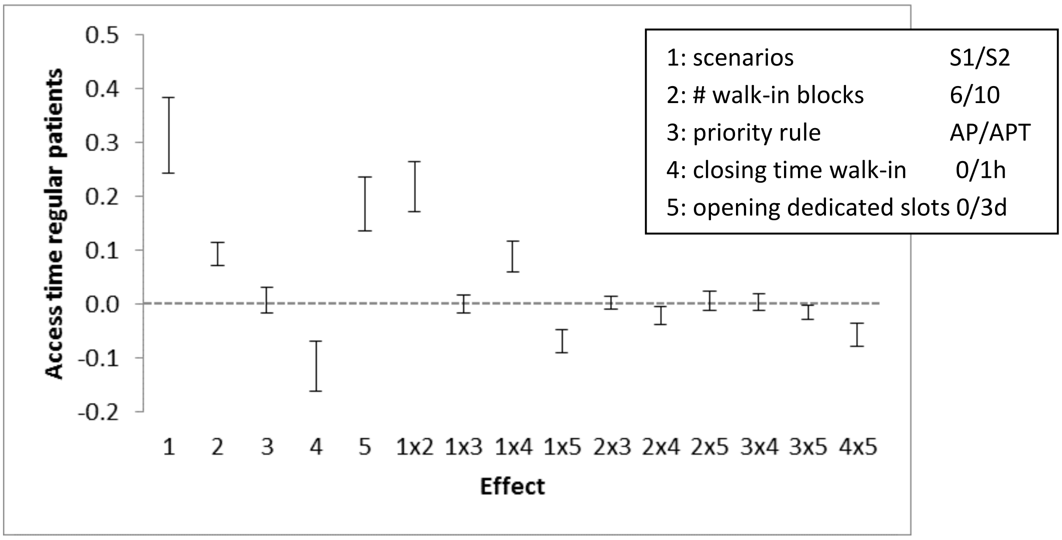

Figure 19 - Confidence intervals of main and interaction effects on access time

The effects on the access time are small but insightful, as the effects give an impression of where in the roster there are opportunities for improvement. In this case this would mean a decrease in number of general appointment slots. The information needed for this tweaking of the roster is also supplied by WAPSIM, as all the performance indicators are also aggregated on the patient-type level. These insights will be used for the sensitivity analysis in Section 7.3.

7.2.4 WAITING TIME

In a combined walk-in and appointment system the overall waiting time and number of patients incurring waiting time will increase due to the increase of variability in the arrival of patients. For the analysis of the five experimental factors we study the fraction of patients incurring waiting time (Figure 20), waiting time of walk-in patients (Figure 21) and waiting time of appointment patients (Figure 22).

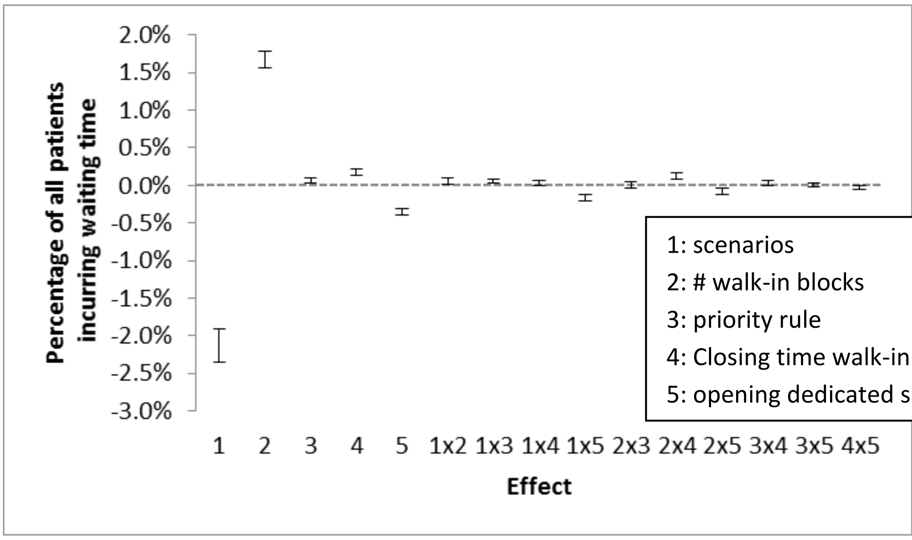

Figure 20 - Confidence intervals of main and interaction effects on fraction of patients incurring waiting time

- Factor 1: in Scenario 1 on average 64.37% of all patients incurred waiting time. In Figure 20 we see that in Scenario 2 this was a smaller fraction of the patients. Also from Figure 22 we can see that the waiting time for appointments increases significantly. This can partially be explained by its dependency on the interactive effects e_{12} and e_{13}. When there are more appointment patients in the system, more appointments have an increased waiting time due to prioritized walk-in patients. With more walk-in patients in the system the prioritization of a walk-in patient will happen more often. A more practical reason for the main effect is the number of slots that is reserved for one punction patient, which is three slots like in the current system. The average processing time of a punction patient is 1h20m, almost six slots. Patients who are scheduled after a punction patient are very likely to have high waiting times, in Scenario 2 the number of patients who experience this higher waiting time is larger (as there are more appointments).
- Factor 2: increasing the number of allowed waiting slots increases the average waiting time for both walk-in and appointment patients, it also means that more patients incur a waiting time. This is the expected effect, as more patients are allowed to enter the system (there are less deferrals).
- Factor 3: with the AP priority rule the average waiting time is 10m19s for appointments and 18m24s for walk-in patients. Changing the priority rule has the greatest effect on waiting time for both categories of patients and is in part dependent Factor 2 (the number of patients who is allowed in the system), as we can see from effect e_{23} in Figure 21and Figure 22.

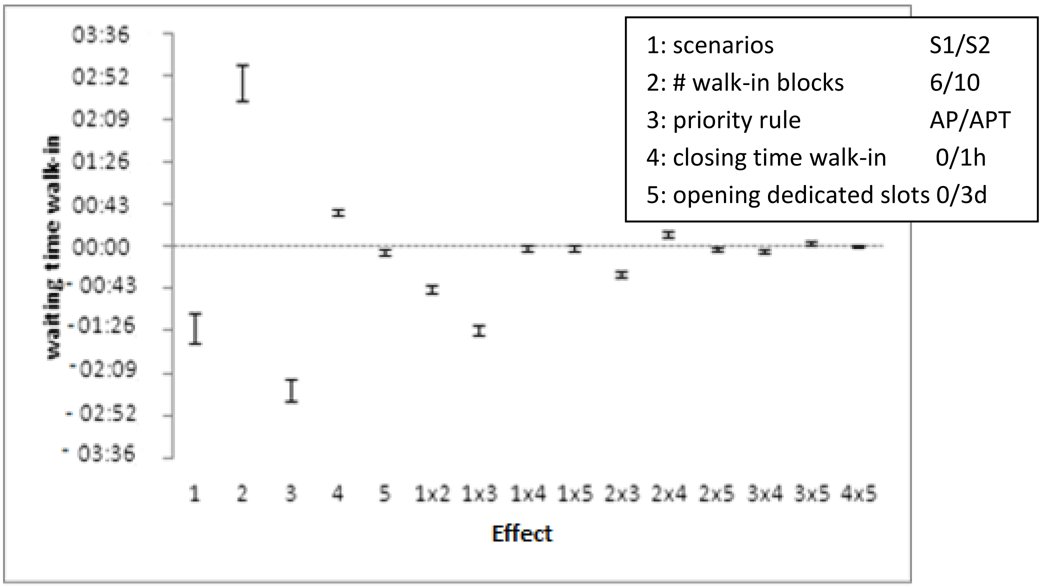

Figure 21 - Confidence intervals of main and interaction effects on waiting time of walk-in patients

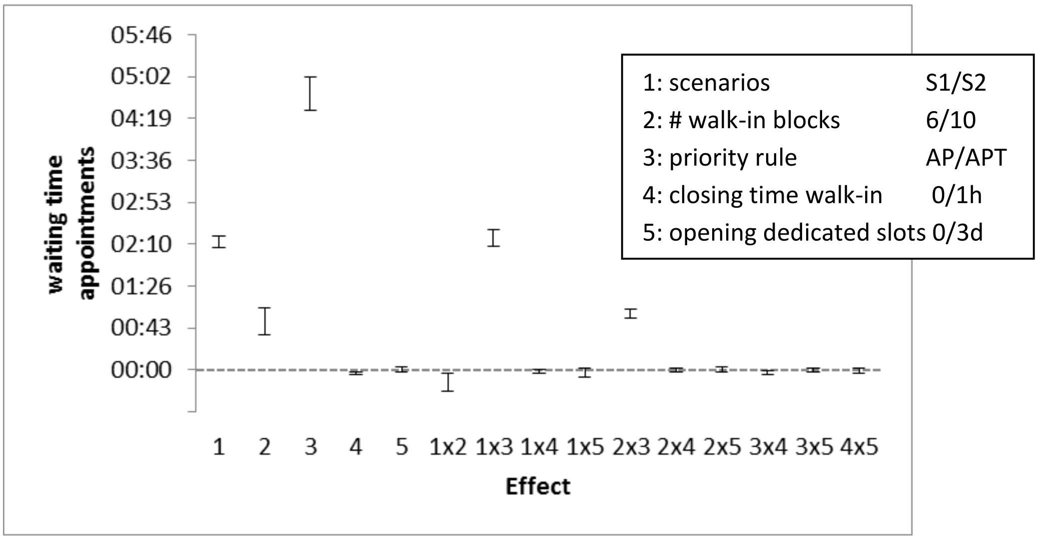

Figure 22 - Confidence intervals of main and interaction effects on waiting time of appointments

The average waiting time in a combined walk-in system is higher than in the current system, the magnitude of the difference depends on the settings that are chosen. In all the simulated experiments the number of patients who incur a waiting time had a relative increase of at least 45.5% compared to the current situation. Lastly we note that using a FCFS priority rule results in higher waiting time for appointments, especially the cardiac patients on Tuesday and Thursday, these patients have to wait for all the walk-in patients who arrived before their appointment. In Appendix D we have added the confidence intervals of the effects on the 50th and 80th percentiles of the waiting time.

7.2.5 Overtime

The last performance indicator we analyze is the percentage of work done out of office hours. In Figure 23 we see that there are two factors with a notable effects on overtime:

- Factor 1: in Scenario 1 there are less appointments scheduled, when we switch to Scenario 2 there are more appointment requests. These patients are for the largest part scheduled in the morning, this in combination with the smaller stream of walk-in patients throughout the day leads to less patients later in the day and therefore less overtime. In other words, more structure in the organization of the patient flow leads to less overtime.

- Factor 4: without a closing time for walk-in, a patient who arrives five minutes before the end of the day will be allowed to enter the system (if the required CT-scan is idle). By introducing the closing time for walk-in there is more control at the end of the day which leads to less over time.

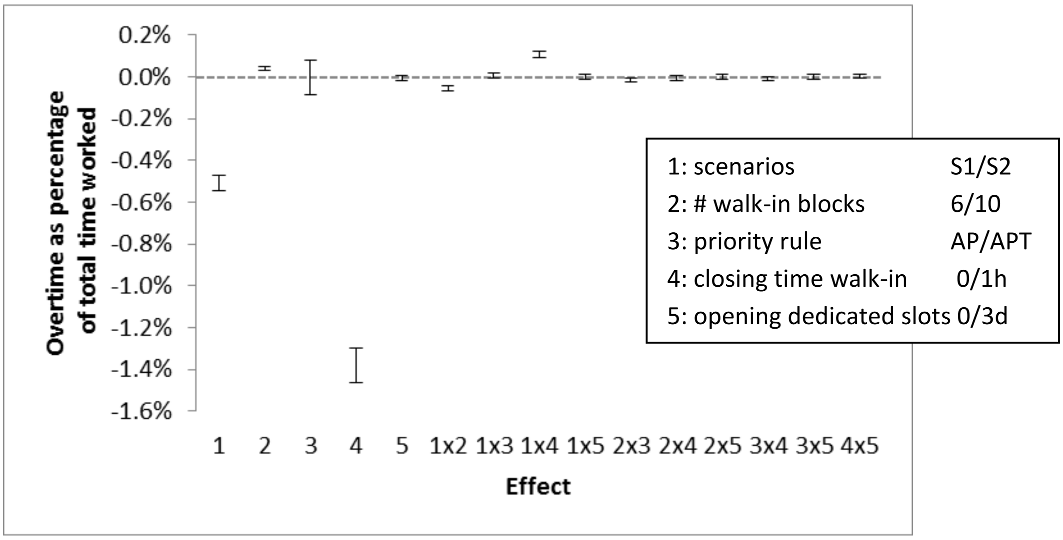

Figure 23 - Main and interaction effects on overtime

For overtime we clearly see a central trade-off in a combined walk-in and appointment system. When more control is added, to planning and during the day, there are less patients who can be helped on a walk-in basis.

7.2.6 Summary of effects

At the start of this section we introduced three trade-offs that are the primary effects of three of the five experimental factors. By studying the main and interaction effects on all performance indicators we found that:

- Factor 4, introducing a closing time for walk-in, has the biggest effect on the number of walk-in patients that is deferred.
- The high deferral rate is possibly caused by the non-optimal appointment schedule that was used for experimentation (to confirm to the practical demand of the radiology department).
- Factor 1 has an unsuspected effect on the waiting time and interacts with Factor 3. The reason for this unsuspected effect is the limited amount of time reserved for punction patients.
- Utilization is higher in the combined walk-in and appointment system because there are less no-shows due to a decrease in the number of appointments. This is also the reason that the biggest effect on utilization is Factor 2, as there are more patients who need an appointment in Scenario 2.
- On average the utilization of CT1 increases to 75.8% and the utilization of CT2 declines to 43.3%.
- The effect on access time of all experimental factors is small. However, through the unexpected effect of Factor 5 on the access time we found that the appointment schedules that are used might have too many slots reserved for general use.
- The effect of Factor 1 on the waiting time of appointment patients is larger than expected, this is caused by the limited amount of time that is reserved for punction patients.
- By studying the effects on overtime we see that more control leads to less overtime, but a decline in performance of some other indicator.

Only studying the primary effects give a good impression of the trade-offs that are caused by the experimental factors, but we would miss a level of details. This shows that the analysis of main and interaction effects is necessary to assess the effects caused by the experimental factors. The power of the analysis is not just to show how large the trade-off effects are, the smaller and unexpected effects can be even more useful. As a final remark we note that more in depth analysis are possible, for example the analysis of individual patient types like all cardiac patients or groups of patient types like all inpatients.

7.3 Sensitivity analysis

Beside the five factors that we experimented with it is interesting to analyze how the system reacts to (drastic) changes in the assumptions that were made. The central question we answer in this section is if the system remains stable. However, some of the factors that are analyzed can also be influenced. So the results of this analysis can be used to help policy making. All the sensitivity analysis changes were done for experiment one, in which all experimental factors are set to their passive form.

Unrestricted appointment schedule

The appointment schedules that were used for experimentation are suboptimal because of the adaptions that were made to confirm to the current working way of the radiology department and agreements with other departments. Based on the results of the experiments it is evident that indeed the appointment schedules that we used are restrictive to performance. Table 16 shows the results of using an unrestricted roster that has:

- Cardiac slots placed on the mornings of Monday, Tuesday and Friday (instead of on Tuesday and Thursday afternoon);
- Appointment blocks of six slots for punction patients instead of three slots;
- Less generic appointment slots.

Table 16 - Confidence intervals of difference between base case and unrestricted roster

Performance indicator	Base case	CI of difference between base case and sensitivity analysis [Lower bound, upper bound]
Deferred walk-in (%)	9.6	[-2.9, -2.7]
Waiting time appointments (mm:ss)	10:13	[-02:04, -01:56]
Fraction of appointments with waiting time (%)	56.8	[-7.8, -7.4]
Waiting time walk-in (mm:ss)	16:12	[-00:52, -00:41]
Fraction of walk-in with waiting time (%)	65.5	[0.7, 0.9]
Access time non-checkup patients (d)	4.9	[0.7, 0.9]
Overtime as percentage of total working time	3.3	[-0.2, -0.2]

There is only one negative effect of using the unrestricted roster, average access time increases. However, all other effects are promising as more walk-in patients can be served on the day of their arrival and waiting time decreases significantly for both walk-in and appointments. One of these changes, the number of slots reserved for a punction patient, can be implemented right away (and would also improve the performance of the current appointment system).

Increased patient arrivals

In the Rijnstate hospital in Arnhem, an increase in production was seen after implementation of a combined walk-in and appointment system [13]. To ensure that a heavier loaded system in the CT-scan case can also effectively combine walk-in and appointments we have added a sensitivity analysis in which the number of all patient arrivals was increased by 20%. Table 17 shows the confidence intervals of the difference between the old and new scenario.

Table 17 - Confidence intervals of difference between base case and increased patient arrival

Performance indicator	Base case	CI of difference between base case and sensitivity analysis [Lower bound, upper bound]
Deferred walk-in (%)	9.6	[4.4, 4.6]
Utilization (%)	59.6	[11.8, 12.1]
Waiting time appointments (mm:ss)	10:13	[-00:03, 00:06]
Fraction of appointments with waiting time (%)	56.8	[7.1, 7.4]
Waiting time walk-in (mm:ss)	16:12	[03:50, 04:07]
Fraction of walk-in with waiting time (%)	65.5	[10.4, 10.7]
Access time non-checkup patients (d)	4.9	[0.3, 0.4]
Overtime as percentage of total working time	3.3	[0.2, 0.3]

The system remains stable, even when utilization increases by about 12%, which is 20% more than current utilization. It is remarkable that even though there are more appointments that incur waiting time, the average waiting time does not change. The number of walk-in patients with waiting time and their waiting time increases, we would argue that this is still acceptable because the Treeknorm is not violated. The fraction of walk-in patients who is deferred increases to almost 15%. If the demand does indeed increase through the implementation of a walk-in and appointment system, it is advisable to consider a setting that improves this deferral rate (for example an unrestricted roster and/or a higher number of allowed waiting slots for walk-in).

SHUTDOWN RATE

The maintenance group of the CT-scans suspects that CT2 will need more maintenance in the coming years because it is an old machine. To see how the system would react to this we have done a sensitivity analysis with a breakdown rate of 16 days per year for CT2, instead of the current eight days. The only significant results are a minor increase of deferred walk-in patients and decrease in the utilization of CT2. The relatively small impact of the increased shutdown rate can be explained by the fact that the utilization of the current system allows for enough flexibility.

7.4 CONCLUSION

In this chapter we evaluated the expected effect of five experimental factors through simulation of the CT-scan case of the AMC. The primary responses, that occur when only one factor is changed, give us an indication of the trade-offs that can be made in a combined walk-in and appointment system:

- Factor 2: Increasing the allowed waiting time for walk-in patients reduces the fraction of walk-in patients who is deferred, but also leads to higher waiting time for walk-in patients;
- Factor 3: By changing the priority rule from '*Appointments first*' to '*Appointments first, unless a walk-in patient is waiting more than an hour*' the waiting time of appointments increases, but the waiting time for walk-in patients decreases.
- Factor 4: When a closing time of one hour for walk-in is introduced, the number of deferred walk-in patients increases while the percentage of work done out of office hours decreases.
- Factor 5: By opening dedicated appointment blocks for general use three days ahead every day, the access time increased.

Only the effect of the first factor, decreasing the number of patient categories eligible for walk-in, is not marked by one of these trade-offs. This factor has a significant impact on all performance indicators analyzed, and cannot be grasped by studying the primary response. The primary responses only give an indication of the effects, for a more extensive analysis we looked at the confidence interval of expected main and interaction effects. These effects are based on all possible 32 combinations of responses and can be used to explain unexpected outcomes such as that of Factor 5, or to make interdependence between several factors apparent. Based on this analysis we can conclude that the current appointment schedule might be too restrictive. Through sensitivity analysis of the roster we showed that three small changes can improve overall performance. Other sensitivity analysis showed that the system remains stable with an increased patient arrival rate or a doubled shutdown rate of CT2.

Some of the results, like the roster improvement, can be used to give practical advice. However, the goal of WAPSIM is to support decision makers at a diagnostic facility with choices about resource and capacity planning regarding the combination of a walk-in and appointment system. In other words, there is no best practice that can be advised, the power of WAPSIM is that all effects can be mapped to aid the decision makers.

8. Implementation

In Chapter 7 we analyzed a broad range of experimental settings and analyzed the output of the simulation study. In this chapter we take a step back from the specific data and look at the sixth research question. We study how the results of the simulation study can be used by decision makers (§8.1), and what other organizational challenges there are (§8.2).

> *"Which recommendations can be made to support decision making during the implementation of a combined walk-in and appointment system at the radiology department of the AMC?"*

8.1 Using simulation results

From the theory in Chapter 2 we see that although simulation is widely applied in healthcare, the results have not always been implemented. This is not necessarily a bad thing, based on the results of a simulation study it can also be concluded that the new working method is not desirable. After the simulation study the results should be discussed with the group of stakeholders that was involved with the research. As we argued in Chapter 7 it is not possible to state that there is one best way to implement a combined system, so when the results of the simulation are discussed there will still be doubts. After the discussion it can be concluded that a combined walk-in and appointment system should be implemented. If this is the case, the project group must then make the step from experimental results to a working method in practice. Making this step might be easier said than done because there is a large amount of information. This is why we suggest the following method:

(1) Explain the main effects that occurred in the simulation, underline that there are several trade-offs and that there is no best way.
(2) Let individual group members pick between the trade-offs we discussed in Chapter 6, and write down the argument for this choice.
(3) Collect the information of the individual group members and aggregate them anonymously per trade-off. During later discussion it will likely become clear who had what opinion/argument, but by keeping it anonymous at first this will be by choice of the group member.
(4) Have a group meeting. It is unlikely that everyone in the group has exactly the same opinion, showing everyone the different perspectives of the other group members can serve as a good base for further discussion.
(5) Start with a trade-off for which (almost) all group members share the same opinion. By studying the interaction effects from the simulation study, we can see if the trade-off depends on other factor(s). When a highly valued trade-off is dependent on another factor, the group members might change their opinion to enable that highly valued trade-off.
(6) Continue this routine until all trade-offs have been discussed. Ideally this leads to a unified front, but in some cases it might be needed to come to a consensus.

The method uses the main effects that were discovered in the simulation, and supports the discussion between the decision makers through the interaction effects. Through this method all information that was computed can be used to support decision making.

8.2 Organizational implications

It is important to realize that the factors that we analyzed through the simulation study are a part of a large project, the decision to (not) implement a combined walk-in and appointment system should not be based solely on these results. Through the review of literature, during the development of the WAPSIM model and meetings with the radiology department of the AMC and other stake holders we found a broad range of organizational implications related to the implementation of a combined walk-in and appointment system.

Internal organization

A good way to get an idea of the organizational changes that are needed internally is to take the flow chart of the new process (Figure 13 in this case). The project group can evaluate a set of questions for each step in the process:

- What information is needed at this step?
    a. Is this information requirement different from the current working way, if so how can we organize that this information requirement is met?
    b. Is this information available in time, if not how can we organize that the required information is available when it is required?
- What are the responsibilities at this step?
    a. Is this a new responsibility, if this is the case what does it entail?
    b. Who will be responsible, is this different from the current working way?
    c. Is the person responsible available in time, if not how can we organize this responsibility in a different way?

When all these questions can be answered for each step in the process, the project group should have a clear view of the organizational changes that are needed.

External organization

Most changes happen internally, and decisions regarding these changes are also made internally. For some of the internal organizational changes the diagnostic facility might be dependent on other departments. Even if this is not the case other departments should be involved in an early stage, as the diagnostic facility of a hospital always interacts with many other departments.

From the work visit at the Rijnstate hospital in Arnhem we learned that this contact does not have to be very extensive, as the change to a combined walk-in and appointment system does not require a lot of change at the external parties. However, it is important that the external parties are informed and given the opportunity to supply feedback and suggestions. This includes information about how the internal organization will look like in the new situation, but also what patients are (not) eligible for walk-in.

Patients

There is also an important process related to the patient who is not part of the internal process, and may not (yet) be a part of external processes. This is the process of informing the patient. The patient does not have to be informed about the whole organizational change, however the patient should be informed on how his/her care trajectory looks. The diagnostic facility and the referring departments need to supply this information appropriately, so the patient can manage his/her expectations. For example, the specialist referring a walk-in patient to radiology should inform the patient who it is very likely that he/she will be scanned that day, but that there also is the chance that he/she will get an appointment if it is too busy at the radiology department.

8.3 Conclusion

The goal of this research was to develop a simulation model that can be used to support decision makers at a diagnostic facility with choices about resource and capacity planning regarding the combination of a walk-in and appointment system. In this chapter we suggest a method in which the main effects from the simulation are used to start a discussion between members of the project group, and the interaction effects between different factors are used as catalyst to come to a consensus. We also note that the factors that can be experimented with in WAPSIM are only one side of the coin, so the results of the simulation study cannot provide all the information that is needed to make decision to (not) implement a combined walk-in and appointment system. Based on the experience of developing the WAPSIM model and meetings with various stakeholders we suggest three areas of attention when it comes to organizational change:

- Internal: map the change in information requirements and change in responsibilities based on the flowchart of the new process.
- External: inform external parties on the possible change and give them time and space to supply feedback and suggestions.
- Patients: the diagnostic facility and external parties need to align who gives what information to the patient, so that he/she can manage his/her expectations about the care trajectory.

9. Conclusions and recommendations

In the final chapter of this thesis we look at the results of answering the first six research questions that we reviewed in the previous chapters. In the first section we discuss the results (§9.1), in the second section we discuss the last research question (§9.2) and in the final section we make recommendations for further research (§9.3).

> *"What are the possible implications of this research for other diagnostic facilities?"*

9.1 Conclusion

We started this research with the following objective: *"Develop a simulation model that can be used to support decision makers at a diagnostic facility with choices about resource and capacity planning regarding the combination of a walk-in and appointment system".* To reach this goal we started with an extensive review of theory, which gave us the concepts, definitions and terminology that we needed to develop a simulation model that can be used to analyze the combination of walk-in and appointments. Through a process analysis of the CT-scan casus of the AMC and by studying the processes described by research conducted at other diagnostic facilities we identified the elements we need to simulate the service process of diagnostic facilities.

By combining the theory and the process analysis to we developed the Walk-in and Appointment Simulation Model (WAPSIM), which has of four elements: (i) the core system with a planner, a choice to allow or defer a walk-in patient and one server, (ii) a preparation component, (iii) a test component and (iv) extra server components. All these elements can be combined to match real world systems, such as that of the radiology department of the AMC. By adding design choices corresponding to when walk-in is possible, how appointments are scheduled and who gets priority in the waiting room, there is a broad range of functionalities to experiment with.

The CT-scans at the AMC are currently organized through a 100% appointment system. Strictly speaking only 10% of all patients must be scheduled to be served on a later date and 12.5% of all patients can get an appointment on the same day. The relatively small service time of a CT-scan in the current situation is an indication that the CT-scans could be organized through a combined walk-in and appointment system. We used WAPSIM to simulate this new situation and the results show that:

- Most walk-in patients can be served on the day of the request;
- There is a decrease in the number of no shows, as there are fewer appointments;
- Waiting time of appointments decreases compared to the current situation;
- Waiting time of walk-in patients is higher than that of appointments;
- More patients incur waiting time than in the current situation;
- Access time for patients who require an appointment as soon as possible does not change;
- The amount of overtime increases.

Furthermore we experimented with five design factors. Three of these factors allow the decision makers to make trade-offs between the performance indicators:

- Increasing the allowed waiting time for walk-in patients reduces the fraction of walk-in patients who is deferred, but also leads to higher waiting time for walk-in patients;
- By changing the priority rule from '*Appointments first*' to '*Appointments first, unless a walk-in patient is waiting more than an hour*' the waiting time of appointments rises, but the waiting time for walk-in patients declines;
- When introducing a closing time of one hour for walk-in, the number of deferred walk-in patients increases while the percentage of work done out of office hours decreases.

These primary trade-offs give an indication of the effects but by only studying these effect we can miss important dynamics between experimental factors. For a more extensive analysis we studied the confidence intervals of expected main and interaction effects. These effects are based on all 32 combinations of the five factors, and can be used to explain unexpected outcomes or to make interdependence between several factors apparent. Based on this extensive analysis we can conclude that the appointment schedule is too restrictive as a result of agreements with other departments and the underestimation of the processing time of some patient types. Through sensitivity analysis of the appointment schedule we showed that three small changes can improve overall performance drastically. Other sensitivity analysis showed that the system remains stable with an increased patient arrival rate or a doubled shutdown rate of one of the CT-scans.

Some of the results, such as the roster improvement, can be used to give practical advice. However, there is not a best practice that can be advised. The power of WAPSIM is that all effects can be mapped to aid the decision makers. To make full use of this power we suggest a method in which the main effects from the simulation are used to start a discussion between members of the project group, and that the interaction effects between different factors are used as catalyst to come to a consensus. We also note that the experimental factors in WAPSIM are only one side of the decisions corresponding to a combined walk-in and appointment system. There are also internal and external organizational changes, such as changes in information requirements and responsibilities. These changes need to be mapped if a department decides to implement a combined walk-in and appointment system. Based on this research the radiology department of the AMC decided to continue with the analysis of these internal and external organizational changes, with the goal to implement a combined walk-in and appointment system for the CT-scans.

9.2 Discussion

In this section we will discuss three topics that relate to the development of WAPSIM and further use of the model: (i) generalizability of results, (ii) validation through more extensive cases, and (iii) the link between theory and practice.

For the first topic we look at the possible implications for other diagnostic facilities. The results for the CT-case of the AMC are promising, and some of the trade-offs we found are likely also relevant for other cases. However we have also seen that case-dependent factors were very determining for the performance of the system, resulting in outcomes that were contrary to our expectations. To avoid erroneous conclusions it is important to note that WAPSIM only allows the user to save time in modeling. The Excel front-end allows the user to run experiments very fast and with a vast number of variables, but the process analysis, data collection and input preparation should not be hastened. Even more so, the last step needs extra attention because the user has to strictly follow the structure of WAPSIM, which could be too restrictive for some cases.

The second topic is closely related to this issue. WAPSIM was validated by simulating the current situation of the CT-scans at the AMC, a system with only appointments. This validation does not in any way ensure that WAPSIM can be used for experiments on other cases that also have an appointment system. In any simulation study done with WAPSIM, validation of the model for that specific case remains a crucial step. It is a limitation of the research that we only reviewed one case extensively. We think that WAPSIM can be used for a broad range of cases, but cannot claim that the model is truly generic.

The last discussion topic is related to the development of the model and the discrepancy between theory and practice. Two suggestions we distilled from the theory review were:

- Define independent components, this allows other modelers to work in a flexible manner. A model to which extra components/elements can easily be added/removed has the most potential when it comes to component based simulation.
- Complete model reuse is so complex that it is considered the holy grail of simulation modeling.

Taking a component based perspective was very useful to think of a workable structure that allows reuse. However, we found that it was not possible to develop *independent* components that are easily combined to form a model that was useable for experimentation with a specific purpose. In other words, some of the components we defined are dependent on the general structure of the model and the availability of information provided by other components. The result is that we developed a model that can be completely reused, is very flexible, but only within the defined limits. The consequence is that if a case requires additional functionalities these can be added, but for most functionalities this will mean that the structure of related components will have to be adapted to this change.

9.3 Recommendations for further research

The foremost recommendation is to continue experimenting with WAPSIM in other settings of different situations, to see if the trade-offs and results are indeed very case dependent or whether the results can somehow be generalized into best-practice concepts and a listing of pitfalls.

We have split recommendations for further research in two categories, functionalities and practicalities. The first category relates to improvements or additions to the model, increasing the experimental flexibility and spectrum of cases that can be simulated through WAPSIM. The suggestions in the second category could improve easiness to use the model.

Functionalities

During the development phase of the model there always was one question dominant in any meeting: "Is this a functionality we need or one we would like to have?" Prior to the recommendations of extra functionalities we point out a possible downside of expanding the model. There can be more to the question than the opportunity to add extra functionalities. With most additions the model will also become more complex and harder to use. Moreover, making decisions based on even more complex results could be cumbersome (while supporting decision making is the purpose of WAPSIM). With that said, possible nice functionalities that could be added or improved are:

- A more realistic shut-down function. In the current model servers have a shut-down probability at the start of each day, in reality this is more likely to be at the start of each job. Also, shutdown time is now set to be deterministic for a multitude of days, in reality the shutdown time will have some statistical distribution (the Erlang distribution is the most common one, data for this distribution might be scarce in practice).
- A bottleneck indicator. The current model assumes that the servers are the bottleneck of the simulated system, as one of the reasons to implement the walk-in and appoint system is to make better use of these resources. If this assumption does not hold, it would be advisable to first find the bottleneck in the system and try to improve the performance of that process. The bottleneck indicator would for example stop the simulation if server components remain idle while another process is constantly busy, or if the waiting time at the server is structurally smaller than at other processes.
- Emergency patients. In the current model there are three types of patients (appointments, advanced access and walk-in), in healthcare emergency patients are common and this patient type could be added to the model. This would mean the addition of an extra arrival process, as this is likely to be distributed different than the arrival of the other patients. Also, the processing of emergency patients will introduce new priority rules, as it is likely that emergency patients are prioritized over all other patients.
- Punctionality of appointments. In the current model all patients show up in time for their appointment. Realistically there will be variability here, patients are either early or late. The challenge of this functionality is not to add this variability, but to let the model capture how the diagnostic facility would react to this variability in a generic way. This functionality gives rise to a broad range of new questions, for example: who has priority, the walk-in patient or an appointment patient who is 10 minutes early? Who has priority, the appointment patient who was 15 minutes late or the one who just arrived and is exactly on time?
-

PRACTICALITIES

The Excel front end allows relatively easy use of the model, but there are plenty of practical improvements that could be made:

- Experimental ease. Experiments in the current version of the model need to be set manually, this is somewhat cumbersome. The reason for this impractical method is the large range of possible experimental factors and their dependency on the number of components. Experimental ease can easily be improved for any given case, but it will be harder to develop a generic approach that will work for all different settings.
- Data aggregation. The model saves run-level information about the performance indicators of appointments and walk-in patients for each experiment. This can be extended to save run-level information for all patient types. For many experiments this will be detailed enough. However the model could also be programmed to aggregate and save day/week/month/year-level information for more specific analysis.

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APPENDIX

A. WAPSIM-GUIDE

To follow this guide, and in extension use the WAPSIM model, an extensive data analysis will have to be done. For the first step the basic characteristics of the diagnostic facilities will be identified. In the second step patient types can be categorized according to their route through the system (a thorough process analysis is required). For steps 3 and 4 the analysis of historical data will be needed. For the last step the user needs to think of/come up with a schedule that can be used in the combined walk-in and appointment system.

1) In the main window of the model, fill in all the parameters in '***Settings***'

- NumServers, the number of available servers;
- NumPreperationSteps, the number of possible preparation steps;
- NumTets, the number of possible tests;
- OpeningTime;
- ClosingTime;
- NumberOfBlocks;
- BlockSize.
- Etc.

	string 1	string 2	string 3	time 4	time 5	integer 6	time 7
string	NumServers	NumPreparationSteps	NumTests	OpeningTime	ClosingTime	NumberOfBlock	BlockSize
1	2	2	2	7:30:00.0000	16:30:00.0000	33	15:00.000
2							

Figure 24 - General WAPSIM settings

2) Fill in the Excel file '***PatientTypeInformation'*** while taking into account the settings of (1), after numbering patient types from 1 to n in the first column, for each patient type n:
- Add walk-in eligibility for each patient type. TRUE for walk-in and FALSE for appointments in column 2.
- Add if patient is an inpatient or outpatient. TRUE for inpatients and FALSE for outpatients in column 3.
- Fill in the number of patients who are observed in column four (a percentage is also fine, the Excel file will calculate the cumulative sum of the parts).
- Add if patient can be served on multiple servers. TRUE for yes and FALSE for no in column 5.
- If the patient type can be served on multiple servers, in column 6 the preferred server can be chosen (the name has to be exactly the same as in other input files).
- Add the planning horizon in column 7, the value has to be an integer.
- Select a planning rule from the dropdown menu in column 8.
- Fill in the estimated processing time and preparation time in a rounded number of slots in column 8 and 9.

Type	Walkin	Clinical	NumberO	CumPart	MultipleS	Preferenc	PlanningH	PlanningR	BlocksReq	ExpectedF
1	FALSE	TRUE	226,8	0,020158	FALSE		5	FirstAvail	1	0
2	TRUE	FALSE	1128,422	0,120454	FALSE		21	FirstAvail	1	5
:	:	:	:	:	:	:	:	:	:	:
:	:	:	:	:	:	:	:	:	:	:
29	FALSE	FALSE	161	0,927029	TRUE	Server1	21	FirstAvail	3	0
30	FALSE	FALSE	821	1	FALSE		21	FirstAvail	1	0

Figure 25 - Example of input file, patient type information

3) Open in the Excel file '***PatientRoutes',*** keep into account the settings of (1) and preference names of (2) when filling in the file.
- Fill in the number of patients who are observed in the fourth column (a percentage is also fine, the Excel file will calculate the cumulative sum of the parts in Column 5).
- Add the names of the Test stations in the following T columns on the first row.
- Add the names of the Preparation stations in the following P columns on the first row.
- Add the names of the Server stations in the following S columns on the first row.

- For each patient type, number the sequence through the system starting at 1. If the patient type can be helped at multiple servers, use the same number again.

Type	Test1GFR	Test21Lab	Prep1IV	Prep2Oral	Serv1CT1	Serv2CT2
1					1	
2	1		2	3	4	
:	:	:	:	:	:	:
:	:	:	:	:	:	:
29				1	2	2
30					1	

Figure 26 - Example of input file, patient routes

4) Open the Excel file ‘***ProcessCapacity’:***
- Use the process names from (3), to fill in in the first column.
- Fill in the capacity of each process in column 2, note that the capacity of servers must always be equal to one.
- In the third column select a priority rule from the dropdown menu.
- If the priority rule ‘PrioritizeAppointmentsUnlessWalkinIsTooHigh’ is selected, add the threshold a time in column 4 in the format hh:mm:ss.
- In column 5 and 6 the shutdown probability per day and duration of a shutdown in days can be filled in for servers.

ProcessName	Capacity	PriorityRule	AllowedWalkInWait	ShutdownProb	ShutDownTime
Test1GFR	100	FCFS			
Test2Lab	10	FCFS			
Prep1IV	1	PrioritizeAppointments			
Prep2Oral	10	FCFS			
Serv1CT1	1	FCFS		2,2%	1
Serv2CT2	1	FCFS		4,4%	1

FCFS
PrioritizeAppointments
PrioritizeAppointmentsUnlessWall

Figure 27 - Example of input file, process information

5) Fill in the Excel file ‘***TestProcesses’***,
- In the first column, fill in the names of the test components as indicated in the rest of the input files.
- In column 2 and 3 the output routes of the test component should be filled in. If the result of the statistical sample is below or equal to the test value, the patient will go on to *route 1*, otherwise the patient will continue to *route 2*.
- Select a distribution from the dropdown menu in column 5 and fill in the cells that light up in green (these are the parameters of the selected distribution), this distribution is used to take test sample.

ProcessName	Route1	Route2	TestValue	TestDistributic	Alpha	Alpha2	Beta	n	p	Mu	Sigma	c	a	b	start	Stop	Time
Test1GFR	Prep2IV	Planner	0,97	Uniform											0	1	
Test2Lab	Panner	Serv1CT1	4	Binomial				10	0,50								

Binomial
Deterministic
Erlang
Gamma
Normal
Lognormal
Triangle
Uniform

Figure 28 - Example of input file, test component information

6) For each patient type make a copy of the Excel file ‘***ProcessInformation’*** and name it ‘***Type+patient type number***’, for example ‘***Type1’*** and ‘***Type2’*** for patient types one and two. This file is used to sample processing times for each patient type.

- In the first column, fill in the names of the test components as indicated in the rest of the input files.
- Select a distribution from the dropdown menu in column 2 and fill in the cells that light up in green (these are the parameters of the selected distribution). **IMPORTANT:** you can either use seconds or minutes, by slightly changing the method 'Determineprocessingtime' in the component 'ProcessControl'.
- In column 3 and 4, minimum and maximum processingtimes can be added.

ProcessName	Distribution	Min	Max	Alpha	Alpha2	Beta	n	p	Mu	Sigma	c	a	b	start	Stop	Time
Test1GFR	Deterministic															0
Test2Lab	Deterministic															60
Prep1IV	Emp															
Prep2Oral																60
Serv1CT1		4,5	40						708	361						
Serv2CT2		4,5	40						708	361						

Emp
Beta
Binomial
Deterministic
Erlang
Gamma
Normal
Lognorm

Figure 29 - Example of input file, processing times

7) Fill in the green area in the Excel '***ArrivalRates***' in accordance to the number of blocks in the settings. Each cell should contain the arrival intensity of patients for that specific block, λ_s. The days are numbered 0 to 6, for Monday to Sunday. For example in Block 0, Day 0, on average 0.39 patients arrive.

StartOfBlock	0	1	2	3	4	5	6
1	0,38655	0,531145	0,331283	0,169167	0,421558	-1	-1
2	0,726942	0,750383	0,518932	0,481084	0,564817		
:	:	:	:	:	:		
:	:	:	:	:	:		
32	1,207575	1,073475	1,204016	1,22952	1,116233		
33	0,301493	0,343287	0,315847	0,45914	0,508519		

Figure 30 - Example of input file, patient arrival rates

8) For each server:
   i. Make a copy of the Excel file '***EmptySchedule***',
   ii. Rename the copies to: '***EmptySchedule+ServerName***' (servername is the name that was given in (2).
   iii. Fill in the empty schedule for each day of the week: if a block should be available for walk-in leave it empty, if a block is reserved for all possible appointments fill in an **'A'** and if a block should be reserved for a certain patient type fill in the corresponding number (this allows you to cluster types, as slots that are numbered with an integer will only be used for that specific patient type). When you fill in a 'C' the slot will be reserved for inpatients, and will never be opened/used for other patient types.

Note: if the patient type cannot be helped at the server *and* slots are still reserved for this patient type, these slots will never be used for an appointment. For example, reserving appointment slots on Server 1 will not be used if the patient can only be served on Server 2.

StartOfBlock	MON	TUE	WED	THU	FRI
1					
2		A	A		A
3		A	A		A
4	6	A	A		A
5	6	A	A		A
6	6	A	A		A
7	6	A	A		A
8	6	A	A	2	
9	6			2	
10	6			2	
11	6			2	
12	2		6	6	
13	2		6	6	
14	2		6	6	
15	2		6	6	
16	2		6	6	
17	2		6	6	
18			6	6	
19		4	2		4
20		4	2		4
21		4	2		4
22		4	2		4
23		4	2		4
24		4	2		4
25	A	4			4
26	A	4			4
27	A	4		A	4
28	A	4		A	4
29	A	4		A	4
30		4		A	4
31		4			4
32		4			4
33		4			4

Figure 31 - Example of input file, an appointment schedule

Run the method: ***LoadInputFiles***, this will initialize the tables in the model and create the system in the screen.

B. Verification

In Chapter 5 we briefly mentioned eight debugging techniques that can be used for verification. In this appendix we clarify how these techniques work and what bugs could be found [44].

Technique 1 – write and debug in components or sub methods

The model was built from the ground up and is based on standalone methods and modules which each have their own sub methods. We verified the functioning of the separate parts, looking for errors/bugs, before we added more parts.

For example, we first realized the arrival of patients according to non-stationary Poisson process in one method and verified it. We then added the planner component that has two sub methods (on for finding the first available slot and one to find the last available slot), using a fictional schedule.

Technique 2 – let more than one person review the computer program

A structured walk-through of any model can be useful to verify the overall structure of the model, the goal is not to find specific bugs (other techniques are more effective for this purpose). During the start of the development phase we did this and made some fundamental changes in the structure, for example the creation of one central waiting room for all servers as opposed to a waiting room for each server.

Technique 3 – Run the simulation under a variety of settings of the input parameters

As the reusability of the simulation model depends solely on flexible input parameters, this technique is the most important technique for the verification of the model. Throughout the coding and debugging of the different components we *'played'* with the different parameters, to see if the model still worked as expected.

Technique 4 – *trace* the state of the simulated system

For several normal processes the events of the model where traced, for example to see if different patient types go through all the steps of their route through the system in the given sequence. Also, to test the functions of the model we stopped simulations in the middle of a run and changed some values to '*fake'* an extreme situation such as an overbooked schedule (in which case walk-in patients should be deferred to receive an appointment). Because of the flexible parameters of the model there could be exceedingly extreme situations that are not foreseen by the user. To account for these situations we implemented some automatic debugs in the model, WAPSIM will give a message to: instructing the to re-evaluate the input data.

For example, the planner is allowed to look for an appointment in the following four weeks for a certain patient type. If no possible appointment block is found this horizon is extend by another four weeks (and the extension is recorded), if in that extended horizon still no appointment block was found the simulation stops and notifies the user with the message *"After extending the planning horizon, still no appointment block was found"*.

Technique 5 – Run the model under simplified assumptions

The most fundamental process is described in Section 4.1. In this core system there are two patient types (walk-in and appointments) and there is one server. For this system Kortbeek et al. [9] developed an algorithm to come up with the optimal cyclical appointment schedule. For a small instance of the problem, with a five days and eight slots per day, the schedule was tested. Even though the arrival structure of [9] and some assumptions are slightly different from that of the WAPSIM-model, the comparison of the performance should be similar.

Table 18- comparison of two systems: WAPSIM and Kortbeek et al.

	WAPSIM	Kortbeek et al.	Results t-test
Fraction unscheduled directly served	0.72	0.69	
Daily fraction unscheduled directly served	[0.76, 0.95, 0.74, 0.23, 0.58]	[0.79, 0.78, 0.50, 0.07, 0.67]	(t-test 0.63)
Service level scheduled jobs	0.95	0.96	
Deferral rate per day	[1.70, 0.20, 0.77, 0.36, 3.23]	[1.46, 1.30, 1.50, 0.74, 1.90]	(t-test 0.83)
Unscheduled Jobs service rate per day	[5.27, 3.09, 2.25, 0.11, 4.52]	[5.04, 4.70, 1.50, 0.06, 3.80]	(t-test 0.89)
Realized utilization per day	[7.27, 5.90, 8.18, 7.42, 7.56]	[7.04, 6.70, 7.48, 7.71, 7.06]	(t-test 0.87)
Arrivals per day	[11.70, 6.80, 5.15, 0.79, 12.99]	[11.5, 6.00, 5.00, 0.80, 12.7]	(t-test 0.93)
Overall Utilization	0.91	0.90	
Overtime	8.8%	0.0%	

The difference between mechanics of the model of Kortbeek et al. and WAPSIM is the cause for two main differences. The first point is that Kortbeek et al. do not allow overtime, patients who arrive in a block are evaluated at the end of the block. If a patient arrives in the last block, he will always be deferred. However, WAPSIM would accept this patient if the server is idle at that time, causing overtime. The second difference is that the model of Kortbeek et al. has two streams of patients who arrive, a daily arrival rate for appointments and a slot specific arrival rate for walk-in. In WAPSIM there is one slot dependent arrival rate for all patients, when a patient arrives it is determined if it is a walk-in or appointment request. To match the two systems, we merged the two Poisson streams of Kortbeek et al. to one stream for WAPSIM. However, there are no appointment requests on day two in the model of Kortbeek et al., only walk-in requests. WAPSIM does not consider this and splits arrivals on this day into appointments and walk-in requests. In other words, the weekly distribution of walk-in and appointments is equal in both models, while the daily distribution is different. In conclusion, the comparison of the two models helped to fine-tune the walk-in decision: "Do we accept the walk-in patient in the system or not?" (which functioned slightly different than expected).

Technique 6 – Compute the sample mean and sample variance and compare to expected values

Different simulation packages may use the same function name for a different purpose, therefore it is always useful to verify that mean and variance are as expected. In WAPSIM there is a selection of distributions that can be selected by the user, the templates that are used show the user what parameters are required for each distribution. We also used this method to verify that the performance data collection worked as expected by setting processing times to deterministic and compared it to the aggregated information. A comparable technique was used to verify the working of the non-stationary Poisson arrival process, comparing the realized arrivals with the expected arrivals showed a significant match.

Techniques 7 and 8 – Use a commercial simulation package and observe animations

We implemented the WAPSIM model in the professional simulation package *Siemens Plant Simulation 10.2*. The package has extensive possibilities to visualize processes, important indicators and follow individual patients through the system.

C. WAPSIM INPUT CT-SCAN CASE

#	Process	Characteristic*1	%	S1*2	S2
1	Oral60+IV+CT1	inpatient	2,02	AA	AA
2	Oral60+IV+CT1	outpatient	10,03	W	W
3	Oral60+IV+CT1	outpatient, no eGFR	0,31	W	W
4	Oral60+IV+CT1	check-up	2,04	W	A
5	Oral30+IV+CT1	inpatient	0,82	AA	AA
6	Oral30+IV+CT1	outpatient	4,09	W	W
7	Oral30+IV+CT1	outpatient, no eGFR	0,13	W	W
8	Oral30+IV+CT1	check-up	0,83	W	A
9	Oral60+IV	inpatient	1,09	AA	AA
10	Oral60+IV	outpatient	5,44	W	W
11	Oral60+IV	outpatient, no eGFR	0,17	W	W
12	Oral60+IV	check-up	1,11	W	A
13	IV+CT1	inpatient	1,13	AA	AA
14	IV+CT1	outpatient	5,61	W	W
15	IV+CT1	outpatient ,no eGFR	0,17	W	W
16	IV+CT1	check-up	1,14	W	A
17	Oral30	outpatient	0,34	W	W
18	IV	inpatient	1,43	AA	AA
19	IV	outpatient	7,11	W	W
20	IV	outpatient, no eGFR	0,22	W	W
21	IV	check-up	1,45	W	A
22	CT1	inpatient	1,95	AA	AA
23	CT1	outpatient	10,00	W	W
24	CT1	check-up	1,98	W	A
25	Only Scan	outpatient	21,15	W	W
26	Only Scan	check-up	4,18	W	A
27	Only Scan	inpatient	4,12	AA	AA
28	Colon	Appointment	1,23	A	A
29	Punction	Appointment	1,43	A	A
30	Cardiac	Appointment	7,30	A	A

1 Typology of the type of patient. Out patients without eGFR need to visit the lab first, check-up patients get an appointment in Scenario 2 and are eligible for walk-in in Scenario 1.

2 AA = advanced access, A = appointment, W = walk-in.

D. Results and aggregated effects based on factorial design

D1: Scenario 1, mean of responses

Scenario 1:

Design point	Overtime (%)	Access Time (First slot possible)	Access time (all)	80th Percentile Waiting Time Walk-in	50th Percentile Waiting Time Walk-in	Waiting Walk-in(%)	Waiting time Walk-in	80th Percentile Waiting Time Appointments	50th Percentile Waiting Time Appointments	Waiting appointments(%)	Waiting time Appointments	Waiting Patients (%)	Waiting time	Overall Utilization (%)	Utilization CT2 (%)	Utilization CT1 (%)	Deferred Walk-in (%)	Walk-in (%)
1	3.25	4.90	4.90	19:29.6	06:22.2	65.54	16:11.5	15:01.5	07:06.7	56.76	10:13.7	63.59	14:34.4	59.57	42.58	76.55	9.58	**77.44**
2	3.25	5.19	5.19	19:26.4	06:21.7	65.43	16:11.7	15:15.0	07:14.8	56.58	10:18.4	63.46	14:35.9	59.61	42.57	76.65	9.62	**77.47**
3	1.78	4.79	4.79	20:30.5	06:46.7	67.19	16:41.8	14:28.1	06:23.8	54.67	10:22.2	63.69	14:52.2	59.51	43.30	75.71	14.87	**77.47**
4	1.76	4.99	4.99	20:18.9	06:41.4	67.13	16:35.6	14:22.4	06:17.5	54.24	10:20.9	63.50	14:47.9	59.51	43.25	75.77	14.86	**77.46**
5	3.26	4.92	4.92	19:30.5	06:23.9	65.61	15:37.2	16:40.3	07:35.0	56.73	11:47.8	63.63	14:34.9	59.56	42.54	76.59	9.58	**77.46**
6	3.27	5.17	5.17	19:29.9	06:22.1	65.38	15:38.2	16:25.6	07:19.8	56.57	11:53.6	63.42	14:37.0	59.58	42.49	76.66	9.65	**77.45**
7	1.76	4.85	4.85	20:25.0	06:44.4	67.21	16:01.5	15:29.9	06:33.7	54.65	11:45.1	63.69	14:47.7	59.53	43.37	75.69	14.84	**77.46**
8	1.76	4.99	4.99	20:20.0	06:44.3	67.08	16:00.4	15:41.7	06:41.0	54.40	11:44.1	63.51	14:46.5	59.53	43.29	75.78	14.91	**77.45**
9	3.37	4.82	4.82	23:00.5	07:02.5	66.69	19:57.1	14:17.2	06:16.1	58.86	10:23.2	65.15	17:25.5	59.63	42.66	76.60	7.76	**77.45**
10	3.35	5.14	5.14	22:47.3	07:00.0	66.65	19:48.5	14:37.3	06:35.7	58.50	10:21.4	65.01	17:19.3	59.58	42.51	76.65	7.76	**77.46**
11	1.88	4.59	4.59	24:54.4	07:34.1	68.56	20:50.6	13:20.9	05:15.2	56.63	10:20.8	65.43	17:54.0	59.53	43.28	75.78	12.83	**77.47**
12	1.88	4.85	4.85	24:38.8	07:28.9	68.31	20:43.1	13:59.1	05:54.6	56.18	10:22.3	65.11	17:49.6	59.53	43.28	75.78	12.82	**77.47**
13	3.36	4.82	4.82	23:01.8	07:01.2	66.62	18:34.6	16:40.0	06:42.8	59.00	13:51.4	65.14	17:19.6	59.58	42.64	76.51	7.76	**77.46**
14	3.33	5.14	5.14	22:58.9	07:03.1	66.63	18:32.4	17:42.8	07:24.0	58.44	13:57.8	64.98	17:20.2	59.56	42.63	76.49	7.73	**77.48**
15	1.84	4.59	4.59	24:50.7	07:36.7	68.58	19:18.8	15:20.7	05:41.7	56.56	13:42.2	65.42	17:44.4	59.53	43.33	75.74	12.85	**77.49**
16	1.85	4.85	4.85	24:33.9	07:28.6	68.42	19:13.5	16:11.9	06:14.4	56.23	13:52.5	65.20	17:43.9	59.54	43.32	75.75	12.83	**77.48**

D2: Scenario 2 mean of responses

Walk-in (%)	Deferred Walk-in (%)	Utilization CT1 (%)	Utilization CT2 (%)	Overall Utilization (%)	Waiting time	Waiting Patients (%)	Waiting time Appointments	Waiting appointments(%)	50% Percentile Waiting Time Appointments	80th Percentile Waiting Time Appointments	Waiting time Walk-in	Waiting Walk-in(%)	50th Percentile Waiting Time Walk-in	80th Percentile Waiting Time Walk-in	Access time (all)	Access Time (First slot possible)	Overtime (%)	Design point
64.74	8.97	75.09	43.76	59.43	14:29.3	61.52	10:25.8	55.96	05:10.6	13:25.3	16:57.1	64.44	06:17.0	20:20.8	24.12	4.98	2.67	17
64.74	8.92	75.15	43.71	59.43	14:29.7	61.16	10:30.7	55.51	04:54.5	13:15.3	16:54.2	64.14	06:14.7	20:08.1	24.31	5.21	2.68	18
64.73	14.59	74.28	44.43	59.36	14:38.0	61.50	10:26.3	54.48	04:41.8	12:59.6	17:20.9	66.07	06:37.6	21:14.3	22.89	5.00	1.42	19
64.72	14.57	74.31	44.41	59.36	14:32.9	61.11	10:20.6	54.04	04:30.7	12:47.7	17:15.9	65.71	06:35.5	21:01.1	22.96	5.09	1.42	20
64.73	9.04	75.42	43.40	59.41	14:49.6	61.55	16:36.8	56.09	08:10.8	22:32.5	13:44.2	64.42	06:04.4	17:33.2	24.09	4.99	2.72	21
64.77	9.08	75.45	43.34	59.40	14:44.4	61.22	16:34.1	55.58	07:44.8	22:04.6	13:37.9	64.20	05:58.9	17:22.4	24.24	5.19	2.68	22
64.74	14.74	74.50	44.19	59.35	14:57.0	61.68	16:30.0	54.62	07:09.6	21:34.7	13:56.7	66.28	06:23.1	18:07.2	22.88	5.02	1.43	23
64.73	14.72	74.58	44.13	59.35	14:52.3	61.26	16:24.1	54.21	06:44.8	21:03.2	13:52.9	65.86	06:17.4	17:58.8	22.92	5.07	1.43	24
64.75	7.11	75.78	43.08	59.43	16:03.5	63.22	10:11.0	57.50	04:21.3	12:23.2	19:29.0	66.06	06:50.8	22:52.0	24.80	5.29	2.69	25
64.76	7.09	75.87	42.92	59.39	15:48.6	62.50	10:07.0	56.53	04:19.6	12:20.6	19:05.9	65.52	06:39.4	22:07.6	24.92	5.47	2.67	26
64.76	12.58	74.91	43.85	59.38	16:22.8	63.54	10:07.2	56.41	04:02.5	12:07.6	20:18.1	67.93	07:19.0	24:34.2	23.53	5.35	1.41	27
64.75	12.55	75.12	43.62	59.37	16:13.9	62.88	10:06.6	55.48	04:02.8	12:07.1	20:01.3	67.48	07:10.3	24:01.1	23.57	5.38	1.42	28
64.75	7.14	75.91	42.90	59.40	16:11.3	63.29	18:09.1	57.68	07:34.0	23:11.7	15:02.3	66.07	06:31.9	19:05.8	24.79	5.31	2.69	29
64.72	7.12	76.13	42.69	59.41	16:03.3	62.67	18:02.4	56.65	07:17.1	22:44.3	14:54.5	65.72	06:24.2	18:47.5	24.95	5.48	2.69	30
64.73	12.66	75.06	43.72	59.39	16:32.8	63.71	18:02.9	56.49	06:52.6	22:29.9	15:36.6	68.19	07:01.8	20:16.9	23.55	5.40	1.40	31
64.73	12.53	75.34	43.43	59.39	16:21.7	63.06	17:58.7	55.53	06:25.8	22:01.9	15:21.8	67.76	06:52.3	19:53.5	23.54	5.37	1.39	32

D4: Means of main and interaction effects

Effect	Overtime (%)	Access Time (First slot possible)	Access time (all)	80th Percentile Waiting Time Walk-in	50th Percentile Waiting Time Walk-in	Waiting Walk-in(%)	Waiting time Walk-in	80th Percentile Waiting Time Appointments	50th Percentile Waiting Time Appointments	Waiting appointments(%)	Waiting time Appointments	Waiting Patients (%)	Waiting time	Overall Utilization (%)	Utilization CT2 (%)	Utilization CT1 (%)	Deferred Walk-in (%)	Walk-in (%)
e1	-0.51	0.31	18.97	-01:33.3	-00:20.2	-0.95	-01:24.2	02:05.9	-00:42.1	-0.76	02:12.3	-2.13	-00:41.3	-0.17	0.66	-0.99	-0.43	**-12.72**
e2	0.04	0.09	0.27	03:04.3	00:38.1	1.47	02:45.7	-00:05.7	-00:35.0	1.73	00:50.1	1.68	02:11.5	0.01	-0.31	0.33	-1.96	**0.01**
e3	0.00	0.01	-0.01	-01:41.8	-00:07.7	0.07	-02:27.4	05:41.7	01:34.0	0.07	04:44.7	0.07	00:05.6	-0.01	-0.11	0.10	0.04	**0.00**
e4	-1.38	-0.12	-0.75	01:13.6	00:25.2	1.79	00:33.3	-00:46.9	-00:46.0	-1.76	-00:03.6	0.17	00:16.9	-0.05	0.74	-0.84	5.36	**0.00**
e5	0.00	0.19	0.18	-00:14.6	-00:04.7	-0.25	-00:06.9	00:02.3	00:00.2	-0.52	-00:00.0	-0.36	-00:04.4	0.00	-0.09	0.09	-0.01	**0.00**
e12	-0.05	0.22	0.39	-00:50.2	-00:05.5	0.23	-00:44.4	00:03.6	00:03.5	-0.25	-00:13.1	0.06	-00:40.9	0.00	-0.34	0.34	-0.02	**0.00**
e13	0.01	0.00	-0.01	-01:42.4	-00:08.6	0.07	-01:27.0	03:50.3	01:10.5	0.05	02:15.7	0.06	00:08.7	0.00	-0.14	0.13	0.04	**-0.01**
e14	0.11	0.09	-0.55	-00:07.4	-00:00.8	0.05	-00:03.4	00:11.2	00:08.2	0.48	-00:01.4	0.03	-00:03.0	0.01	0.01	0.00	0.20	**-0.01**
e15	0.00	-0.07	-0.08	-00:05.9	-00:02.0	-0.13	-00:03.2	-00:19.8	-00:15.6	-0.19	-00:03.1	-0.16	-00:02.8	0.00	-0.05	0.04	-0.02	**0.00**
e23	-0.01	0.00	0.01	-00:14.0	-00:00.4	0.03	-00:30.0	00:42.0	00:06.6	-0.01	00:57.5	0.01	-00:03.1	0.00	0.05	-0.04	-0.03	**0.00**
e24	0.00	-0.02	-0.04	00:24.2	00:04.6	0.12	00:11.6	-00:00.3	00:00.8	0.05	-00:00.2	0.13	00:07.0	0.01	-0.01	0.03	-0.09	**0.01**
e25	0.00	0.00	0.01	-00:06.4	-00:01.7	-0.02	-00:03.9	00:11.9	00:10.7	-0.17	00:00.1	-0.08	-00:02.3	-0.01	-0.04	0.02	-0.02	**0.00**
e34	-0.01	0.00	0.00	-00:09.1	-00:00.4	0.05	-00:05.7	-00:14.1	-00:09.6	0.00	-00:03.1	0.03	-00:01.2	0.01	0.03	0.00	0.01	**0.00**
e35	0.00	-0.02	-0.01	00:03.8	00:00.1	0.01	00:01.8	-00:02.8	-00:03.8	0.00	00:00.3	0.01	00:00.9	0.00	-0.01	0.01	0.00	**0.00**
e45	0.00	-0.06	-0.05	-00:01.3	-00:00.9	-0.03	-00:00.7	00:00.6	00:01.1	0.00	-00:00.8	-0.02	-00:00.7	0.00	0.00	0.01	-0.01	**-0.01**

D4: Confidence intervals of the 50th and 80th percentiles of the waiting time of walk-in and appointment patients