Master Thesis Applied Mathematics
Faculty of Electrical Engineering, Mathematics and Computer Science (EEMCS)

Reducing access times for radiation treatments by aligning the doctors' schemes

A case study in the Academic Medical Center in Amsterdam

Confidential version

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Preface

This report is the result of my graduation project, which I have completed as a part of the Master of Science program in Applied Mathematics at University of Twente (UT). The research leading to this report was performed at the Department of Quality Assurance and Process Innovation (KPI) of the Academic Medical Center (AMC) in Amsterdam, from March until December 2013. The work deals with identifying logistic interventions that can reduce the access times for radiation treatment at the Radiotherapy department, using an Integer Linear Programming and computer simulation approach.

Finishing this master program means a lot to me. In the past years I realized that I was not only studying applied mathematics, but also how to persevere and endure. Though I found the courses difficult, I really enjoyed learning and mastering the material. And then, after spending years at the University, the time came for the 'applied' in Applied Mathematics. I had been working in the AMC before, but at that time I could not imagine coming back to work on such a complex topic as process innovation. It was amazing to learn more about the inspiring work that is carried out for the hospital by the KPI department and I feel honored to be a part of that. Also this project was not easy, but that makes it even more enjoyable to reach the finish line.

I would like to thank Richard Boucherie, for leading me in the direction of health care logistics and for trying to get the best out of me. Nikky Kortbeek for the inspiring discussions, his valuable feedback and for his reassurance that continuing this project in the AMC/UT would be suitable for me. In addition, I would like to thank Rob van Os for introducing me to the world of radiotherapy, for providing all the information I needed and for his kind support. It was a pleasure to work for such a supportive department.

Thanks to my fellow graduate students at KPI, for making me laugh during the lunches and for guiding me into the wonderful world of Excel, VBA, Visio and Plant Simulation. Thanks are also due to Nikoletta for making a start on the simulation program. Further, throughout my study I have had a great student life in Enschede. Thanks to my friends and housemates, for all the good times we had in the last eight years. Most of the time this had nothing to do with studying, and most of the time that was exactly what I needed.

My sincere thanks to both my parents for supporting me throughout my study. You have encouraged me to make my own choices, although the apple did not fall far from the tree!
Finally I would like to thank my sister Jacolijne, for her company in travelling to the AMC and for reminding me every now and then what is really important in life.

Ingeborg Bikker

Summary

Background and motivation

Radiotherapy is the most common treatment for cancer patients in the Netherlands. Delays in treatment are associated with psychological distress and decreased cancer control. To this end, national standards for the access times for radiation treatment are set, which are currently not met in many Dutch oncological centers. Access time is defined as the number of calendar days between the referral and the start of the treatment.

Since there are several patient types, different priorities and various interdependent stages involved in the treatment process, the access times are influenced by many factors. Variability also plays a role. The aim of this research is to identify logistic interventions that are expected to reduce the access times for regular and subacute patients, by making use of the available resources in an efficient way. The Radiotherapy department of the AMC is used as a case study.

Current situation and bottleneck analysis

In the AMC, most of the patients are treated on linear accelerator (linacs). The treatment consists of exposing patients to radiation sessions on consecutive days. Before these sessions can start, several stages need to be performed, depending on the patient type. An overview of the treatment process for subacute (palliative) and regular (curative) patients is given in Figure 1, either carried out in the AMC or in the satellite location the Flevo hospital. The first consultation is scheduled at the moment of referral, in a consultation slot of a doctor specialized in the patient's treatment area. The remaining appointments are scheduled after the patient is discussed in the physicians' meeting. Time constraints are involved between some stages, due to medical reasons or due to the department's policy. Consultations and contouring moments take place according to a cyclic weekly doctors' scheme.

Literature on capacity planning and control in Radiotherapy has mainly focused on the short term planning level and on parts of the treatment process, for example patient-to-appointment assignment on linacs. There are many longer term questions in the radiotherapy treatment process that have so far not been addressed in literature, for example: in which time slots should the consultations and contouring moments be planned in the weekly doctors' scheme?

The national standards and the current performance in the AMC can be found in the following table.

	Subacute		**Regular**	
	$\leq$ 7 days	$\leq$ 10 days	$\leq$ 21 days	$\leq$ 28 days
Norm	80%	100%	80%	100%
2012	50%	62%	17%	42%

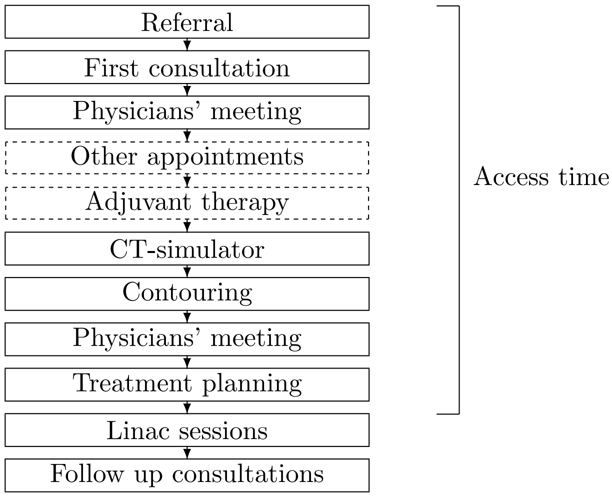


Figure 1: General treatment process for regular and subacute patients treated on a linac

From the bottleneck analysis we learned that the capacity of the CT-simulator (CT-sim) is in general enough to avoid congestion and to treat patients within one day. This also holds for the number of consultations, but here delays are more common because doctors only treat patients within their focus area. The utilization of the linacs in the AMC is quite high and congestion is likely, especially in the case of three linacs. However, access times are not only influenced by queueing effects: also the capacity allocation (especially the doctors' scheme) and scheduling rules play a role. An investigation of the shortest possible access times in the department ('lower bound' of the access times) in the situation where the current doctors' scheme and scheduling rules are used, made clear that for some patient groups, the standards can not be met even when no queueing effects occur.

Approach

Our research focus is therefore on optimizing the weekly doctors' schemes. Besides the promising effects on the access time, another advantage of this intervention is that the impact on the department and the personnel would be limited, since it only implies swaps in physicians' activities. An Integer Linear Programming (ILP) model is developed to create optimal doctors' schemes, containing time slots for consultations and contouring per physician on both treatment locations, such that the lower bounds of the access times in the department are minimized. A discrete event simulation model is developed to evaluate the consequences of several doctors' schemes in a stochastic environment where queueing effects are taken into account.

Results and conclusion

Several experiments are carried out with the simulation model, where the original doctors' scheme and a doctors' scheme created by the ILP model are used as input. The interventions with an optimized scheme cover: 1) changing the policy with respect to which doctors can treat which patient types, 2) scheduling the consultation and CT-sim on the same day, 3) performing contouring immediately after the CT-sim, and 4) increased capacity for the CT-sim, linacs and consultation time slots.

The validation of the simulation program was not succesful, so the results do not necessarily correspond in a sufficient extent with the actual situation. However, the simulation results do provide us with an indication about the effect of the interventions. All mentioned interventions had a beneficial effect on the access times. The introduction of a scheme created by the ILP model has a larger effect than the other interventions: the percentage of regular patients treated within 21 days increased from 50% to 80% and the percentage of regular patients treated within 28 days increased from 80% to 95% when using a scheme created by the ILP model. A large reduction in the entry times (time between referral and consultation) for breast patients is recorded when using a scheme created by the ILP model. If all doctors would treat breast and urology patients, a further improvement is recorded such that 80% has an entry time within two days instead of twelve in the original situation. For subacute patients, the percentage treated within the required ten days lies around 20% in all investigated situations. The main cause for this is the rule of scheduling five days between the contouring and the start of the treatment that is currently used by the department.

Discussion and recommendations

Potential causes for the unsuccessful validation of the simulation model are the assumptions and simplifications we used (for example: in reality, the linac sessions are not carried out at once, and doctors may be absent due to holidays and conferences) and the incomplete historical data which complicated modelling and the choice of parameter values. A recommendation for further research on the doctors' scheme is to take more parameters into account in the optimization. Recommendations to the department are to avoid using only three linacs in the AMC and to implement a scheme such as created by the ILP model.

Contents

Chapter 1

Introduction

At the Radiotherapy department of the Academic Medical Center (AMC) in Amsterdam, patients with cancer are treated with radiation. The access times for these treatments currently exceed the national standards. The aim of the research presented in this master thesis is to identify interventions that can reduce these access times, by making use of the available resources in an efficient way. Since there are several patient types, different priorities, two treatment locations and various interdependent stages involved in the treatment process, the access times are influenced by many factors. Knowledge about the effect of these factors is essential for gaining insight in the bottlenecks of the process and in designing possible interventions that can reduce these bottlenecks.

1.1 Radiotherapy and cancer

Radiotherapy (or radiation therapy) is one of the most commonly used cancer treatment therapies, along with surgery and chemotherapy. It is based on the medical use of ionizing radiation to control or kill malignant cells. Radiation therapy may be curative in a number of types of cancer, or if it is not possible to effectively cure the cancer, the radiotherapy is used for palliative purposes in the sense of pain relieve. Radiation treatment can be given in addition to surgery or chemotherapy to improve treatment outcomes.

Most of the radiotherapy patients are treated with external beam radiation produced by a *linear accelerator* (linac). This consists of exposing the patient to radiation beams, with the intent of destroying the cancerous cells while minimizing damage to the surrounding organs. To allow enough time for the healthy organs to recover, the radiation is divided in sessions that take place on consecutive weekdays. The number of sessions depends on different factors, such as the location, size and type of cancer, and the overall pathological conditions of the patient.

In the Netherlands, patients are categorized as *acute*, *subacute* or *regular* patients. Acute treatment is mainly required for patients with a threatening spinal cord injury or who have trouble to breath. These patients usually receive one session of radiation. Subacute patients receive treatment for palliative reasons, generally in one to ten sessions. The majority of the patients is categorized as regular patients: their treatment is curative and normally consists of 25 to 39 radiation sessions.

Figure 1.1: Treatment on a linear accelerator

1.2 Access times and national standards

Delays in radiation therapy are associated with tumor progression, persistence of cancer symptoms, psychological distress and decreased cancer control (for example [10]). For this reason, the Dutch Association of Radiotherapy and Oncology (NVRO) has set national standards for the access times of radiotherapy treatments (the so-called 'Treeknorm') [3], where the access time is defined as the number of calendar days (weekends and holidays included) between referral to the department and the first treatment session.

The national standards are stated below. The lines should be read as '80% of the regular patients should have an access time within 21 calendar days'. Patients with elective delay (that is, delay for clinical reasons in the interest of the patient, for example surgery or postoperative recovery) or delay caused by unavailability of the patient are not to be considered in the norm. It is not specified in the definition of the norm whether the access times should be evaluated *prospectively* (that is, looking forward to what the access time will be for a patient referred now) or *retrospectively* (that is, looking back to what the access time was for a treated patient).

Priority	**Access time requirement**
Regular patients	80% within 21 calendar days 100% within 28 calendar days
Subacute patients	80% within 7 calendar days 100% within 10 calendar days
Acute patients	100% within 1 calendar day

1.3 Research motivation

The motivation for this research is provided by the Radiotherapy department of the Academic Medical Center. At this moment, the (retrospective) access times for treatments of subacute and regular patients on linear accelerators in the department exceed the national standards. It is not clear to the management of the department what is the cause of this and which changes in the work processes could reduce the access times, using the current available resources.

This issue fits in a broader scope of logistic developments in healthcare. Over the past decades, healthcare delivery systems are under increased pressure to deliver high quality care with limited resources. For this reason, healthcare institutions are giving more and more attention to managing their processes in the best way. In this context, the development of procedures that improve patient flow, provide timely treatment and maximize the utilization of available resources, plays a crucial role. In the last decades, the application of Operations Research to health care has shown that OR can play a significant role in addressing this type of logistic health care challenges.

1.4 Problem description

At the Radiotherapy department of the AMC, the access times for treatments of subacute and regular patients on linear accelerators are not met. There are many factors that influence the access times. Due to the interdependence between different stages in the treatment process and the many different patient types, it is not straightforward which effect each factor has on the access times. To be able to reduce the access times, it is essential to gain insight in the bottlenecks of the process and to identify interventions that can contribute to a reduction of the access times.

Within the department, the largest group of patients is treated with external beam radiation and the linacs are the machines with the highest utilization, therefore we will restrict ourselves to this treatment type. Because of the department's preferences to make use of the current available resources, our focus will be on interventions that leave the available resources unchanged.

Research question

Which interventions in the radiotherapy process, that make use of the current available resources, can cause a reduction of the access times for subacute and regular patients, treated on linear accelerators in the AMC and what are their predicted consequences?

Subquestions

1. What is the current situation of the treatment process, the organizational characteristics and the access time performance at the AMC Radiotherapy department?
2. Which interventions in the radiotherapy process or similar situations, that leave the current available resources unchanged, have been reported in literature?
3. What are the largest bottlenecks in the current situation on the AMC Radiotherapy department?
4. Which interventions, taking the facility's capacity as a given, are likely to cause a reduction of the access times for subacute and regular patients?
5. What are the effects of the interventions formulated in response to subquestion 4, on the access times of subacute and regular patients?

1.5 Outline of this thesis

The current situation of the treatment process and the organizational characteristics of the Radiotherapy department are described in Chapter 2. In Chapter 3, a literature review is provided and an overview is given of logistic decisions that are relevant for the department. A data analysis is carried out in Chapter 4, followed by a bottleneck analysis to investigate the contribution of queueing effects and the organizational characteristics on the length of the access time. In Chapter 5 we determine to focus on adapting the doctors' scheme, such that the interrelated doctors' activities are aligned. An Integer Linear Program (ILP) model is presented for creating new doctors' schemes and a simulation model is used to evaluate the effect of the interventions on the access times. The experimental results of this study can be found in Chapter 6, followed by the conclusion and the recommendations for further research in Chapter 7.

Chapter 2

Radiotherapy in the AMC

In this chapter, the current situation of the treatment process and the organizational characteristics of the Radiotherapy department of the AMC are described. The context analysis of the treatment process and working methods at the AMC Radiotherapy department is based on protocols (from Kwadraet, the system used to store quality documents), interviews with employees of different positions in the department (information specialist, quality manager, physician, receptionist, appointment planner, technician and software developer), observation of the working methods (at the reception, the physician's meeting, the Planning office, the treatment planning, a session on the CT-scan, the contouring process, the mould room and a session on the linear accelerator) and analysis of the data of past years (data from X-Care, the information system used for registering consultation dates and times, and Mosaiq, the information system used to store treatment information and to register dates and times for preparation appointments and linac sessions).

2.1 AMC and the Radiotherapy department

The Academic Medical Center, founded in 1983 as a merge between the Wilhelmina Gasthuis and the Binnengasthuis, is one out of eight university hospitals in the Netherlands and is affiliated with the University of Amsterdam. In 2011, the AMC had 1,002 registered beds, employed 7,041 people and performed 387,549 outpatient visits [2]. The AMC has a close collaboration with the VU University Medical Center Amsterdam (VUmc). In 2011, the two hospitals declared the intention to form an alliance, with the aim to merge in the future [1].

The Radiotherapy department of the AMC employs 23 radiotherapists and around 50 laboratory technicians, who jointly carried out 29,940 radiation sessions on 1981 patients in 2012. The department covers two treatment locations: the main location in the AMC in Amsterdam, where four linear accelerators (linacs) are available, and since 2008 a satellite location in the Flevo hospital in Almere is operating with two linacs. The department is usually operating on working days and closed on some holidays, where holidays compensated by opening on Saturday or Sunday.

Besides the most important activity, performing external radiation treatment on linacs, the department provides three other treatment types: *brachytherapy*, where a radioactive source is implemented in the patient's body, *hyperthermia* treatment, where treatment consists of heating a certain part of the body, and external beam treatment on an orthovolt machine. These other treatments are only provided in the main location in Amsterdam. Patients receive either one of the therapies or a combination of external beam radiation with brachytherapy, hyperthermia, chemotherapy and/or surgery.

Indications for radiation arise from almost all types of cancer in all organs, resulting in hundreds of potential cancer sites and treatment types. The most common treatments at the Radiotherapy department are given for breast, bonemetastasis, prostate and oesophagus tumors. Because of the alliance with the VUmc, it is likely that in the future both hospitals will specialize in certain cancer types and treatments.

2.2 The multi-step treatment process

This section describes the stages of the treatment process for a subacute or regular patient treated on a linac, either in the AMC or in the Flevo hospital. In Figure 2.1, a general overview of the process is displayed and in Figure 2.2 an example is given for the time path of a specific patient in the treatment process. The exact stages a patient has to pass through and the number of radiation sessions differ per patient type, but most patient types follow the general process. The stages are explained below.

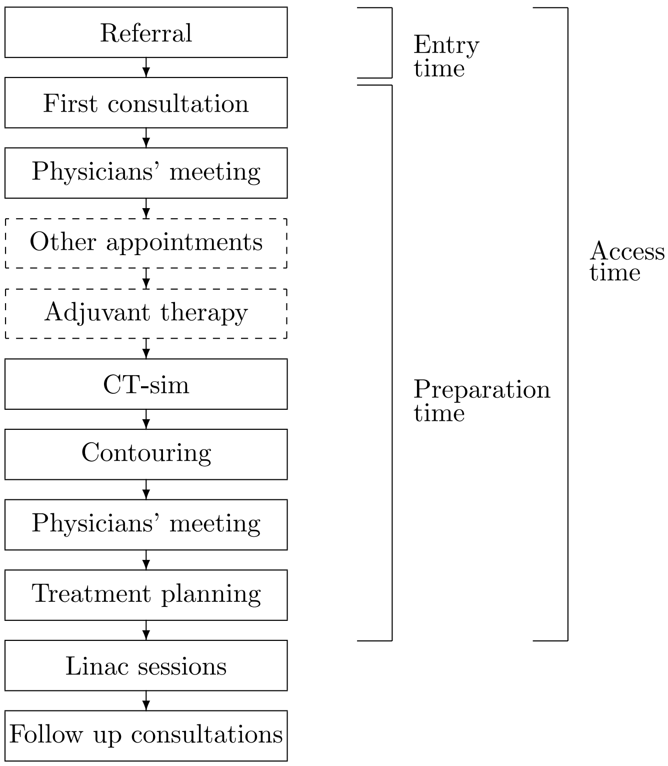


Figure 2.1: General treatment process for a patient with a standard first consultation

2.2.1 Referral and first consultation

A patient 'enters' the department at the moment of referral, which can be a phone call or a fax by the patient's general practitioner or specialist. The referrals are collected by *Desk 1* (the reception) and if all the required information regarding the patient's diagnosis is available (which is usually the case), the first consultation is scheduled immediately. In the first consultation a physician, physician assistant or physician in education (hereafter abbreviated to physician) discusses the treatment procedure with the patient and sometimes carries out a physical examination. Regardless of the patient type, the scheduled length of time for a first consultation is 45 minutes for a physician and 60 minutes for a physician assistant or physician in education. For subacute patients, besides a standard first consultation it is possible to have a so-called *one stop shop* (OSS) consultation. This will be explained later on.

	Mon	Tue	Wed	Thu	Fri	Sat	Sun
Week 1	Referral		Consult	Meeting			
Week 2	CT-sim			Contouring	Meeting		
Week 3	Planning			Linac	Linac		

Figure 2.2: Example of a time path of a patient (access time: 17 days)

2.2.2 Preparation phase

The working day after the first consultation, the patient's treatment proposal is discussed by the physicians in a so called *physicians' meeting* that takes place every morning. The patient could either start with the treatment directly, receive no treatment at all or first undergo surgery or chemotherapy. There are protocols with guidelines for the treatment of every patient type, but the exact treatment proposal depends on the specific condition of the patient.

If a patient is suitable for treatment, the preparation can start. In some cases, additional consultations are needed before the preparation can take place (this will be explained later), but in general the next step is an appointment on the *CT-simulator* (CT-sim), which is a combination of a CT-scanner and a simulator. In this appointment, a CT-scan is made to define the treatment area and the patient's position on the linac is simulated, such that marks can be made with permanent ink on the patient's body for position verification later on in the sessions. Depending on whether a patient needs intravenous contrast beforehand, the time reserved for the scan is between 15 and 30 minutes.

After this scan, the patient's physician marks the tumor on the scan. This is called *contouring* and takes place in a computer room, without the patient's presence (Figure 2.2.2). The result of the contouring is again discussed in a physician's meeting. After this, a technician prepares a treatment planning, containing a detailed description of the dose of radiation and the shape and angles of the radiation beams (Figure 2.2.2). The planning has to be signed by the physician and then implemented in the linac system, before the treatment can start. The time needed for contouring and for the treatment planning can vary considerably due to the complexity of the tumor and the required accuracy of the planning. In general, contouring and the treatment planning require less time for subacute patients than for regular patients.

2.2.3 Treatment and follow up consultations

The radiation sessions are executed on a linac by *laboratory technicians* and take place at consecutive days, with exception of the weekends. One session normally takes ten or twenty minutes. For a patient all sessions have the same length, except for the first one where ten extra minutes are scheduled for the explanation of the procedure. Breakdowns of the linac are very rare and

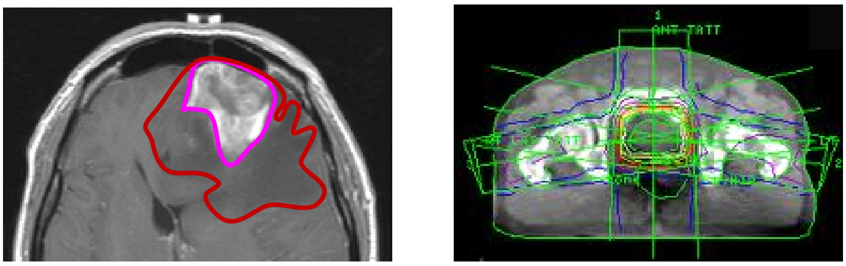


Figure 2.3: Contouring a tumor (left) and defining a treatment planning (right)

when they occur, the machines are usually repaired immediately by the department's internal technicians, without cancelling appointments on the day of occurrence.

During the treatment, short *checking consultations* are scheduled for a patient each week to discuss the progress and side effects with the physician. When the treatment is finished, a patient has to come back regularly for *follow up consultations*, normally once every couple of months or years. A follow up consultation might lead to a new treatment session; in that case, the follow up consultation counts as a first consultation and the preparation phase starts immediately.

2.2.4 Additional stages

Depending on the patient type, a patient may need to visit stages that are additional to the regular treatment process. Some patients get beads implemented in their body for a good recognition of the relevant organs on the CT-scan:

- Beads implementation: some patients with oesophagus or pancreas tumors get beads implemented. This procedure is performed at the Endoscopy department.
- Gold beads implementation: some prostate patients get gold beads implemented. This is done by two radiotherapists and takes place in an operating room.

After the implementation of the beads, the body has to recover for several days before an accurate CT-scan can be made. For some patient types it is necessary to make other scans or visualizations additionally to or instead of the CT-scan.

- Pet-CT-scan: some gynaecological and lung patients need a Pet-CT-scan. This scan is made at the Nuclear medicine department.
- 4d-CT-scan: for some lung patients, a four-dimensional CT-scan is required. This scan is made on the CT-simulator of the Radiotherapy department.
- MRI-scan: this scan is not prescribed in any protocol, but it is requested occasionally. The scan is made at the Radiology department.
- Cystoscopy: this procedure is used for imaging purposes inside the bladder and is carried out at the Endoscopy department.

It might be necessary to use extra devices for the treatment, which have to be made and tested before the treatment can start. In protocols this is described as 'plan/mal check'.

Figure 2.4: A mould for fixation during the sessions

- Mould/mask: if lying in a certain position is difficult or it is extra important that there is no movement, a mould can be made for a specific body part. This is required for brain patients, certain breast patients and occasionally for children. The mould is made in the mould room of the department before the CT-scan takes place.
- Another type of mould is sometimes used to control the shape of the linac beams. The mould has to be tested on a linac in the patient's presence. The guideline is to do this one day before the start of the treatment. This is done for, among others, retreatment of breast patients.

The complete set of scans is used in contouring the tumor. In combination with radiotherapy, other treatments can be applied:

- Surgery: this can be done before the radiotherapy treatment (for some breast, rectum and bladder patients) or after the treatment (for some prostate, rectum, stomach, cervix and vulva patients).
- Chemotherapy: in general, chemotherapy does not have to take place in exactly the same period as the radiation sessions; it can start before, during or after the radiation treatment. It is suitable for some rectum, endometrium, bladder and lung patients.
- Brachytherapy: this should be performed short before or after the radiation treatment series and is suitable for cervix patients and some endometrium and prostate patients.
- Hyperthermia: the hyperthermia appointments have to be scheduled within several hours from the radiation sessions. It is used for retreatment of breast patients and for some rectum, bladder and melanoma patients.

2.2.5 OSS consultations and acute patients

Instead of a standard first consultation, patients can be scheduled for a one stop shop (OSS) consultation, where the stages from the first consultation until the start of the treatment take place on the same day and the morning meetings are skipped. In the AMC, there is time reserved for one OSS consultation every day, meant for acute or subacute patients. In the Flevo hospital there is no time reserved for OSS consultations.

Acute patients usually get treated within 24 hours of their referral. If the next available OSS consultation in the AMC is not within 24 hours, the acute patient is treated in between the already scheduled appointments in the AMC or the Flevo hospital. It is possible that the scheduled appointments are slightly delayed because of this, but in practice this will be compensated by overwork, so already scheduled appointments are not canceled.

2.2.6 Different treatment pathway

Not all patients that receive treatment have had a first consultation at the Radiotherapy department: patients can also ‘enter’ the treatment process through a *multidisciplinary meeting* with oncologists of other specialties or a *GIOCA* consultation, that is a fast diagnostics consultation for gastroenterological diseases. If patients with a follow up consultation need retreatment, the first consultation is skipped. In these cases, the patient only has a preparation time and no entry time.

It is also possible that after the first consultation or the CT-sim appointment, it turns out that an external beam treatment is not suitable for the patient. In that case, the patient only has an entry time and no preparation time.

2.3 Organizational characteristics

This section describes the department’s organizational characteristics, that is, the logistic layout of the radiation treatment process and the scheduling procedures currently used in the department.

2.3.1 Scheduling the first consultation

The first consultations and the follow up consultations are scheduled at Desk 1 and registered in the electronic calendar system X-Care (by McKesson). The first consultations are scheduled according to a weekly scheme, where each physician has certain time slots in the week reserved for first consultations and OSS consultations. This scheme is a cyclic weekly blueprint made beforehand; it is not dynamically adapted based on the actual patient arrivals.

In the AMC, a physician usually treats regular patients within his focus area(s) and subacute patients of all areas. In the Flevo hospital, all physicians treat all patient types. Each day, one of the physicians visits Desk 1 to determine the priority of referred patients and the type of first consultation these patients need (standard first consultation or OSS) and if standard, to assign the written referrals to a specific physician or focus area. Once this is done, the first consultation is scheduled. The referrals by phone are assigned to a physician or focus area by the employees of Desk 1 themself and the first consultation is scheduled immediately.

To schedule a consultation, the planners take the first available free consultation slot of a physician that can treat the considered patient type, with the earliest possibility on the next day. For patients that need a OSS consultation, the first available free OSS consultation is taken or if this is too far ahead, the patient is treated as an acute patient.

A summary of the scheduling procedure:

	Scheduling procedure Desk 1
Step 1	Determine priority and type of first consultation, and assign to focus area/physician
Step 2	For subacute OSS patient: schedule first available OSS time slot, or, if too far ahead, treat patient as acute For subacute non-OSS patient: schedule first available standard consultation of all physicians For regular patient: schedule first available consultation of a physician in focus area

2.3.2 Scheduling the preparation and treatment

The CT-sim appointment, the sessions, the checking consultations and the additional appointments within the department are planned by the *Planning office* and registered in the electronic system Mosaiq. This is done once the physicians' meeting on the day after the first consultation is finished. The additional appointments that take place on other departments are scheduled by these departments, but the Planning office coordinates the appointment requests.

There are several constraints for the scheduling procedure.

- The contouring should be done by the physician the patient is assigned to, and each physician has one or more day parts in the week reserved for contouring, as stated in the weekly physician's scheme. On one contouring day part, multiple scans can be contoured.
- Since the linacs do not all have the same characteristics, the sessions should be scheduled on a machine that is suitable for the patient type.
- Regular patients do not start their treatment on Friday, because one session of radiation before having two days 'off' is not effective for the treatment.

For the scheduled time between the stages, the department uses some guidelines:

- There is a prescribed minimum of days between the contouring and the start of the treatment, in order to ensure that there is enough time for the treatment planning and for implementing the treatment details in the machinery. Usually this is five working days for treatment in the AMC and six working days for treatment in the Flevo hospital, because the file transport between the AMC and the Flevo hospital is done only once a day.
- Taking into account previous requirement, the time between the CT-scan and the start of the treatment should be minimized, because the tumor size can vary over time and the markings on the body fade. If the tumor size changed too much or the lines faded too much, the patient has needs another consultation for a new scan or new markings before the start of the treatment.

The scheduling procedure that is used by the planners:

	Scheduling procedure Planning office
Step 1	Search for the first available time slot on CT-sim
Step 2	If applicable: from this date, search for first available slot for other appointments
Step 3	From the date of the last scan, search for the first available contouring moment of the treating physician
Step 4	From this date, add the prescribed number of days, search for first available starting date on suitable linac such that sessions can take place on consecutive days from then on
Step 5	Schedule patient for the linac appointment obtained in step 4
Step 6	Look for latest contouring moment before start, take into account prescribed number of days
Step 7	Schedule patient for latest available CT-sim appointment before the contouring moment

Because of the interrelatedness of the stages and all the constraints, the construction of a schedule proposal for the preparation and treatment is a time-consuming task. Planners indicate that they usually spend between ten and 60 minutes on finding a feasible schedule proposal for a series of treatments for a patient. For all appointments, no-shows or patients arriving late rarely occur.

2.3.3 Department's resources

In the treatment process, a variety of resources is used: machines (CT-sim and linacs), personnel (physicians, physician assistants, physicians in training, planning staff and laboratory technicians) and other equipment (rooms for first consultations, licenses for the contouring software and treatment planning software).

The number of consultation slots varies during the year, because physicians in education regularly have internships in different hospitals, and physicians may have maternity leave, holidays or conferences. In the Flevo hospital, it is required to have two physicians present each day according to satellite quality standards of the NVRO. Besides the standard first consultations, one OSS appointment takes place each day in the AMC, which is also counted as an consultation time slot.

In the AMC, four linacs are available and in the Flevo hospital there are two. In both hospitals there is one CT-scan available. The machines are opened on working days on specific hours. Maintenance is done once a week during working hours and breakdowns rarely occur. In the weekend and in certain holidays the department is closed, but closures of more than two days a week are compensated by opening the CT-scans and linacs on a Saturday or Sunday. More information about the capacity and the utilization can be found in Sections 4.2 and 4.3.

Besides the consultations and machines, there are other resources that have limitations as well. The number of licenses for contouring software and for treatment planning software puts limitations on the number of physicians contouring at the same time and the number of laboratory technicians working on the treatment planning. Further, in the Planning office congestion can occur in processing the treatment requests. In 2012, 22 of the 2165 treatments were delayed (1%) because the preparation activities could not be finished in time.

2.3.4 Two locations

Since 2008, the Radiotherapy department has a satellite location in the Flevo hospital in Almere with two linacs. This is an advantage for patients living in the neighbourhood of Almere, since they have to travel to the hospital every day during their treatment. For health insurance companies this also has financial advantages, since in some cases taxi costs are reimbursed by the health insurance. The travel time between the AMC and the Flevo hospital is approximately half an hour by car or one hour by public transport.

The first consultations, CT-sim appointments, physicians' meetings and radiation sessions can take place at both locations. Each day of the week, two of the physicians are present in the Flevo hospital according to the weekly physician's scheme. The contouring for all patients can be done on both locations (it does not matter where the patient is treated). The appointment scheduling and the treatment planning are performed in the AMC, as well as some of the additional stages. Once a day, a transportation service takes (paper) patient records from one location to the other. The brachytherapy and hyperthermia treatments only take place in Amsterdam: combination treatments are therefore always performed in the AMC.

Patients without combination treatments usually have a preference for a treatment location, based on the travel time or the reputation of the hospitals. It is possible that patients switch locations before or after the first consultation. In cooperation with the Zuiderzee hospital in Lelystad and the Onze Lieve Vrouwe Gasthuis hospital in Amsterdam, once a week there is a possibility for first consultations on these locations. These consultations are performed by an AMC physician. If the patients continue for treatment, this takes place in the AMC or the Flevo hospital.

2.3.5 Temporary capacity changes in busy periods

At the moment the access times exceed a certain threshold, temporary measures are taken by the department to reduce the access times. The linac opening hours can be extended with one hour a day, but since laboratory technicians have to be scheduled for these working hours as well, this is not usually done. The number of available first consultations can also be extended.

At the moment the access times at the two locations differ more than a week, the personnel of Desk 1 tries to convince patients to choose the the other location for their consultation and/or treatment. The same is done by the Planning office when the preparation times differ more than a week. The experience of the department is that patients usually prefer to wait longer for treatment on the location of their preference than to switch locations. In 2012, only eleven patients were treated in the Flevo hospital although they lived significantly closer to the AMC.

The management's experience is that these measures often are taken too late, in the sense that the access times are already high at that moment and still remain high for patients that are referred after the action is taken: the effect of the measure can sometimes be seen only weeks later.

2.3.6 Radiotherapy in other hospitals

From interviews with doctors and laboratory technicians in other hospitals we know that treatment processes in other Dutch hospitals are quite similar to the process described in the previous sections, because the stages to pass through (except for the meetings) and the protocols per patient type are more or less standardized. However, the logistical layout of the department can be different in other hospitals. Some differences are described below.

- In the University Medical Center Utrecht, the CT-scan is made on the same day as the first consultation, if there are no additional stages required in between. The patient is only discussed in a physician's meeting once the contouring is done. There are no fixed moments reserved for contouring, the physicians do this in between their other activities. The first consultation and the preparation and treatment appointments are scheduled immediately after referral. This is also the case in the Antoni van Leeuwenhoek (AvL) hospital in Amsterdam.
- In the AvL hospital, there is no prescribed number of days between the contouring and the start of the treatment. The planners estimate the necessary time per case. First consultations for the most common patient groups are clustered per focus area: each week certain time slots are for example reserved for lung patients, where a physician, a physician assistant and a physician in education have consultations simultaneously. The next day there is a physicians' meeting for the focus area where the treatment proposal is discussed.
- In the Radiotherapy Institute Medical Center in Leeuwarden, physicians have time slots for first consultations every working day. Physicians perform the contouring on the day of the CT-scan, and some days later the treatment starts. The utilization of the CT-scan and the linacs is very low and the availability of the machines is usually not a cause for delays.
- Some institutes have their facilities opened on Saturday or in the evening hours. In general this is experienced as a patient friendly, because some patients have the preference to be treated outside working hours.
- The AMC is not the only institute with a satellite location: among others, the AvL hospital and the Erasmus Medical Center in Rotterdam have the same construction with one satellite.

Chapter 3

Literature review

The aim of this chapter is to provide a complete view on which logistic planning issues could be the focus of this research, and to obtain information on how the access time performance of the complete treatment process could be evaluated. To this end, first the role of Operations Research in health care is described in Section 3.1, followed by an overview of capacity planning and control topics that have been addressed in literature (Section 3.2). The topics where research is carried out within radiotherapy are described, together with some relevant research on similar relevant processes in health care. Based on this information and the process analysis of Chapter 2, we constructed a list in Section 3.3 of capacity planning and control decisions that are under the responsibility of the Radiotherapy department and that possibly influence the access time performance. In Section 3.4, several methods are discussed to model the complete treatment process, such that the effects of possible changes in capacity planning and control on the access times could be evaluated. Finally, the contribution of our work to the existing knowledge is described in Section 3.5.

3.1 Operations Research in health care

The field of Operations Research (OR) is an interdisciplinary branch of applied mathematics, engineering and sciences that deals with the application of advanced analytical methods to support decision making [4]. This field covers a wide range of problem-solving techniques and methods, such as simulation, mathematical optimization, queuing theory, Markov decision processes, data analysis, statistics and decision analysis. OR has been widely applied to diverse areas such as manufacturing, telecommunications, transportation and service industries. In the last decade of the 20th century, the expanded application of OR to health care has shown that OR can play a significant role in addressing logistic health care challenges.

The process of investigating a real-world problem via OR starts with carefully observing and formulating the problem, including gathering all relevant data [16]. The next step is to construct a mathematical model that attempts to abstract the essence of the real problem. This model should be a sufficiently precise representation capturing the essential features of the situation so that the solutions and conclusions obtained from the model are also valid for the real world. The experiments conducted to verify whether this is the case are referred to as model validation. Next, by quantitatively predicting the consequences of potential solutions, the goal is to inform and make recommendations to decision makers so that they are eventually able to make the best possible decisions. The final step is to come to the implementation of a solution. Because implementation often requires people to do things differently, it often meets resistance. Involving users throughout the modeling and experimentation process is essential [16].

3.2 Literature on capacity planning and control

Many capacity planning and control issues have been topic of research in radiotherapy and similar processes in health care. In this section, a complete list is provided of capacity planning and control topics in ambulatory care services (covering amongst others the Radiotherapy department) that have been addressed in literature [18]. To be able to position these planning decisions, the taxonomy of Hulshof et al. [18] is used. After stating the list of topics in ambulatory care services, we will zoom in on topics that have been investigated for the radiotherapy treatment process and we also discuss some interesting research done in similar care processes.

3.2.1 Taxonomic classification

In [18], a taxonomic classification is given of planning decisions in resource capacity planning and control in health care, that can be supported with OR methods. The taxonomy contains two axes. The vertical axis reflects the hierarchical nature of decision making in resource capacity planning and control, and the horizontal axis the various health care services. Since radiotherapy is considered an ambulatory (outpatient) care service and since we want to discover relevant questions for the radiotherapy treatment process, we will restrict our overview of capacity planning and control decisions in the next section to this care service.

The vertical axis contains four hierarchical levels of planning: the strategic, tactical, offline operational and online operational level. While strategic planning addresses structural decision making, tactical planning addresses the organization of the operations and the execution of the health care delivery process (that is, the 'what, where, how, when and who' questions). Operational planning involves the short-term decision making related to the execution of the health care delivery process. Offline reflects the in advance decision making and online the real-time reactive decision making in response to events that cannot be planned in advance.

The levels are strongly connected, because higher-level decisions demarcate the scope of and impose restrictions on lower level decisions. The nature of planning and control decision making is such that decisions disaggregate as time progresses and more information becomes available. Aggregate (strategic) decisions are made in an early stage, while more detailed information supports decision making with a finer granularity (tactical, operational) in later stages.

3.2.2 Overview of topics in outpatient care services

In this section, a complete overview is given of capacity planning and control problems in outpatient care services (covering amongst others the Radiotherapy department) that have been addressed in literature [18] and that could be a topic relevant in the Radiotherapy process as well. The bold printed terms contain research done on Radiotherapy and are highlighted afterwards. In the strategic level of ambulatory care services, topics of research are:

- Regional coverage: this involves determining the number, size and location of facilities in a region to find a balanced distribution of facilities with respect to the geographical location of demand. Main trade-off in this decision is between patient accessibility and efficiency.

- Service mix: this consists of the particular services that the facility provides. The service mix specifies which patient types can be treated.

- Case mix and panel size: the case mix is the volume and composition of patient groups that the facility serves. The service mix restricts the decisions to serve particular patient groups. The panel size is the number of potential patients of a facility.
- Facility layout: this concerns the positioning and organization of various physical areas in a facility, for example a reception, a waiting area and consultation rooms.
- **Capacity dimensioning:** a facility determines the number of resources, such as staff, equipment and space in a trade-off between access times and resource utilization.

In the tactical level, topics of research are:

- Access policy: concerns the waiting list management that deals with prioritizing waiting lists such that access time is fairly distributed over different patient groups.
- Admission control: given the access policy decisions, admission control involves the rules according to which patients are selected to be admitted from the waiting lists.
- **Capacity allocation:** resource capacities settled on the strategic level are subdivided over all patient groups. Patient groups are assigned to resource types and a time division for the resource's capacity is made.
- Temporary capacity change: the balance between access times and resource utilization might be improved when resource capacity can temporarily be increased or decreased, to cope with fluctuations in patient arrivals.
- Staff-shift scheduling: deals with the problem of selecting what shifts are to be worked and how many employees should be assigned to each shift to meet the patient demand.
- **Patient routing:** the route of a patient is defined as the composition and sequence of stages that need to be fulfilled in the treatment. An effective and efficient patient route should match medical requirements, capacity requirements and restrictions, and the facility's layout.
- **Appointment scheduling:** appointment schedules are blueprints that can be used to provide a specific time and date for appointments. Appointment scheduling comprises the design of such blueprint schedules and involves amongst others setting the length of the appointment interval and a queueing discipline.

In the offline operational level:

- **Patient-to-appointment assignment:** based on the appointment scheduling blueprint developed on the tactical level, patient scheduling comprises scheduling a single appointment, a combinational appointment or an appointment series in particular time slots for particular patients.
- Staff-to-shift-assignment: based on the staff-shift schedule determined on the tactical level, the staf-to-shift assignment deals with providing a date and time to staff members to perform particular shifts.

In the online operational level we have:

- Dynamic patient (re)assignment: unplanned events, such as emergency patients, extended consultation duration or equipment breakdown, may disturb the planned appointment schedule. Dynamic patient (re)assignment concerns the reaction in response to such events.
- Staff rescheduling: before and during a shift, it might be necessary to adjust staff capacities to react to unpredicted demand fluctuations and staff absenteeism.

3.2.3 Capacity dimensioning

At the strategic level, ambulatory care facilities dimension their resources, such as staff, equipment and space, with the objective to maximize clinic profit, patient satisfaction and staff satisfaction [18]. To this end, provider capacity (rooms, staff, consultation time, equipment) must be matched with patient demand, such that performance measures such as costs, access times and waiting times (that is, the time a patient spends in the waiting room) are controlled. Examples of resource dimensioning outside radiotherapy can be found in [14, 18, 27]. For radiotherapy, Thomas [36] developed a Monte-Carlo simulation model to calculate the percentage of spare capacity required to keep access to treatment short. He found that for a matched pair of linacs, in a department that closes on bank holidays, about 10% spare capacity is required to ensure that 86% of patients are able to start radiotherapy within a week of completing the treatment planning process.

3.2.4 Capacity allocation

In the tactical level, one can look at a statical or dynamical capacity planning of the available resources. Static approaches result in long-term plans that are often cyclical. Dynamic approaches result in intermediate-term plans in response to the variability in demand and supply. When patient demand changes over time (e.g. seasonality), a dynamic capacity planning, updated based on current waiting lists, already planned appointments and expected requests for appointments, performs better in terms of access times and resource utilization than a long-term, static subdivision of resource capacity [39].

In Radiotherapy, Pérez Rivera developed a model to optimally assign patients to linacs based on their cancer type, taking into account that some requests may follow in the future [33]. This is useful because not all linacs are the same, some are only suitable for certain types of patients. By setting a limit to the number of patients of a certain type to be treated on a certain machine, the general access times for all patients can be reduced.

Joustra et al. [20] addressed the question whether to pool (sub)acute and regular patients into different groups for scheduling a first consultation at the Radiotherapy department. The research showed that pooling is not always beneficial with regard to the access times of (sub)acute patients.

Reducing the variability of the capacity is also studied in previous research carried out for the Radiotherapy department of the AMC in 2007. Kolfin [25] made a capacity analysis on the outpatient clinic, preparation machines and the linear accelerators. At the outpatient clinic a strong varying capacity (in terms of the weekly number of consultations for new patients) was recorded, causing the variance in patient flow to be higher after the first consultation than before. The recommendation was to reduce the variability of the weekly number of consultations, later supported by a queueing model of Joustra et al. [22]. The utilization of the machines was high and the preparation time was relatively long. On the occasion of this research, the department decided to buy an extra accelerator and to keep the number of first consultations per week constant.

There are several examples of research in capacity allocation outside the scope of radiotherapy, such as changing a CT scanner's opening hours [39], changing doctor consultation time [14], and the development of a master surgical schedule in operating room departments [38], where operating room capacity is allocated to several specialisms in a cyclic blueprint schedule.

3.2.5 Patient routing

Identifying different patient types and designing customized patient routes for each type, prevents superfluous stages and delays [27]. For example, instead of two visits to a doctor and a medical test in between, some patient types may undergo a medical test before visiting the doctor, which saves valuable doctor time. In radiotherapy, not requiring the same physician to perform all activities in one patient's treatment process could also improve the access time in some cases [32].

3.2.6 Appointment scheduling & patient-to-appointment assignment

Several papers dealt with the problem of scheduling radiotherapy treatments, especially scheduling the radiation sessions. Developing a blueprint schedule can be seen as a tactical problem (appointment scheduling), while scheduling the patients to specific appointments is considered to be an operational problem (patient-to-appointment scheduling). The existing literature has mainly focused on the offline operational planning decision of appointment scheduling. An exception is the research of Sauré that dealt with guidelines for scheduling patients for linac appointments using Markov decision theory [35].

Research on the operational level is characterized by scheduling individual appointment series, where the appointment series have to fit in the existing appointment schedules that are partly filled with already scheduled appointments. Kapamara et al. provided a review of radiotherapy patient scheduling problems (both pre-treatment and treatment, offline as well as online), concluding that this problem is similar to a dynamic stochastic job shop problem [23]. Mathematical models were developed for offline scheduling appointments on the linear accelerators using integer linear programming [7, 11–13, 19] and heuristics [30]. For scheduling the preparation phase using (stochastic) linear programming [29] and mathematical programming and heuristics [8] were used. The objective in these models is to schedule as many patients as possible in a short period of time (e.g. one week), considering treatment slots of equal length and one type of linac. However, the above mentioned models do not consider all the constraints imposed on real-world radiotherapy scheduling.

A comprehensive survey of research on appointment scheduling in outpatient services in other departments is given by Cayirli et al. [9]. Most of the research is about single appointment scheduling, often in combination with no shows or appointment cancellations. Generally, outpatient clinics have the objective of minimizing the waiting time (time spent in the waiting room), which is not of main concern in our research. However, there are similar scheduling problems that require combination appointments with many different resources and precedence constraints in a multidisciplinary setting, that might be useful to the field of Radiotherapy. Braaksma et al. [6] presented a methodology to plan appointment series and combination appointments for rehabilitation outpatients, based on an integer linear programming formulation. In addition, the combination appointment scheduling in the 'Children's Muscle Center Amsterdam' [37] using integer linear programming and the scheduling of multi-step sequential procedures in nuclear medicine [28] (stochastic linear programming) are both examples of multidisciplinary scheduling within the day, requiring many resources and interrelated appointment constraints. In these articles, the access time is considered as a key performance indicator.

3.3 Logistic decisions in the Radiotherapy department

The current organizational characteristics of the department, as described in Section 2.3, are a result of several decisions on capacity planning and control that are made in the department. Based on the overview of topics of Section 3.2.2 and the process analysis of Section 2, we constructed an overview of the logistical decisions that the department is faced with, subdivided in the levels of capacity planning and control as explained in Section 3.2. We combined the offline (advance) and online (real-time) operational levels, because the questions posed in this operational level can be considered both offline and online. In the column 'literature', the logistic research carried out in Radiotherapy so far is classified according the logistic decisions they address.

3.4 Modelling the treatment process

Modelling in health care is often used to estimate consequences of several scenarios, without actually changing the system, which can be costly and time consuming to perform experiments with. Furthermore it is often used to create understanding across professional and organizational boundaries. In this section, several methods are discussed to model the complete treatment process, such that the effects of possible changes in capacity planning and control on the access times could be evaluated.

There are two methods that are often used to model a department: queueing models and simulation models. An example of the use of queueing theory is given in [42], where queuing theory was used to model an anesthesia clinic. The clinic was modeled as a multi-class open queueing network model, which was possible because the arrival process and the service process had the characteristics of a queue with several continuous servers (at least, during the day).

However, the most used technique to model complete departments is simulation and especially discrete-event simulation (DES). Discrete event simulation is the type of modeling where the state variable changes only in discrete times and by discrete time steps, and it is often used to carry out statistical experiments on the computer, where the stochastic variables are drawn by a random generator and the computer program adjusts the variables in discrete time steps. Discrete event simulation has been used in a wide range of applications in health care: outpatient clinics, emergency departments, radiology units, chemotherapy services and also in radiotherapy. Günal et al. provided an overview of discrete event simulation models used in health care [15]. Sometimes a combination of the two methods is used (for example: [14]).

Since the radiotherapy treatment process consists of many different stages with precedence relations and scheduling constraints, a queueing model is not able to capture the working of the complete treatment process in a detailed way and to accurately show the effect of changes on the access times. Therefore (parts of) the radiotherapy treatment process are often modeled as a discrete-event simulation. For the UK, Proctor et al. modeled the preparation and treatment [32] and Kapamara a treatment process using Simul8 software [24]. Werker et al. [40] built a simulation model for the preparation and treatment in Canada using Arena simulation software. The simulations differ in level of detail and the treatment process is slightly different from the one we observe. In the literature we could not find any research that used Plant Simulation software for modelling in health care.

Strategic (long term) planning		Literature
Capacity dimensioning	How many machines (of which type), rooms and equipment to buy/build?	[36]
	How many doctors (with which focus areas) and other staff to hire?	
	How many locations for facilities to open and where?	
	Which service mix to provide and which population size/case mix to serve?	
Tactical (mid term) planning		
Patient routing	Should the contouring for a patient be done by the same doctor that did the consultation?	[32]
	Should the patient be discussed in two doctors' meetings and/or a multi-disciplinary meeting?	
	Should the CT-sim appointment take place at the same day as the consultation?	
Capacity allocation	What should the opening days and hours of the machines be? (Should testing and maintenance be done during the day?)	
	How many doctors to station in each location?	
	Should the contouring be done according to a scheme or should the doctors manage their contouring time themselves?	
	Should consultations and contouring be carried out according to a cyclic schedule?	
	How many consultations and how much contouring time to plan?	[22]
	Should capacity be reserved for specific patient types or treatment intents? (for example one stop shop appointments)	[17, 20]
	Should guidelines be used for taking over consultations in case of absence?	[22]
Capacity allocation (doctors' scheme)	How many consultations to schedule for each doctor on each location?	
	How many contouring moments to schedule for each doctor on each location?	
	At which moments should each doctor have consultations and contouring moments?	
	Which patient types should be treated by which doctors?	
Admission control	Should some patient types be treated with priority? (e.g. acute/subacute patients)	
	Should patients be advised in their treatment location choice, when and how?	
Appointment scheduling	Should all appointments for a patient be scheduled at once, or should it be done in parts?	
	Should appointments be scheduled as they come (online) or once per time period (offline)?	
	Which patient types should be treated by which doctors?	
	Which patient types should be scheduled on which machines?	[33]
	Which guidelines for patient-to-appointment assignment to use? (prescribed number of days between stages, always take first available time slot, etc.)	
Temporary capacity change	When and how to adapt the treatment process in busy periods? (Adapt opening hours, extend number of consultations, location advise)	[17]
Operational (short term) planning		
Staff scheduling	Should we allow this doctor to go on holiday or to a conference?	
Patient-to-app. scheduling	Which consultation slot to assign to a patient?	
	Which time slots for preparation activities (incl. CT-sim) to assign to a patient?	[8, 23, 29]
	Which time slots for linac linac sessions to assign to a patient?	[7, 11–13]

Table 3.1: Capacity planning and control decisions in the Radiotherapy department

3.5 Conclusion literature review

In this chapter, we provided an overview of logistic planning issues that the management of the Radiotherapy department is faced with and that possibly influence the access times, together with the relevant scientific literature on capacity planning and control in Radiotherapy and similar processes. The conclusion is that the Radiotherapy treatment process is a broad and complex system, where many logistic decisions play a role that are often closely related.

We found that literature on capacity planning and control in Radiotherapy has mainly focused on the operational planning level and on (small) parts of the treatment process, for example the patient-to-appointment assignment on treatment machines. Many tactical questions in the radiotherapy treatment process have not been addressed in literature so far, for example on doctor capacity allocation and determining blueprints for appointment scheduling. Research in the field of appointment planning and patient-to-appointment assignment outside radiotherapy can be useful for this, because other care processes such as for rehabilitation care or neuromuscular diseases show similarities with the radiotherapy treatment process in a multidisciplinary nature and the use of different resources. The coming section reveals that our contribution to the literature will be on the capacity allocation topic, in the form of the design and evaluation of an optimal doctors' scheme.

Additionally, some methods were discussed to investigate the effects of capacity planning and control decisions on the access times of the complete treatment process. Discrete-event simulation is the most used method in literature and is suitable to capture the detailed nature of the treatment process in a model.

Chapter 4

Bottlenecks in the treatment process

To find the bottleneck(s) in the treatment process, we will first analyze the current access time performance to get an impression what factors are important for the access time (Section 4.1). From literature we know that strategic decisions provide a framework for the logistical layout of the treatment process and therefore we will consider them first. In this case, the strategic questions are primarily regarding the capacity: what is the current capacity utilization and is it in general enough to serve all the patients? Once this is known, we can address tactical questions, for example: is the current capacity allocation a bottleneck, are the current used scheduling methods delaying the treatment? Therefore, in the following sections we will first focus on the capacity utilization of the stages (Section 4.2), followed by an analysis to determine whether the current available capacity is in general enough to serve the patient flow in Section 4.3. After that we will focus on the way the capacity of certain stages is allocated by the department (Section 4.4).

4.1 Access time performance

As stated before, the access time is the sum of the entry time and the preparation time. Data about the entry time is derived from X-Care, an information system for clinical appointments used by the AMC. Data about the preparation time is derived from Mosaiq, a system for storing information about the preparation phase and the treatment.

4.1.1 Treatment pathways

The numbers of first consultations and treatments that have been carried out in 2011 and 2012 for acute, subacute and regular patients are listed In Table 4.1. Besides the AMC and Flevo hospital, first consultations can also take place in the Zuiderzee hospital (ZZZ) in Lelystad and Onze Lieve Vrouwe Gasthuis (OLVG) in Amsterdam. If these patients continue their treatment, it takes place in the AMC or Flevo hospital.

The number of the first consultations and the treatments are not equal, since not all patients receive external beam treatment after the first consultation and patients can also enter the department via another consultation or a multidisciplinary meeting. The GIOCA and surgery

		First consultations		Treatments	
		No.	Percentage	No.	Percentage
2011	AMC	1384	67%	1566	70%
	FLEVO	507	25%	663	30%
	ZZZ	131	6%	0	
	OLVG	36	2%	0	
	Total	2058	100%	2229	100%
2012	AMC	1335	67%	1283	70%
	FLEVO	504	25%	737	30%
	ZZZ	141	7%	0	
	OLVG	4	1%	0	
	Total	1984	100%	2020	100%

Table 4.1: Number of first consultations (standard and OSS) and treatments. Source: X-Care and Mosaiq

consultations are not arranged by the department. The information to determine the entry time of these patients is not known.

The treatment pathways of all patients with an entry time and/or a preparation time can be found in Table 4.2. The 'x' denotes that patients following this treatment pathway have an entry and/or preparation time; a '-' denotes that they do not have one or that it is not registered by the department. The patients in this scheme can either have an acute, subacute or regular priority. Recall that an OSS (one stop shop) consultation means that the first consultation, the preparation and the start of the treatment take place at one day.

Treatment pathway	**Possible at location**	**ET**	**PT**	**No.**	**Total**
Referral → First consultation	Both	x	-	350	
Referral → First consultation → Brachy/hyperthermia	AMC	x	-	339	689 (23%)
Referral → First consultation → Linac treatment	Both	x	x	1406	
Referral → OSS consultation (incl. linac treatment)	AMC	x	x	216	1622 (55%)
Other consultation → Linac treatment	AMC	-	x	157	
Follow up consultation → Linac treatment	Both	-	x	104	
Multidisciplinary meeting → Linac treatment	Both	-	x	380	641 (22%)

Table 4.2: Possible treatment pathways of patients with an entry time (ET) and/or preparation time (PT) and the number of patients in 2012, derived from X-Care and Mosaiq

4.1.2 Evaluation of the national standards

To evaluate the national standards, it is necessary to link the entry times and preparation times for specific patients. However, the information systems that record the entry times and the preparation times are not linked automatically. From X-Care the entry times are known, but the diagnoses and priorities of the patients are not recorded, and it is also not registered whether the consultation is OSS or standard and whether a patient continues treatment or not. In Mosaiq it is not recorded how a patient entered the treatment (by a standard or OSS first consultation, GIOCA or follow up consultation) and when this consultation took place. Therefore we can not distinguish acute from subacute patients in a systematic manner and it is not straightforward to connect information about the entry time and preparation time for specific patients and patient

		Subacute		**Regular**		
		≤ 7 days	≤ 10 days	≤ 21 days	≤ 28 days	Total no.
	Norm	80%	100%	80%	100%	
2011	AMC	62%	71%	27%	57%	941
	Flevo	41%	59%	13%	38%	380
	Total	56%	68 %	23%	51%	1321
2012	AMC	56%	64%	17%	44%	737
	Flevo	37%	57%	17%	38%	403
	Total	50%	62%	17%	42%	1140

Table 4.3: Estimated performance on the access time norms, obtained by matching data from X-Care and Mosaiq

types in a systematic manner. Reconstructing the access times is therefore a time-consuming task that is prone for errors.

The evaluation of the national standards (norms) as stated in Section 1.2 can be found in Table 4.3. Especially the performance for regular patients is much lower than the norm. The AMC performs better for subacute patients than the Flevo hospital, most likely because of the OSS consultations that only take place in the AMC. Note that the performance in 2012 was worse than in 2011 although less patients were treated. This is most likely due to the closure of one linac in the AMC between September and December 2012.

As described above, the data of the subacute patients also contains some of the acute patients (the management estimated that 5% of the total number of patients is acute), implying higher percentages of subacute patients in above table than should be the case. We further note that, since we could not distinguish elective delays in the data other than taking the entry times above 40 days and preparation times above 90 days out of the data set, the percentages of both groups may be biased.

4.1.3 Access times per patient group

In Table 4.4 the access times are listed per patient group, together with the entry times and preparation times of patients that follow the treatment process from consultation to linac sessions. A graphical overview can be found in Figure 4.1. More information about the aggregation of diagnoses into patient groups will be provided later in Section 4.4. The access time per diagnosis can be found in Appendix A.2.

Note that the access time is slightly more than the sum of the entry time and the preparation time in most cases, because the date that we take as starting point for the preparation time, is in practice often the day after the consultation; in the access time, this day is counted as well. The assumption that the booking date is the same as the referral date is normally true, but these dates can differ from each other if a decision upon the allocation to a physician is made the next day.

We note that especially some large patient groups have high access times, for example the mamma (that is, breast) patients and the ‘urology with gold beads’ patients. The access times of the ‘mamma with surgery’ group may be biased by the fact that often a surgery is performed just before or after the first consultation and some recovery time might be taken into account. According to the definition of the norm, these patients should not be counted in the norm. However, for us it was not possible to take these patients out of the data set, since it is not registered which patients have undergone surgery and how this surgery influences the measured mean access time. On the other hand, we know that ‘mamma with plan/mal’ patients are

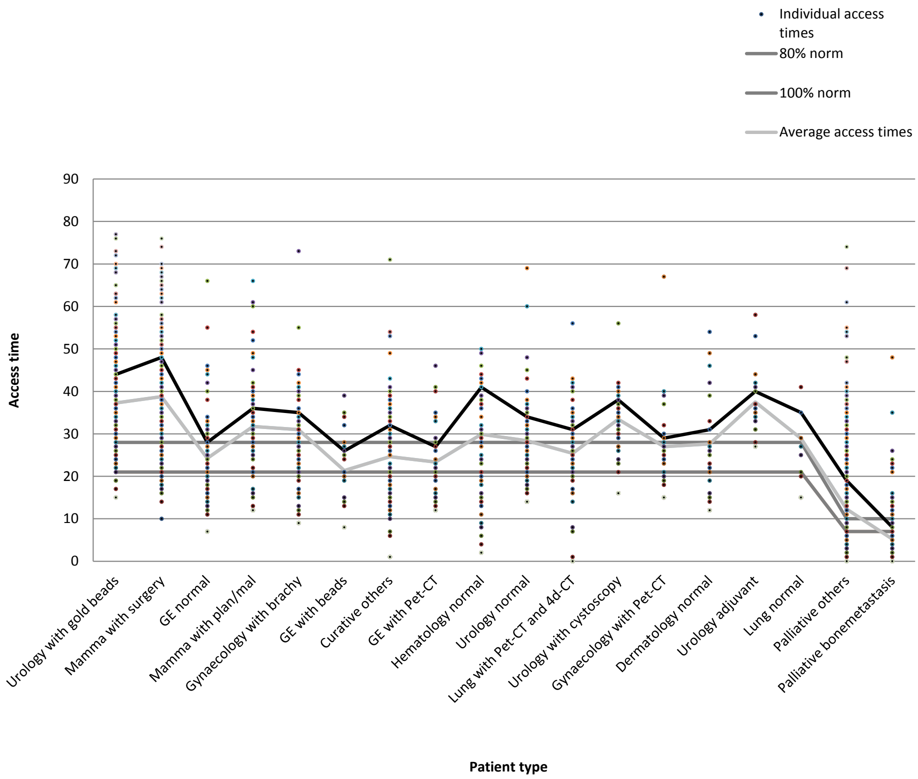


Figure 4.1: Access times per patient type in calendar days, in 2011-2012

	AMC				**Flevo**			
Patient group	No.	ET	PT	AT	No.	ET	PT	AT
Curative others	74	5.4	19.6	25.6	12	3.5	15.1	19.0
GE with beads	79	0.9	19.8	21.6	12	0.6	18.7	19.9
GE with Pet-CT	54	2.9	20.4	23.9	9	1.3	18.2	19.9
GE normal	124	4.6	19.9	25.0	64	5.8	16.4	22.8
Gynaecology with Pet-CT	30	5.1	21.4	27.0	-	-	-	-
Dermatology normal	19	6.1	21.2	27.6	9	5.3	21.9	27.8
Urology normal	46	5.7	21.6	27.7	23	7.4	22.1	29.9
Lung with Pet-CT and 4d-CT	45	6.2	21.8	28.3	33	3.8	17.4	21.5
Hematology normal	52	14.8	15.3	30.3	8	6.1	21.3	27.4
Lung normal	7	8.9	23.1	32.6	3	4.7	15.7	20.3
Gynaecology with brachy	81	6.5	23.8	31.0	-	-	-	-
Mamma with plan/mal	91	8.2	22.9	31.7	-	-	-	-
Urology with cystoscopy	36	6.4	25.7	32.8	5	9.2	27.2	38.4
Mamma with surgery	177	12.2	21.6	34.2	283	16.4	24.5	41.6
Urology with gold beads	242	7.3	28.9	36.8	88	9.0	28.9	38.5
Urology adjuvant	16	7.4	27.8	38.1	2	5.0	24.0	32.5
Palliative bonemetastasis	186	3.6	0.7	4.3	51	4.2	3.6	8.5
Palliative others	319	4.3	8.1	12.9	180	4.0	6.8	11.2
Unknown	264	5.0	11.6	17.0	202	6.1	13.2	19.8
Total	1942	6.0	16.8	23.3	984	8.6	17.1	26.3

Table 4.4: Patient groups with their mean entry (ET), preparation (PT) and access times (AT) in 2011-2012, ranked on access time in the AMC

patients who receive a retreatment and therefore they do not undergo surgery. So the access times for the ‘mamma with plan/mal’ group are quite reliable on that point and they are a good indication for the actual ‘mamma with surgery’ access times, since the steps and time constraints only differ from each other in the plan/mal check.

4.1.4 Fluctuations in entry and preparation time

In Figure 4.2 the number of referrals per month for 2011 and 2012 can be seen and in Figure 4.3 the mean entry times per month are shown for the AMC and Flevo hospital. Although the arrival process and the mean entry times fluctuate per month, we do not observe significant seasonal trends. Table 4.5 provides the average entry times for referrals on different days in the week are displayed. The mean entry times on different days of arrival fluctuate. The fact that on Friday the entry times are higher than on other days is due to the department’s closure in the weekend. In the Flevo hospital there are normally no consultation slots on Friday: this explains the high entry times for patients referred on a Thursday.

	AMC		**Flevo**	
Referral day	Entry time	No. of patients	Entry time	No. of patients
Monday	5.6	278	5.3	88
Tuesday	5.7	264	6.0	115
Wednesday	6.8	232	5.1	92
Thursday	6.4	289	7.4	114
Friday	6.5	272	6.9	95
Total	6.2	1335	6.1	504

Table 4.5: Average entry times in calendar days, per referral day 2012 (Source: X-Care)

In Figure 4.4 the mean preparation times per month are shown for the AMC and Flevo hospital. The preparation times fluctuate between eleven and 21 days. In the beginning of 2012 the preparation times were relatively short and they increased in both hospitals over the first half year. According to the department, this can partly be explained by the introduction of a new types of radiation treatments for urology patients.

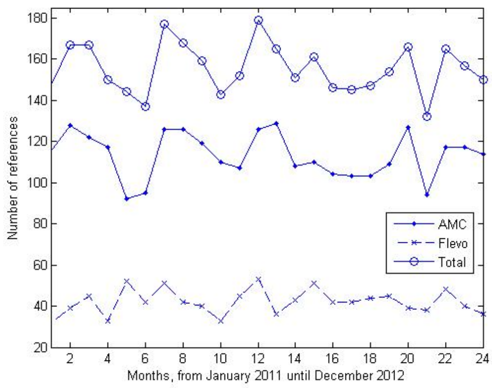


Figure 4.2: Number of referrals per month in 2011 and 2012 (Source: X-Care)

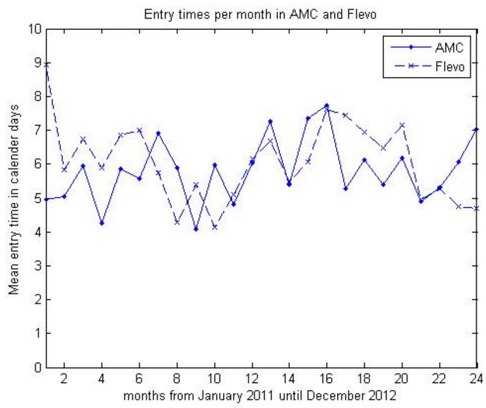


Figure 4.3: Mean entry times per month in 2011 and 2012 (Source: X-Care)

Location	Referrals Average	Referrals St.dev	Realized consultations Average	Realized consultations St.dev	Available consultations Average	Available consultations St.dev	Utilization Average
AMC	25.8	7.0	25.6	5.8	31.9	3.9	80%
Flevo	9.7	3.4	9.7	3.3	11.8	0.9	82%

Table 4.6: Number of referrals and consultations per week in 2012 (Source: doctors' schemes and Mosaiq)

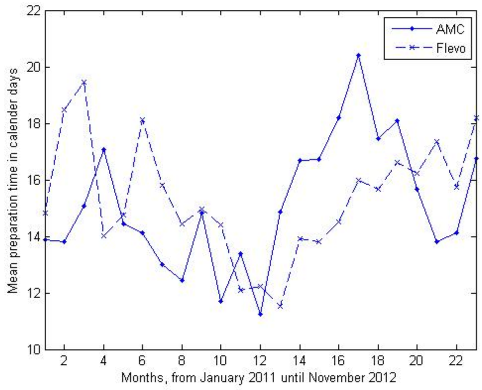


Figure 4.4: Mean preparation times per month in 2011 and 2012 (Source: Mosaiq)

4.2 Capacity and utilization

In the treatment process, a variety of resources is used: machines (CT-sim and linacs), personnel (physicians, physician assistants, physicians in training, planning staff and laboratory technicians), rooms for first consultations and equipment (licenses for the contouring software and treatment planning software). After observing the current performance of the department with respect to the access times in Section 4.1, we know from Section 3.3 that decisions on the strategic level are often long term and define the framework for decision making in the tactical and operational level. Decisions on the tactical level translates strategic planning decisions to guidelines that facilitate operational planning decisions. In addressing our objective (the reduction of the access times), it would therefore be good to start with the strategic question: is there enough capacity available? In this section, we will analyze the current utilization of the available capacity.

4.2.1 Consultations

For the first consultations we choose to express the capacity as the number of first consultation time slots week. The utilization of the first consultations can be determined by observing the number of referrals ('demand') and the number of consultation time slots per week ('supply'). To analyse the latter, we used the weekly schemes of physicians of the last year. Besides the standard first consultations, one OSS appointment takes place each day in the AMC, which is also counted as an available consultation. The number of referrals, the number of realized consultations and the number of available consultations per week are given in Table 4.6.

Day	**AMC** Referrals	First consultations	**Flevo** Referrals	First consultations
Mon	278	316	88	125
Tue	264	365	115	104
Wed	232	191	92	107
Thu	289	254	114	92
Fri	272	209	95	76
Total	1335	1335	504	504

Table 4.7: Number of referrals and consultations per day in 2012 (Source: X-Care)

It can be seen in Table 4.6 that the variation in number of first consultations is slightly smaller in general than the variation in patient arrivals. Variation is mostly due to absence (holidays or conferences) for physicians and the physicians in training have a part of their education outside the AMC. Due to internships elsewhere, a physician in training can be absent for longer periods. Compensation for these absences is not always arranged, only when the entry times really get out of hand.

If we look at a more detailed level, we see that the number of referrals and the number of realized consultations differ per day (Table 4.7). The first possibility for a referred patient to have a consultation is the next working day, but from the table we can see that the number of realized consultations is not similar to the number of referrals on the day before.

4.2.2 CT-simulator

The opening hours of the CT-sim in the AMC are 10:30 until 12:00 and 13:00 until 15:30 on all working days except Wednesday, when it is 10:30 until 12:30 o'clock. In the Flevo hospital the CT-sim is opened between 13:30 and 15:30 o'clock on working days. In the weekend, the CT-sims are closed. Maintenance is done outside the opening hours. On certain holidays the hospital is closed, but sometimes this is compensated by opening on Saturdays or Sundays. In 2012 this resulted in 258 opening days instead of the expected 260 opening days.

If the machines were always working, they would be open for seven days a week, 24 hours a day. The departments' policy is that the CT-sim and linac are open on certain parts of the day, so only at those moments there is personnel available to use the machinery. An overview of this data can be found in Table 4.8. According to the department, the decision to open the CT-sim only for such a small amount of time is not based on the demand but on the current limited availability of suitable laboratory technicians that can operate the machinery. The number of laboratory technicians is low and in the morning they often have meetings to attend.

	CT-sim		**Linacs**		
	AMC (1 unit)	Flevo (1 unit)	AMC (4 units)	(3 units)	Flevo (2 units)
Maximal weekly capacity (h)	168	168	672	504	336
Weekly opening hours (h)	18	10	128	85.5	76
Opening percentage	11%	6%	19%	13%	23%

Table 4.8: Weekly opening hours of the machinery, compared to the maximal weekly capacity

In Table 4.9 the utilization of the CT-simulators with respect to the opening hours is displayed.

	CT-sim		**Linacs (6 units)**		**Linacs (5 units)**	
	AMC	Flevo	AMC	Flevo	AMC	Flevo
Total yearly duration sessions (h)	719	310	5564	2252	4556	3326
Total yearly opening hours (h)	936	528	6656	3952	4446	3952
Utilization	77%	59%	84%	57%	102%	84%

Table 4.9: CT-sim and linac utilization in 2012 (Source: Mosaiq)

4.2.3 Linear accelerators

In the AMC, four linacs are available (units 1-4) and in the Flevo hospital there are two (units 5 and 6). The current opening hours for the linacs are from 8:00 until 16:30 o'clock at both locations on working days, but in there is extension possible until 17:30 o'clock. This extension is only used in busy periods. In the weekend the machines are closed. Each linac is in maintenance one morning each week (8:00-12:30) and at unit 3 and 4 there are physical tests going on one morning each week, not at the same time. On certain holidays the hospital is closed, but sometimes this is compensated by opening on Saturdays or Sundays. Unit 1 is currently out of order, since September 2012 (week 37). An overview of the opening percentages of the linacs can be found in Table 4.8.

The linacs have different characteristics, making them useful for subtypes of radiation treatments and cancer sites. Therefore not every patient can be treated on each linac. In the AMC, unit 2 is the oldest one and doesn't contain cone beam scan. In practice it is used as a reserve unit in case the other machines are in maintenance or used by tests: in that case the laboratory technicians temporarily move with these patients to unit 2. Also acute and subacute patients are normally scheduled on unit 2.

To determine the utilization for the linear accelerators, we divided the total demand by the scheduled availability of the linear accelerators. In Table 4.9 the utilization of the machines compared to the opening hours is displayed. The scheduling of patients on linacs is restricted to the availability of a sequence of sessions on consecutive days and certain patients can only be treated on certain linacs, treatments for regular patients do not start on Friday, patients have to be treated at the same machine for 75% of the time. From the table it can be seen that the utilization of the linacs in the AMC after closure of Unit 1 exceeds 100%. This reflects that overwork has been done regularly. If we state the opening hours every day until 17:30 instead of 16:30, this would imply ten hours more per week, so 4966 hours on yearly basis. The utilization of that would be 92%.

Comparing the numbers of patients on the CT-sim and the linacs for 2012, we see that in the AMC on average there have been 12.5 more patients on the CT-sim than on the linacs on weekly basis, which means that on average 12.5 patients either had an extra CT-scan before their treatment or had a CT-scan without having treatment.

4.3 Utilization and queueing effects

From the previous section we know the current utilization of the capacity for the consultations, CT-sim and linacs. The next question is: which consequences do these utilizations of these three processes have on the access times? And hence: are these processes bottlenecks in the treatment process?

In each stage, the arrival rate of patients fluctuates and in the service there is also variability. From queueing theory (the mathematical study of waiting lines) we know that in general it is not wise to match supply and demand exactly (that is, achieve a utilization of 100%) in systems with uncertainty in supply and/or demand, because congestions will be very likely and waiting times will rise accordingly. The relation between utilization and waiting times generally has the shape of Figure 4.5. An introduction to queueing theory can for example be found in [5].

For the Radiotherapy process, it is not possible to calculate the consequences of the utilizations of each stage separately, because they have specific service characteristics and the arrivals at the stages are dependent of the service of the previous stage. However, to provide a global insight in each process, in this section we will assume the processes are independent so that they can be considered separately.

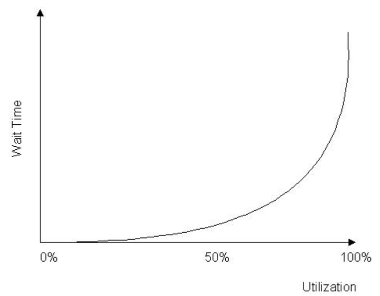


Figure 4.5: An indication of the relation between utilization and waiting time

4.3.1 Consultations

When we look at a weekly level, we see that the number of arriving patients (demand) at both locations differs per week. For the supply, it is the number of available consultations at both locations that determines the number of patients that can be served per week. The duration of each individual appointment is not very important here. We can model this process as one queueing model if we assume that each patient can be seen by each doctor.

The number of arriving patients per week in 2012 fitted a Poisson distribution (see Figure 4.6), which could be expected since patients arrive independently from each other. The number of available consultations varies per week, due to holidays, conferences and illness of doctors and is usually independent of the patients' arrival process. The number of available consultations in the AMC fits a general distribution. Although the consultations are carried out by about twenty doctors, they do not often work simultaneously, so for simplicity we assume there is only one server. The two locations work quite independently from each other, therefore two separate M/G/1-queues are used to model them (that is, a queue with Poisson distributed arrivals, general distributed services and one server). Calculations in Appendix A.3 show that the mean waiting time for an M/G/1-model with the departments characteristics is less than a day in general on

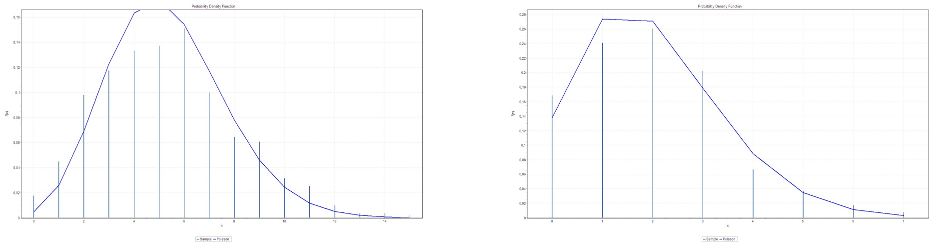


Figure 4.6: Arrival process of referrals in AMC (left) and Flevo (right)

both locations. In practice, the mean waiting time (in our case, this has the meaning of the time a patient is delayed at one certain stage due to queueing effects) might be larger since patient types can only be treated by doctors within their focus area, service is not done continuously, the weekends are also counted as waiting time and the consultations may not be spread evenly over the week.

Joustra et al. [21] stated that a reduction of the variability in the number of consultation time slots would reduce the entry time, because a M/D/1-model (where the D stands for deterministic service) with the same utilization rate performes better in terms of the mean waiting time than a M/G/1-model. Since the department can influence the weekly number of consultation time slots to a large extent, the recommendation of Joustra to the management of the Radiotherapy department was to reduce the variability of the number of consultations.

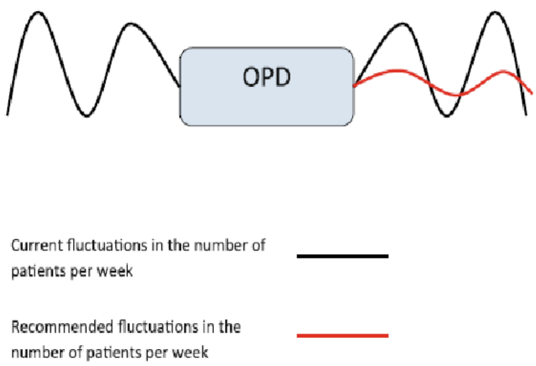
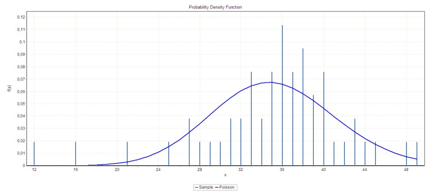


Figure 4.7: Level of fluctuations in the outpatient department (OPD), as displayed in [21]

4.3.2 CT-simulator

If we again look at a weekly level, we see that the number of arriving patients (demand) at the CT-sim varies per week and the number of patients that are served per week varies as well. Although the number of requests for appointments on the CT-sim depends on the service in the outpatient department, we assume the weekly number of requests for appointments on the CT-sim on each location also has a Poisson distribution (see Figure 4.8). For the service, the number of patients that have a CT-sim appointment each week is determined by the scheduled



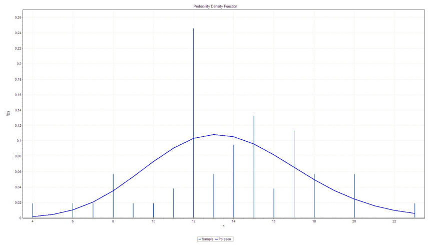


Figure 4.8: Arrival process at the CT in AMC (left) and Flevo (right)

duration of the appointments. The length of the appointments lies between 5 and 60 minutes.

The CT-sims on the two locations work independently from each other. Each CT-sim can therefore be represented by a M/G/1-model, that is, a model with Poisson arrivals, general services times (that is, service times that may have any distribution) and one server (the CT-sim). Calculations in Appendix A.3 show that the mean waiting time for an M/G/1-model with the department's arrival and service rate is less than a day on both locations. In practice, this mean waiting time might be slightly more because the weekends are also counted as waiting time, the facility closes at the end of each working day and the facility has limited opening hours on Wednesdays.

4.3.3 Linear accelerators

The number of arriving patients (demand) at the linacs varies per week and depends on the service at the CT-sim. For the service, the number of patients that are treated on the linac each week is determined by the scheduled number of the appointments and their duration. The complicating factor for modelling the linacs in a queueing model, is that the linacs do not all have the same characteristics and the treatment consists of sessions on consecutive days, that have to be planned on the same machine each day. Combining the duration of all the sessions to one large session and model the linacs as a M/G/n-queue (n the number of linacs) would be an option, but we expect the time constraints for treatment on consecutive days to have a large influence on the use of the linac. For example: if there are no sessions at all scheduled on Monday but the Tuesday is fully booked, the patient can still not be treated on Monday - so it can be possible that waiting times for the linacs build up while the utilization is relatively low. Therefore, we have decided not to perform these analytic calculations but to search for alternatives to get insight in the effects of the utilization rate of the linacs.

We found that a Monte-Carlo model was developed by Thomas [36] to calculate the percentage of spare capacity required to keep waiting times to treatment short. For a matched pair of linacs it turned out that, in a department that operates on working days, about 90% utilization is required to ensure that 86% of patients are able to start radiotherapy within a week of completing the treatment planning process. Although the characteristics of our treatment system might be different from the study of Thomas (who considered a hospital the UK), we can roughly say that with a utilization of 88% in the AMC, the queueing effects at the linacs have a larger influence on the access times than the other considered processes. This was definitely the case in the end of 2012 in the AMC, when the utilization was 102%. In this case, the waiting times rise extensively.

To determine the precise consequences of the current utilization in terms of expected waiting times for the linacs in the treatment process of the AMC, further reseach is required.

4.3.4 Conclusion utilization and queueing effects

The capacity of the CT-sim at both locations is in general enough to avoid congestions and to serve all patients within a day. The number of consultations is in general enough to serve all patients within a day, but patients might be delayed if they can not be treated by all doctors. In the AMC, the queueing effects for the linacs are a larger bottleneck than the consultations and the CT-sim. When only three linacs are operating, the waiting times are expected to rise extensively and in this case, the linacs are the largest bottleneck for the access times.

4.4 Bottleneck analysis

As we have seen in Section 4.3, queueing effects arise for the consultations, CT-sim and linacs. But this does explain the whole length of the access time. From literature we know that not only the capacity dimensioning is important for the performance of a facility, but also the organizational characteristics of a facility; amongst others, the capacity allocation and scheduling rules.

In this section we will investigate the contribution of these organizational characteristics on the access time. This can be done as follows. The protocols per patient type, that prescribe the stages a patient has to pass through and the minimum prescribed time between them, imply an absolute minimum access time for each patient type (that is, the minimal access times as medically prescribed). This is observed in Section 4.4.1. In practice however, not all stages are available on each day of the week and the department puts restrictions on which doctor treats which type of patients. The actual 'lower bound' of the access time (that is, the shortest possible access time for a patient, in the organizational characteristics of the department) is therefore higher than the medical minimum; this will be calculated in Section 4.4.2. In Section 4.4.3 the realized access times will be compared to the lower bounds.

4.4.1 Patient groups and medical minima of the access times

For simplifying purposes, we clustered the different diagnoses into groups. For each patient type there is a protocol prescribing the stages that need to be performed and the time constraints for scheduling the appointments. We grouped patient types together based on focus area and similar protocols, that is stages the patient has to pass through and the time constraints between them. The number of radiation sessions is not considered in the clustering, because we are interested in the access time and therefore only the first linac session is relevant. An overview of the groups and their protocols can be found in Table 4.10 and a list of the patient types in these groups can be found in Appendix A.2.

For patient types that pass through the treatment process without additional stages, the stages could (medically seen) all take place at one day. For patients that need beads implementation, a cystoscopy or a 4d-CT-scan, a minimum number of days has to be taken in account to recover from the procedure or to neutralize the effect of the former procedure. An overview of the medical minima of the access times can be found in Table 4.12.

4.4.2 Lower bound of the access times

In this section, the lower bound for the access time is calculated for the different patient groups. This lower bound is the shortest access time that is possible for a patient in the current logistical layout of the department. This means that we observe the radiotherapy process with the current doctors' scheme and the guidelines for scheduling used at the department.

Patient group	**No.**	**Trajectory after first consultation**
Dermatology normal	19	CT-sim, contour, preparation, start
GE normal	131	CT-sim, contour, preparation, start
GE with beads	81	Beads, wait 3 days, CT-sim, contour, preparation, start
GE with Pet-CT	52	Pet-CT, CT-sim, contour, preparation, start
Gynaecology with brachy	55	CT-sim, contour, preparation, start
Gynaecology with Pet-CT	10	Pet-CT, CT-sim, contour, preparation, start
Hematology normal	32	CT-sim, contour, preparation, start
Lung normal	5	CT-sim, contour, preparation, start
Lung with Pet-CT and 4d-CT	46	Pet-CT, next day 4d-CT, contour, preparation, start
Mamma with surgery	290	CT-sim, contour, preparation, start
Mamma with plan/mal	58	CT-sim, contour, preparation, plan/mal one day before start, start
Urology normal	36	CT-sim, contour, preparation, start
Urology with gold beads	157	Gold beads, wait 3 days, CT-sim, contour, preparation, start
Urology with cystoscopy	29	Cystoscopy, wait 1-3 days, CT-sim, contour, preparation, start
Urology adjuvant	13	CT-sim, contour, preparation, start and start adjuvant therapy
Curative others	62	CT-sim, contour, preparation, start
Palliative bonemetastatis	204	CT-sim, contour, preparation, start
Palliative others	345	CT-sim, contour, preparation, start
Unknown	395	-
Total	2020	-

Table 4.10: Overview of patient groups, yearly treatment numbers (2012) and protocols

For each patient group we determined the dates of different appointments, given their referral day and treatment location. We used the following guidelines for the planning process that reflect the current scheduling rules in the department:

- Physicians only treat patients in their own focus area or subacute patients (AMC), or all patient types (Flevo).
- A patient sees the first available physician specialized in their type (next day is first possibility).
- The day after first consultation, patient is discussed in physicians' meeting; after this, the planning of the other appointments takes place (next day is the first possibility).
- Once a patient is allocated to a physician, this physician does the contouring as well.
- If there are no time constraints between stages, at most two stages take place at one day.
- Treatment for regular patients cannot start on Friday.

The following time constraints have to be taken into account:

- Between (gold) beads implementation and CT-sim should be at least three days.
- Between Pet-CT and 4d-CT should be at least one day.
- Between cystoscopy and CT-sim should be at least one day.
- The number of days between contouring and start of the treatment is five (AMC) or six (Flevo). This extra day is scheduled to allow enough time to transport the (paper) patient files from one hospital to another.

Stage	**Department**	**Available in AMC**	**Available in Flevo**
Consultation	Radiotherapy	Fixed day per physician	Fixed days per physician
Contouring	Radiotherapy	Fixed day per physician	Fixed days per physician
Treatment	Radiotherapy	Regular pt do not start on Friday	Regular pt do not start on Friday
CT-sim	Radiotherapy	Working days	Working days
4d-CT	Radiotherapy	Working days	Working days
Moulding	Radiotherapy	Each afternoon	Each morning
Gold beads	Radiotherapy	Monday morning	Not possible
Beads	Endoscopy	On request	Not possible
Pet-CT	Nuclear medicine	Wednesday morning	Not possible
MRI	Radiology	On request	On request
Cystoscopy	Endoscopy	On request	Not possible

Table 4.11: Availability of the stages

For some patients, the treatment has to be tuned with chemotherapy, hyperthermia or brachytherapy. Since we do not have a good overview of the constraints of these treatments (the preparation time of the chemotherapy medicines, any preparational visits to the brachytherapist, fixed days for treatment) we do not take any constraints into account with respect to the requirements of these treatments.

In Table 4.11 it can be seen which stage takes place at which moments in the week. 'On request' means that there are no special time slots reserved for Radiotherapy patients, but the stages are available on all working days. Based on the focus areas of physicians, a table of which physician treats which group is made (Table A.5), based on the current situation, at both locations. Although the physician assistants change during the year due to internships in several hospitals, we took a blueprint for the weekly schemes of physicians as a starting point, see Table 4.9.

With this information, the lower bounds were calculated for all patient types on all referral days on both locations. Calculating the lower bounds was done manually at first, but later a model was developed to do this. (The model will be presented in Section 5.2.3.) The data of the lower bounds and the measured preparation times in 2011 can be seen in Tables 4.12 and 4.13. In these tables, it can be seen that the lower bound is already quite high compared to the realized data. Some remarks:

- The lower bound for the 'urology with gold beads' patients is 21.6 (AMC) or 21.6 (Flevo) days, which means that in the current working methods the national standards can never be achieved for these patients.
- There is no realized data for 'gynaecology with brachy', 'gynaecology with Pet-CT', 'GE with Pet-CT' and 'mamma with plan/mal' patients in the Flevo hospital, because they are generally treated in the AMC since they need brachytherapy, a Pet-CT scan and hyperthermia respectively which are only done in the AMC.
- For some patient groups, the difference between the lower bound and the realized access times is really high, for example 'mamma with surgery' and urology patients. Recall that the realized data for the 'mamma with surgery' patients may be biased because of surgery recovery.

	Mon		Tue		Wed		Thu		Fri	
Doctor 1			A(2)		A	A				
Doctor 2										
Doctor 3	A		A(1*)		A					
Doctor 4	F(1')		F(1)				A	A		
Doctor 5	A(3)				A	A			F(2)	
Doctor 6			A		A(2)		A(1)			
Doctor 7	A	F(1*)								
Doctor 8	A(3)					A				
Doctor 9					F(2)		A(1)			A
Doctor 10		A			A		F(1)			
Doctor 11				A(1)				A		
Doctor 12		F(2)	A							A
Doctor 13				F(2)	F(1)					A
Doctor 14	A	A		A(2)			A	A	A(1)	
Doctor 15		F(2)					F	F(2)	F	F
Doctor 16			A(2)				A	A		A(2)
Doctor 17				A(2)			A	A		A(2)
Doctor 18		A(2)			A				A(1)	
Doctor 19		A(2)							A	A
Doctor 20	A(2)							A(2)	A	A

A(n)	n consultations in AMC
F(n)	n consultations in Flevo
A	Contouring in AMC
F	Contouring in Flevo
*	Only in even weeks
'	Only in odd weeks

	Mon	Tue	Wed	Thu	Fri	Tot
Consultations AMC	12	9,5	2	4	6	33,5
Consultations Flevo	5	3	3	3	2	16
Contouring	5	2	8	10	9	34

Scheme of December 2012

Figure 4.9: Blueprint of weekly doctors' scheme, version December 2012

AMC	**Access time**			**Entry time**			**Preparation time**		
Patient group	Min.	Bound	Real	Min.	Bound	Real	Min.	Bound	Real
Dermatology normal	0	13.5	27.6	0	2.0	6.1	0	11.5	21.2
GE normal	0	14.7	25.0	0	2.0	4.6	0	12.7	19.9
GE with Pet-CT	0	20.1	23.9	0	2.0	2.9	0	18.1	20.4
GE with beads	3	18.5	21.6	0	2.0	0.9	3	16.5	19.8
Gynaecology with brachy	0	16.1	31.0	0	1.6	6.5	0	14.5	23.8
Gynaecology with Pet-CT	0	18.5	27.0	0	1.6	5.1	0	16.9	21.4
Hematology normal	0	14.1	30.3	0	2.0	14.8	0	12.1	15.3
Lung normal	0	16.8	32.6	0	1.6	8.9	0	15.2	23.1
Lung with Pet-CT and 4d-CT	1	19.0	28.3	0	1.6	6.2	1	17.4	21.8
Mamma with surgery	0	14.4	34.2	0	2.0	12.2	0	12.4	21.6
Mamma with plan/mal	0	15.7	31.7	0	2.0	8.2	0	13.7	22.9
Urology normal	0	14.9	27.7	0	1.4	5.7	0	13.5	21.6
Urology with gold beads	3	21.6	36.8	0	1.4	7.3	3	20.2	28.9
Urology with cystoscopy	1	16.9	32.8	0	1.4	6.4	1	15.5	25.7
Urology adjuvant	0	14.9	38.1	0	1.4	7.4	0	13.5	27.8
Curative others	0	14.0	25.6	0	2.0	5.4	0	12.0	19.6
Palliative bonemetastasis	0	1.4	4.3	0	1.4	3.6	0	0.0	0.7
Palliative others	0	1.4	12.9	0	1.4	4.3	0	0.0	8.1
Average	0.4	14.8	23.3	0	1.7	6.0	0.4	13.1	16.8

Table 4.12: Medical minima ('Min.'), calculated average lower bounds based on doctors' scheme of December 2012 ('Bound') and realized average access times ('Real') in 2011-2012, in calendar days

Flevo	**Access time**			**Entry time**			**Preparation time**		
Patient group	Min.	Bound	Real	Min.	Bound	Real	Min.	Bound	Real
Dermatology normal	0	14.9	27.8	0	1.4	5.3	0	13.5	21.9
GE normal	0	14.9	22.8	0	1.4	5.8	0	13.5	16.4
GE with Pet-CT	0	20.7		0	1.4	1.3	0	19.3	18.2
GE with beads	3	19.8	19.9	0	1.4	0.6	3	18.4	18.7
Gynaecology with brachy	0	14.9	-	0	1.4	-	0	13.5	-
Gynaecology with Pet-CT	0	19.8	-	0	1.4	-	0	18.4	-
Hematology normal	0	14.9	27.4	0	1.4	6.1	0	13.5	21.3
Lung normal	0	14.9	20.3	0	1.4	4.7	0	13.5	15.7
Lung with Pet-CT and 4d-CT	1	19.8	21.5	0	1.4	3.8	1	18.4	17.4
Mamma with surgery	0	14.9	41.6	0	1.4	16.4	0	13.5	24.5
Mamma with plan/mal	0	16.3	-	0	1.4	-	0	14.9	-
Urology normal	0	14.9	29.9	0	1.4	7.4	0	13.5	22.1
Urology with gold beads	3	21.9	38.5	0	1.4	9.0	3	20.5	28.9
Urology with cystoscopy	1	18.4	38.4	0	1.4	9.2	1	17.0	27.2
Urology adjuvant	0	14.9	32.5	0	1.4	5.0	0	13.5	24.0
Curative others	0	14.9	19.0	0	1.4	3.5	0	13.5	15.1
Palliative bonemetastasis	0	14.3	8.5	0	1.4	4.2	0	12.9	3.6
Palliative others	0	14.3	11.2	0	1.4	4.0	0	12.9	6.8
Average	0.4	16.6	26.3	0	1.4	8.6	0.4	15.2	17.1

Table 4.13: Medical minima ('Min.'), calculated average lower bounds based on doctors' scheme of December 2012 ('Bound') and realized average access times ('Real') in 2011-2012, in calendar days

4.4.3 Lower bound and real access times

In Tables 4.12 and 4.13, also the historical data about the access times is provided for the years 2011-2012. The access times deviate from the lower bounds because doctors and machines can only treat one patient at a time, and therefore queueing effects play a role that cause delays.

The realized entry times are especially high in comparison to the lower bound for hematology and 'mamma with surgery' patients. The preparation times are especially high in comparison to the lower bound for 'urology adjuvant' patients, which can be explained by the fact that tuning the different treatments causes extra delay. For the subacute (palliative) patients in the Flevo hospital, the lower bound is higher than the realized access times: most likely some of these subacute patients were treated as acute patients, without scheduling appointments for them. In this way they have a lower access time than the lower bound because the scheduling procedures were not followed.

4.5 Conclusion bottlenecks in the treatment process

Roughly we could say that the length of the access times in the Radiotherapy department is influenced by:

- the medically required stages a patient has to pass through and the medical prescribed time in between;
- queueing effects (result of capacity dimensioning): the machines can only handle a limited number of patients per day, such that patients are delayed by already scheduled appointments;
- organizational characteristics (result of capacity allocation and scheduling rules): the logistical layout of the treatment process as determined by the department, such as the scheduling rule of a prescribed number of days between contouring and the start of the treatment.

In the last section we have seen that the lower bound is quite high compared to the realized access times. This is an indication that a large part of the access times are due to the characteristics of the department. In Chapter 5 we will describe our approach to design changes in the organizational characteristics such that the lower bound is decreased, and we will explain how to evaluate if these changes causes the average access times to be reduced as well.

Chapter 5

Approach of the research

5.1 Focus of the research

In Section 3.3, an overview was provided of logistic decisions that play a role in the Radiotherapy treatment process and that are often closely related. Based on insights from the access time performance, the bottleneck analysis and the literature review, we decided in cooperation with the Radiotherapy department in the AMC that the focus of this research will be on answering the tactical capacity allocation question: ‘At which moments should each doctor have consultations and contouring moments?’. This questions is relevant in terms of access time performance, and another advantage of changing is the limited impact on the department and the personnel, since it only implies activities swaps for physicians. To emphasize the objective of reducing access times, the question is reformulated to ’What is the best doctors’ scheme in terms of the percentage of patients treated within the norm?’.

5.1.1 The ‘best’ doctors scheme

We are interested in developing the best doctors’ scheme in terms of consequences for the access times, that is a scheme that ensures that patients are delayed as little as possible, taking into account that doctors have a certain number of consultations and contouring moments each week. The management of the department has the preference of a weekly cyclic scheme that is known beforehand, so it is not adapted after the patients arrive. In our case, a doctors’ scheme contains the time slots on which each individual doctor has consultations and contouring moments. In practice it also contains other activities and obligations, but in this research we take these moments as fixed and assume doctors are not available at these moments. Whether or not a scheme is optimal, depends on many factors and the outcome of the decisions in Table 3.1. In the list below, we made a subdivision of predetermined factors (that influence the lower bound) and factors that concern queueing effects and variability.

Predetermined factors:

- The doctors’ skills and the department’s decision of which doctors treat which patients;
- The doctors’ availability for consultations and contouring moments (e.g. doctors might have part time days, educational obligations and multidisciplinary meetings);
- The number of consultations and contouring moments to be scheduled for each doctor and the locations where the doctors are stationed;

- The medical prescribed care trajectories and the guidelines for patient routing (that is, determining which stages to pass through and the time constraints);
- The decision on whether or not consultations are reserved for specific patients;
- The days on which different stages are carried out (e.g. gold beads implementation only takes place one morning a week);
- The appointment scheduling guidelines used by the department, and by other departments that arrange several stages (e.g. cystoscopy);

Factors that concern queueing effects and variability:

- Already scheduled appointments for consultations, CT-sim and linacs, which depend on:
  - The arrival distribution of patient types at different referral days on both locations;
  - The capacity of the CT-sim (because if a patient for example has to wait three days on average for the CT-sim, the scheme might be different than if there is no waiting time for the CT-sim in general)
  - The capacity of the linacs
- Temporary absence of doctors due to conferences, holidays and illness;

5.1.2 Methodology

Optimizing the doctors' scheme, taking all above factors into account is a complex and extensive optimization problem. Especially since some of the queueing effects that influence the scheme, are in their turn also influenced by the scheme. An example is the demand for the CT-sim: if the scheme for example implies many patients need a CT-scan on Monday, new queueing effects will arise on this day, that influence the scheme.

Instead of using one model that uses both the predetermined and variable parameters to optimize the doctors' scheme, resulting in a new access time performance, another approach will be used to simplify the problem to a manageable size. As can be seen in Figure 5.1, we will use the predetermined parameters to optimize the doctors' scheme, and after that the resulting scheme is put in a simulation model that takes the variable parameters into account, in order to find the new access time performance.

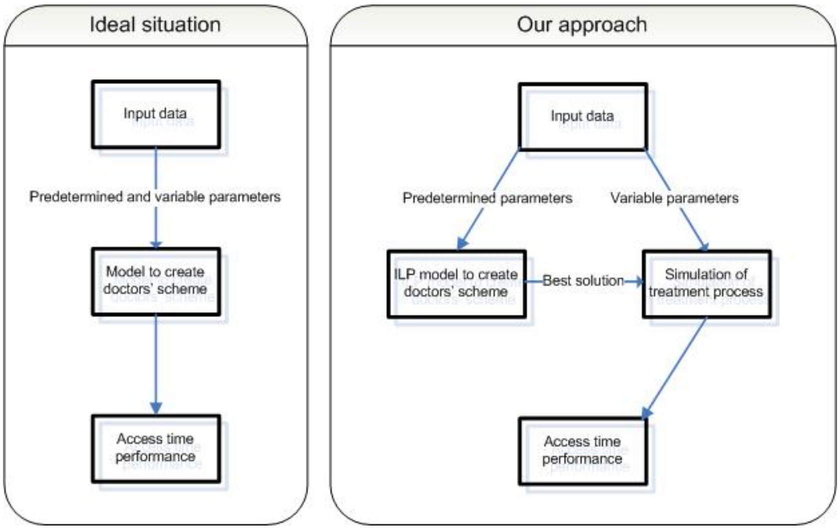


Figure 5.1: Overview of the proposed method to find an optimized doctors' scheme

ILP model

An *Integer Linear Programming* (ILP) problem is a mathematical optimization problem with in which some or all of the variables are restricted to be integers. It is often used in deterministic planning problems. In this case, the ILP minimizes the weighted access times for patients of all types, referred on different weekdays and the locations AMC and Flevo hospital, assuming there are no already scheduled appointments for consultations, machines and other stages and there are no temporary absences of doctors. These access times are referred to as 'lower bounds', since they are the shortest access time a patient can have in the treatment process with the used guidelines.

Simulation model

In practice, patients possibly are delayed, because other patients already might have appointments. In the simulation model, these other patients and already scheduled appointments are modeled as well. Simulation is the type of modeling that is suitable to carry out complex statistical experiments on the computer. The simulation model can therefore be used to compare situations with different doctors' schemes. Note that in this way we do not necessarily achieve the scheme that gives the highest percentage of patients treated within the norm, since we only optimize the lower bounds. However, a part of the scheme is optimized and in this way we can show that changing the scheme has a certain effect on the access times.

5.2 ILP model to create doctors' schemes

In Section 4.4 we have seen that the current doctors' weekly blueprint scheme is a bottleneck for the access times of patients. In this section the goal is to design an blueprint scheme that minimizes the lower bound for the access times of the average patient flow in the department. For this, an Integer Linear Programming model is developed. This approach will be explained in Section 5.2.1 and the model will be posed in Section 5.2.2, followed by the assumptions we made (Section 5.2.4) and information on choosing the parameter values (Section 5.2.5).

5.2.1 Method

A linear program (LP) is a mathematical optimization problem in the following form:

$$\begin{array}{lll} \text{minimize} & c^T x & \\ \text{subject to} & a_i x = b_i & \forall i \in I, \\ & a_i x \geq b_i & \forall i \in [n] \setminus I, \\ & x_j \geq 0 & \forall j \in J, \text{ and} \\ & x_j \text{ unrestricted} & \forall j \in [d] \setminus J. \end{array} \tag{5.1}$$

Here, $I \subseteq [n]$ and $J \subseteq [d]$, where n is the number of equations and d the number of variables. The vectors $a_1, \ldots, a_n, c$ and the numbers $b_1, \ldots, b_n$ are given, while $x_1, \ldots, x_d$ are variables.

In an integer linear program (IP or ILP) we have in addition the requirement that $x \in \mathbb{Z}^d$. In a mixed integer program (MIP), some of the variables are required to be integrals, while the other variables can assume any real value. An important special case are binary integer programs, where the integer variables are restricted to be either 0 or 1.

An $x \in \mathbb{R}^d$ is called a feasible solution of (5.1) if it fulfills all constraints. It is called an optimal solution if it minimizes $c^T x$ among all feasible solutions. The value $c^T x$ is called the value of the solution x.

More literature on linear programming can for example be found in the book of Wolsey [41].

5.2.2 Model description

The output of the model is a weekly scheme for all doctors, consisting of time slots for each doctor to do the consultations and contouring. There are several factors to take into account in order to obtain this output. Doctors are not available all the time: they might weekly have a part of the day off or activities that can not be rescheduled such as education. Further they are scheduled to be in the AMC or in the Flevo hospital; this is taken as a starting point in this model. They all have a fixed number of consultations and contouring moments each week, this should be maintained. From capacity reasons there can only be a maximum number of consultation and contouring time slots be scheduled at the same time, due to a limited number of consultation rooms and a limited number of licenses for the contouring software. To include the consequences for the patients, we need to know information about the patient's trajectories: the sequence in which each patient group has to undergo several stages and the minimal time between them, which doctor can treat which patient groups. Patients are clustered into groups on the tumor type (the type of doctor that could see them) and the stages the patient has to pass through and possibly the relations between them (the length of the treatment is not taken into account). Further, some stages in the patient's trajectory from referral to treatment can only take place on certain days, such as a Pet-CT or the implementation of gold beads.

For a possible scheme, we have to determine the consequences on the lower bounds of the access times. Each patient type can come in on every day of the week on both locations (we know average numbers from historical data), and for each of them we need to calculate a lower bound on the access time. Note that in the model, we do not assign patients to consultation time slots based on the current arrival patterns, but we consider the situation for one patient at time with a certain type, coming in on a certain day on a certain location.

5.2.3 Mathematical description

The sets, indices, parameters and variables used in this model are given below.

Set	**Index**	
A	a	number of physicians, physician assistants and physicians in training
P	p	number of patient groups
L	l, l'	number of treatment locations
S	s, t	number of stages (e.g. arrival, consultation, CT-sim, start treatment)
B	b	number of time slots per day
D	d	number of time slots per week ($7 * \|B\|$)
U	u, u'	number of time slots in the time horizon
R	r	number of referral days per week

Parameters		
c_{adl}	if physician a is available at time slot d on location l	binary
d_{pal}	if patient type p can be treated by physician a on location l	binary
f_{sdl}	if stage s is possible at time slot d on location l	binary
v_{pst}	if patient p has to visit stage t after stage s	binary
q_{pstl}	prescribed minimal time between stages s and t on location l	integer
g_{al}	number of consultations for physician a per week on location l	integer
h_a	number of contouring moments for physician a per week	integer
m_l	maximum number of consultations at the same time at location l	integer
k_l	maximum number of physicians contouring at same time at location l	integer
w_p	if patient type p is regular (1) or subacute (0)	binary
n_{prl}	average number of patient group p at location l with a referral at day r	$\mathbb{N}$
b_p	weight factor for patient group p	$\mathbb{N}$
z_1, z_2	weight factors in the objective function	$\mathbb{N}$

Variables		
Decision variables		
X_{adl}	if physician a has first consultations at time slot d on location l	binary
Y_{adl}	if physician a has contouring moment at time slot d on location l	binary
Z_{prla}	patient type p arriving at day r on location l is assigned to physician a	binary
W_{prlsu}	patient type p arriving at day r on location l has stage s at time slot u	binary
General variables		
AT_{prl}	access time of patient type p arriving at day r on location l	integer
ET_{prl}	entry time of patient type p arriving at day r on location l	integer
C_{prlad}	patient p,r,l could have consultation at time slot d if assigned to doctor a	binary
D_{prlad}	patient p,r,l could have contouring at time slot d if assigned to doctor a	binary
F_r	the difference in the number of consultation time slots at day $r+1$ and the average arrival rate at day r	

Before defining the constraints, we will specify some stages that the model always contains.

s	**Stage**
1	Arrival
2	Consultation
3	Contouring
4	Start of the treatment

Constraints

Creating the doctors' scheme

1. The number of first consultation time slots of physician a on location l is a given parameter.

$$\sum_d X_{adl} = g_{al} \quad \forall a, l \tag{5.2}$$

2. The total number of contouring time slots of physician a is a given parameter.

$$\sum_d , lY_{adl} = h_a \quad \forall a \tag{5.3}$$

3. The number of first consultations at any time slot d on location l is restricted to the facility's capacity.

$$\sum_a X_{adl} \leq m_l \quad \forall d, l \tag{5.4}$$

4. The number of physicians contouring at any time slot d on location l is restricted to the facility's capacity.

$$\sum_a Y_{adl} \leq k_l \quad \forall d, l \tag{5.5}$$

5. Physician a can do at most one activity on time slot d, and only if he is available.

$$X_{adl} + Y_{adl} \leq c_{adl} \quad \forall a, d, l \tag{5.6}$$

Calculating the lower bound of the access time

6. Patient type p arriving on day r at location l is assigned to exactly one doctor a.

$$\sum_a Z_{prla} = 1 \quad \forall p, r, l \tag{5.7}$$

7. Patient type p arriving on day r at location l can be assigned to doctor a, only if the patient type can be treated by the doctor on this location.

$$Z_{prla} * (1 - d_{pal}) = 0 \quad \forall p, r, l, a \tag{5.8}$$

8. Patient type p arriving on day r at location l can have a consultation at time slot d, only if he is assigned to doctor a that has consultations during that time slot and that location ($s = 2$ is consultation).

$$\sum_a C_{prlad} \geq W_{prlsu} \quad \forall p, r, l, u, s = 2, d = (u-1)mod(7|B|) + 1 \tag{5.9}$$

9. Patient type p arriving on day r at location l can have contouring at time slot d, only if he is assigned to doctor a that has a contouring moment during that time slot ($s = 3$ is contouring).

$$\sum_a D_{prlad} \geq W_{prlsu} \quad \forall p, r, l, u, s = 3, d = (u-1)mod(7|B|) + 1 \tag{5.10}$$

10. Stage s can only take place at location l on time slot u, if the stage is available on that time slot at that location.

$$\sum_{p,r} W_{prlsu} * (1 - f_{sdl}) = 0 \quad \forall l, s > 3, d = (u-1)mod(7|B|) + 1 \tag{5.11}$$

11. Each stage s has to take place in at most one time slot for each patient group p arriving on day r at location l.

$$\sum_u W_{prlsu} \leq 1 \quad \forall p, r, l, s \tag{5.12}$$

12. If a stage is not necessary for patient type p, then it should not take place.

$$\sum_{u,l,r} W_{prlsu} \geq \sum_t v_{pts} * |L||R||U| \quad \forall p, s > 1 \tag{5.13}$$

13. All patients arrive ($s = 1$ is arriving) on their referral day r.

$$W_{prlsu} = 1 \quad \forall p, l, s = 1, u = |B| * r \tag{5.14}$$

14. Stages have to be fulfilled in the right order and with the right time constraints between them for each patient type p. (If stage t has to take place after s (that is, $v_{pst} = 1$), then the number of time slots between stage s and t must be more than or equal to $q_{pstl} + 1$.)

$$\sum_u (u\ (W_{prltu} - W_{prlsu})) - (1 + q_{pstl}) + (1 - v_{pst})\ |U| \geq 0 \quad \forall p, r, l, s, t \tag{5.15}$$

15. For regular patients, treatment can not start on Friday.

$$w_p W_{p,r,l,s,u} = 0 \tag{5.16}$$

$$\forall r, l, s = 4,$$

$$(u-1)mod(7|B|) + 1 > 4 * |B| + 1 \text{ and } (u-1)mod(7|B|) + 1 < 5 * |B|$$

Variable definitions

16. Definition of the access time ($s = 4$ is start of treatment).

$$AT_{prl} = \sum_u W_{prlsu} \lceil \frac{u-r}{|B|} \rceil \quad \forall p, r, l, s = 4 \tag{5.17}$$

17. Definition of the entry time ($s = 2$ is consultation).

$$ET_{prl} = \sum_u W_{prlsu} \lceil \frac{u-r}{|B|} \rceil \quad \forall p, r, l, s = 2 \tag{5.18}$$

18. Definition of C_{prlad}, the variable that defines if patient p,r,l could have consultation at time slot d if assigned to doctor a.

$$C_{prlad} \leq Z_{prla} \quad \forall p, r, l, d, a \tag{5.19}$$

$$C_{prlad} \leq X_{adl} \quad \forall p, r, l, d, a \tag{5.20}$$

$$C_{prlad} \geq Z_{prla} + X_{adl} - 1 \quad \forall p, r, l, d, a \tag{5.21}$$

19. Definition of D_{prlad}, the variable that defines if patient p,r,l could have contouring at time slot d if assigned to doctor a.

$$D_{prlad} \leq Z_{prla} \quad \forall p, r, l, d, a \tag{5.22}$$

$$D_{prlad} \leq \sum_{l'} Y_{adl'} \quad \forall p, r, l, d, a \tag{5.23}$$

$$D_{prlad} \geq Z_{prla} + \sum_{l'} Y_{adl'} - 1 \quad \forall p, r, l, d, a \tag{5.24}$$

20. Definition of F_r, the variable that reflects the difference in the number of consultation time slots at day $r+1$ and the average arrival number of patients referred at day r.

$$F_r = \sum_{a,d^*,l} X_{adl} \left(\frac{\sum_{p,r,l} n_{prl}}{\sum_{a,l} \sum_l g_{al}} \right) - \sum_{p,l} n_{prl} \tag{5.25}$$

where $d^* = (2r)Mod(5|B|) + 1$ and $d^* = (2r+1)Mod(5|B|) + 1$

Objective

The aim is to obtain a scheme that is optimal in terms of lower bound access times for all patients. The objective is:

$$min \sum_p b_p \sum_{r,l} n_{prl}(AT_{prl} + z_1 ET_{prl}) + z_2 \sum_r F_r \tag{5.26}$$

In the first part of the objective, we minimize the total weighted lower bound access time for patients ($\sum_p b_p \sum_{r,l} n_{prl} AT_{prl}$). Some patient types are more common than others and on certain days more referrals occur than on other days, this is taken into account by the weight factor n_{prl}. The weight factor b_p is used because it might be more important to the management of the department that the lower bound is low for subacute patients than for regular patients. The addional $+z_1 ET_{prl}$ is used to ensure that patient types are assigned to the first available doctor specialized in their tumor type instead of doctors that have a consultation slot later; this reflects the scheduling rule currently used by the department. The second part of the objective ($z_2 \sum_r F_r$) is used to tune the number of consultation time slots on a working day with the arrival pattern of the previous day.

5.2.4 Assumptions

The following assumptions are made in the model:

- Scheduling the first consultation is done immediately after arrival;
- Once a patient is allocated to a physician, this physician does the contouring as well;
- Treatment for regular patients cannot start on Friday;
- Patients do not stop after the first consultation and all patients that are treated have had a first consultation.

5.2.5 Choosing parameter values

In this section we will briefly comment on factors that are relevant when choosing the parameter values.

- c_{adl}: the availability of doctors on both locations depends on the logistic decision of the department about how many and which doctors are to be present in the Flevo hospital each day, constrained for example by NVRO quality rules for the number of doctors on a satellite location. Further the doctors may have part time days or (educational) obligations that prevent them from being available for consultations or contouring.
- d_{pal}: which doctors can treat which patient types depends on the department's policy whether or not a doctor should be trained to be able to treat a particular patient group. Mostly this is the case, which means the parameter value depends on the doctors' skills.
- f_{sdl}: the availability of stages that are arranged by the Radiotherapy department are mostly managerial decisions, however they can be constrained, for example by the division of surgery time. The availability of stages arranged by other departments are seen as external influences.

- v_{pst} and q_{pstl}: the stages to fulfill for each patient group and most of the time constraints between them are based on medical arguments, but also on logistic decision decisions made by the department: for example, the decision that a patient is discussed in two physicians' meetings and the time between contouring and start of the treatment should be five days.
- g_{al} and h_a: the number of consultations and contouring moments per physician depend on decisions made by the department.
- m_l and k_l: these capacity parameters depend on the number of available consultations rooms and contouring licenses for the computers on both locations.
- n_{prl}: the average number of patients of a certain type arriving each day is seen as an external factor that is not influenced by the department.
- b_p, z_1, z_2: these parameters are weight factors in determining the doctors' scheme, so it does not represent or depend on a system characteristic, but on the user's preferences.

5.3 Simulation model of the treatment process

Since it is not known beforehand at which moment patients will arrive and what their patient type is, the exact consequences of the possible interventions on the access time are uncertain. However, the expected consequences can still be observed by making use of a model.

Due to the interrelatedness of the stages and the specific moments in the week for some stages, a queueing (or network of queues) model could not accurately represent all the stages of the Radiotherapy treatment process. A simulation model is a more suitable tool for a detailed study of the characteristics of the radiotherapy process, because it can be adapted to real-life guidelines and system characteristics. In this research, a discrete-event simulation model will be developed to compare the performance in the current situation to the performance with the physician's blueprint scheme as described in Section 5.2. First the conceptual model will be described and the parameter values are given. Besides the mentioned interventions, other situations with additional interventions will be considered. These interventions are determined in cooperation with the department.

In the conceptual model, the general characteristics of the simulation model are described. The work of Robinson [34] is used as a guideline for developing a conceptual model. Robinson states that six elements should be present in any conceptual model: the model objective, the input, the content, the output, the assumptions and the simplifications.

5.3.1 Model objective

The following model objectives should be achieved by the simulation model.

- The model gives a reliable reflection of the patient flow of subacute and regular patients in the treatment process at the Radiotherapy department in the AMC;
- The model allows to simulate the dynamical behavior of the system (queueing due to varying service times and non-stationary arrivals);
- The model output offers an insight in the access times of patients to be considered in the norm (stated in Section 1.2) and the utilization for various stages;
- The model should be detailed and flexible; parameters must be easy to change in order to easily assess various interventions in the process.

Note: since we are not interested in the waiting times (in the waiting rooms) in the day-to-day process, the exact time that appointments take place is not important; only the scheduled day of the appointment is important to us.

5.3.2 Input

The following data is used as input for the simulation model.

Patient characteristics

- Arrival rate of patients at a working day;
- Percentage of patients of each patient type and at each location;
- Percentage of subacute patients in need of a OSS appointment.

Routing information

- The trajectories for each patient type at each location and the (medically prescribed and currently used) time constraints between the stages;
- A table of which doctor can treat which patient types.

Service information

- The doctors' weekly scheme for consultations and contouring, for the AMC and the Flevo hospital;
- The number of servers (doctors, machines or other resources) for the various stages;
- The availability/opening hours of the various stages;
- The service time for the various stages.

5.3.3 Content

In Figure 5.2, a graphical overview can be found of the different steps in the conceptual model. The actions and routing at each step are described below.

Referral

- Start entry time measure;
- Assign the property 'patient type' to the patient. This is done based on the percentage of occurrence;
- Assign the property 'location' to the patient. This is done based on the percentage of occurrence (independent of the situation in the locations);
- For a subacute patient (a patient with a palliative patient type) in the location AMC, it is determined if patient is treated in a one stop shop (OSS) appointment. This is done based on the percentage of occurrence (independent of the situation in the OSS process);
- A patient that should be treated in the OSS process goes to the OSS consultation queue; in all other cases, the patient goes to the consultation queue of the associated patient type and location.

Consultation queues (per patient type and location)

- In this queue, patients are processed via the 'First come, first serve' principle;
- A patient goes to the first available doctor in the associated location that can treat their patient type;
- A doctor is available if he is having consultation hour (according to the doctors' weekly scheme) and is idle at the moment.

Consultation (per doctor and location)

- Stop entry time measure, start preparation time measure;
- One patient at the time can be seen by a doctor;
- The processing time for a consultation is fixed, since the scheduled time is known on beforehand. This processing time is independent of the patient type;
- Assign the property 'doctor' to the patient;

One stop shop consultation (in the AMC)

- Stop entry time measure, start and stop preparation time measure;
- There is one OSS consultation possible each day;
- The processing time in a OSS consultation is less than a working day;
- Afterwards, the patient leaves the system.

Physicians' meeting

- Every working day, in the morning a physicians' meeting takes place where all patients eligible for treatment of both locations are discussed (served) at the same time;
- Afterwards, the patient travels to the CT-sim or to an additional stage, depending on the protocol of the patient type.

Additional stages (Pet-CT, 4d-CT, beads, gold beads, cystoscopy)

- The processing time for each of the additional stages is fixed, since the scheduled time is known on beforehand;
- A patient from the Flevo hospital that needs an additional stage comes to the AMC for this stage. Afterwards the patient travels back to the Flevo hospital;
- For some stages, time constraints between the stages need to be taken into account;
- The beads implementation and the cystoscopy are arranged by other departments. Since we have no insight into these planning processes, we use a 'black box' for the waiting time of these appointments, that has a fixed length that does not depend on the number of patients requesting treatment;

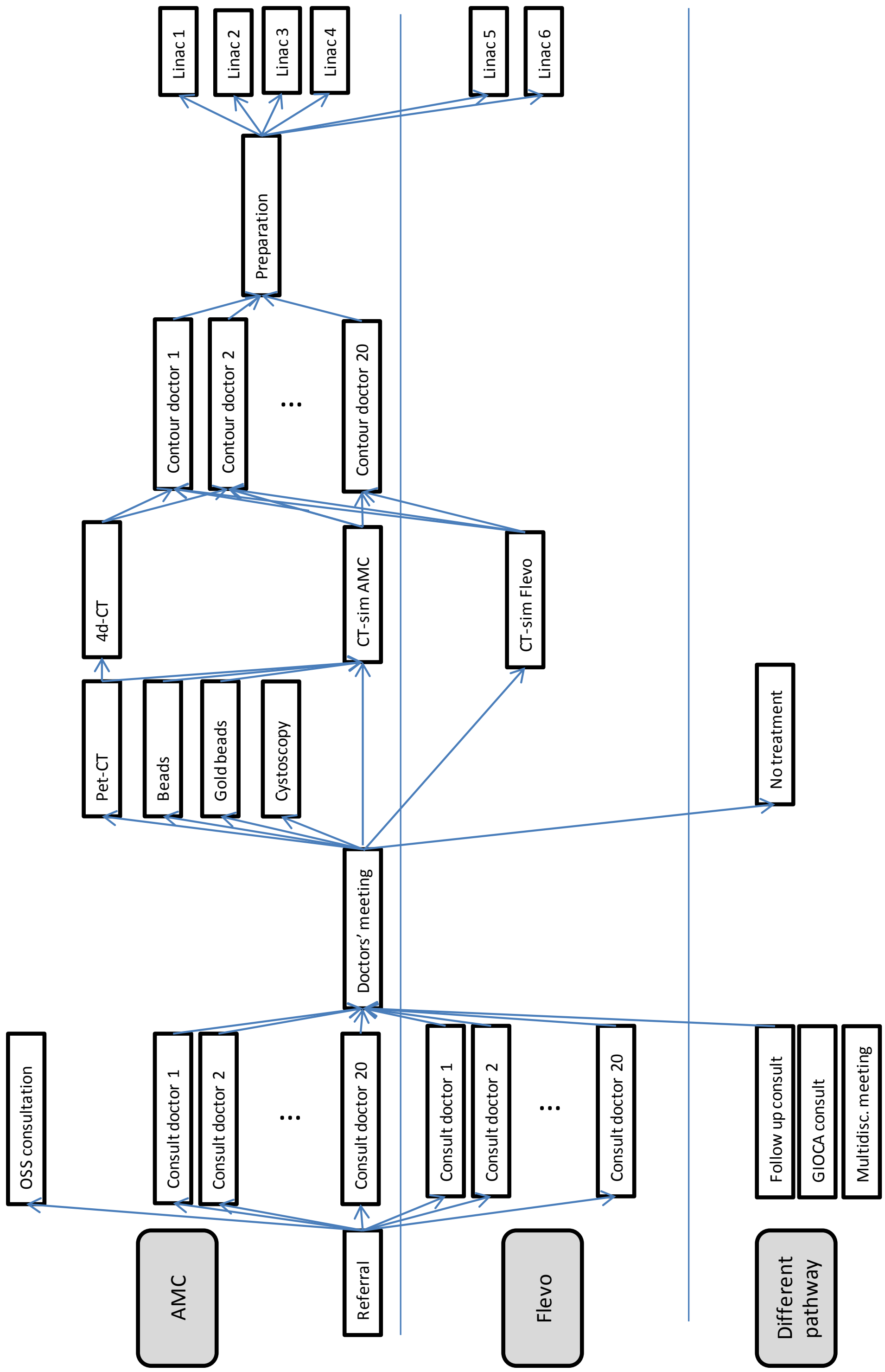


Figure 5.2: Conceptual model of the simulation

CT sim (per location)

- The processing time at the CT-sim is fixed, since the scheduled time is known on beforehand. This processing time is independent of the patient type;
- Afterwards, the patient travels to the contouring stage of the doctor he was assigned to before.

Contouring (per doctor)

- Contouring for all patients can be done at both locations (it does not matter where the patient is treated);
- The processing time for the contouring can vary per patient and partly depends on the patient type.

Preparation phase

- In this simulation, the preparation phase is a 'black box' that contains the activities physicians' meeting, treatment planning, physician's approval on the treatment planning and parameter implementation;
- The processing time is a fixed number of days, possibly different in both locations;
- The preparation phase can process an unlimited number of patients at the same time.

Start treatment (per location)

- A patient starts the treatment on the first available linac (the linacs are assigned randomly);
- The processing time at the linac is fixed and consists of one large session with the duration an average total session series. This processing time is independent of the patient type and the linac;
- Stop preparation time measure.

5.3.4 Output

The output parameters for our model are the parameters used for evaluating the performance of the radiotherapy department.

- **Access time per type (mean and 80% and 100% percentiles)**: The access time is measured in days between referral and the start of the treatment. We measure the retrospective access time based on patients realized access time in the simulation. The entry time and preparation time together are the access time. With this, we can calculate the average access time and the percentage of patients treated within a certain time frame (to evaluate the norm).
- **Time per stage**: To look at each stage more specifically, we would like to compare the historical data between several time steps with the simulated time between several time steps.
- **Utilization and production per stage**: Daily utilization is measured as the sum of service time per machine/doctor in regular opening hours, divided by the total time the machine was open/the doctor was available for the activity. Production is measured as the amount of patients treated per day on each machine.

5.3.5 Simplificating assumptions

The assumptions of the ILP model, as described in Section 5.2.4, also hold for the simulation model. In addition, the following assumptions are incorporated in the simulation model:

- The patient type is known at the moment of referral;
- Patients are always available.
- During the opening hours of the CT-sim and linac there are enough laboratory technicians present to serve the patients.
- We neglect the probability of no-show, since it is very low.
- We neglect the probability of breakdown, as the consequences are minimal (in practice all patients are served on that day as overwork).
- All patients can be treated on all linacs.
- A patient joins the queue for an appointment at the moment he is finished with the previous one.
- All patients receive treatment after a first consultation; patients do not come in via another consultation, and they do not stop after the consultation. They do not switch locations during the treatment process.
- Patients are treated according to the protocol of their patient type.
- Doctors work according to the weekly scheme, so there is no variability in the number of first consultations over the time.
- Acute patients are treated as subacute patients.
- No temporary measures are taken in case of high access times.
- Patients do not choose the treatment location depending on the current access time.

5.3.6 Choosing parameter values

In this section we will briefly comment on factors that are relevant when choosing the parameter values.

- Choosing the parameter values for the patient-doctor allocation, the availability of the stages, the patient trajectories and the time constraints between them is already commented in Section 5.2.5.
- The arrival rate of patients at a working day, the percentage of each patient type at each location and the percentage of subacute patients in need of a OSS appointment are considered as an external factor that is not influenced by the department.
- The number of servers (doctors, machines or other resources) for the various stages depend on the available capacity at the department and other departments.
- The doctors' weekly scheme can be varied, but is limited due to various parameters and constraints that are determined by the department, as explained in Section 5.2.2.
- The service time for the various stages is considered as a factor that can not be influenced.

Chapter 6

Numerical experiments

In this chapter, the results of several experiments are given. Each experiment consists of several runs of the simulation model, using the current doctors' scheme or a scheme created by the ILP model als input. In this way, the access times in different settings are evaluated.

The ILP model is implemented in AIMMS 3.13 and solved with the CPLEX algorithm. The simulation model is implemented in the simulation software Tecnomatix Plant Simulation 10.1, ©2010 by Siemens PLM Software. A start is made by Nikoletta Pittokopiti, student Operations Research in Cardiff University [31]. Details of the experiment setup, including the used parameter values, can be found in the Section 6.1. In Section 6.2 the validation of the models is described and in Section 6.3 the different experiments are be explained. The results of the experiments are given in Section 6.4.

6.1 Experimental setup

Before we can use the models described in Sections 5.2 and 5.3, we need to define input parameter values, such as the number of doctors and machines. In the experiments, some of the parameter values will be changed to see the effect on the access times. However, most of them will remain the same for all the experiments. We will refer to these values as the 'basic settings' of the models. They are provided in the next sections.

6.1.1 Basic settings ILP model

For the ILP model of Section 5.2, we used the current situation in the AMC to determine the basic settings for the set and parameter values. The set values are given in Table 6.1. The choice of sets and parameters is explained below. For parameters that vary over time, the situation of December 2012 was used as basis, as this month was representative for the situation in the department.

- $|P|$, $|S|$: the diagnoses are divided into the 18 patient groups of Table 4.10. According to the same table there are eleven stages to fulfill, which are listed in Appendix A.5.
- $|B|$: in general we look at access times on the day-to-day level, so the exact hour of a consultation is not relevant to us. In practice, stages do not take place on the same day part (except for OSS consultations), but they can take place on the same day (for example a scan in the morning and contouring in de afternoon). Therefore we divide each day in two time slots.

Set	Meaning	Value
A	physicians, physician assistants and physicians in training	20
P	patient groups	18
L	treatment locations	2
S	stages	11
B	time slots per day	2
U	time slots in horizon	70
R	referral days	5

Table 6.1: Set values

- $|U|$, $|R|$: from evidence we know that the lower bounds are all below 30 days, so 70 time slots should be enough for the time horizon. Patients can be referred on each working day.
- c_{adl}: each doctor is available in the AMC or Flevo during the week, as in the situation of December 2012. Part time days and (educational) obligations are not taken into account. (See Appendix A.5.)
- d_{pal}: according to the current situation, in the AMC each doctor is allowed to treat patients of his focus area and subacute patients of all types; in the Flevo hospital, all doctors are allowed to treat all patient types. (See Table A.5.)
- f_{sdl}: according to the current situation, stages are always available, with exception of the gold beads implementation (Monday morning) and the PET-CT (Wednesday morning). See Table 4.11.
- v_{pst} and q_{pstl}: according to the current situation, the stages to fulfill for each patient type can be found in Table 4.10 and the time constraints between them in Appendix A.5.
- g_{al} and h_a: for each doctor, the number of contouring moments and consultations per location are according to the situation of December 2012, and can be found in Appendix A.5.
- m_l and k_l: according to the current situation, the number of consultations that can take place in one time slot is 20 in the AMC and eight in the Flevo hospital. On both locations there is a maximum of six doctors that can do contouring in a time slot.
- n_{prl}: the number of patients arriving each day is derived from historical data (the number of patients arriving for a complete treatment in 2011-2012) and can be found in Appendix A.5.
- b_p, z_1, z_2: in determining weights for patients groups, we used the basic rule that for large patient groups and for subacute patient it is slightly more important to minimize the lower bound than for other patient groups. The numbers can be found in Appendix A.5. For the objective weights, the value $z_1 = 10$ and $z_2 = 1$ are chosen.

6.1.2 Basic settings simulation model

For the simulation model of Section 5.3, the current situation in the AMC was used to determine the basic settings for the input values. The choice of input parameters is explained below.

- From the historical data of 2011-2012 we derived that the number of arriving patients fits a Poisson distribution (see Figure 4.6). This seems reasonable, because we assume the arrivals are independent from each other. The average number of arriving patients per working day can be found in Appendix A.5.
- The patient-doctor allocation table, the trajectories of patient types and the time constraints between them are the same as in the ILP model and can be found in Figure A.5, Table 4.10 and Appendix A.5 respectively.
- The doctors' weekly scheme is either the scheme of December 2012 or a scheme created by the ILP model.
- The opening hours of the CT-sims and linacs are determined based on the situation of the beginning of 2012. They can be found in Section 4.2.
- The number of doctors and machines and their service time are based on the current situation and can be found in Table 6.2. The consultations and contouring are assumed to have a deterministic distribution because they are scheduled for a fixed time slot beforehand. For the appointments on the machines, we just assume each appointment or each treatment series has the same duration (the average duration in 2011-2012). The contouring distribution is derived from Kolfin's findings in the AMC [25] and we estimated the duration in cooperation with the department.

Resource	**No.**	**Service distribution**	**Service parameter**	**Available**
Doctors for consultations	20	Deterministic	45 or 60 min	According to scheme
Doctors for contouring	20	Uniform	30-60 min	According to scheme
CT-sim (AMC)	1	Deterministic	24 min	Opening hours CT-sim
CT-sim (Flevo)	1	Deterministic	24 min	Opening hours CT-sim
Linacs (AMC)	4	Deterministic	16 min	Opening hours linacs
Linacs (Flevo)	2	Deterministic	16 min	Opening hours linacs
Plan/mal	1	Deterministic	16 min	Opening hours linacs
4d-CT (AMC)	1	Deterministic	60 min	Opening hours CT-sim
Gold beads (AMC)	1	Deterministic	30 min	Monday morning, 5 patients
Pet-CT (AMC)	1	Deterministic	20 min	Wednesday morning, 4 patients
Beads (AMC)	1	Deterministic	30 min	Working days, 7 days waiting time
Cystoscopy	1	Deterministic	30 min	Working days, 7 days waiting time

Table 6.2: Resource input parameters

6.1.3 Simulation runs

Before we can perform experiments with the simulation model, we need to specify the number of runs, the length of the runs and the warm up period. We choose to perform five runs per situation with a length of one year (365 days). Here we omit access times of patients that arrived in the first three months (warm up period) and we also do not take account the access times of patients arrived in the last month, since most of them can not finish the treatment before the end of the simulation run and this biases the data. In each run we use different seeds for the distributions of arrival, location choice, OSS treatment, doctor allocation and contouring duration.

Calculations on determining an appropriate warm up period are carried out according to Welch's graphical procedure and can be found in Appendix A.4. In our case, the access time seems to converge after about a year, although a longer simulation run should be carried out to see if the average access times really converge. Due to practical limitations on the size of the data set, a manageable number of three months is chosen as warm up period.

The number of replications is based on a procedure described in [26]; the calculations can also be found in Appendix A.4. The number of five runs per experiment turned out to be enough for a reliable average access time of all patients, but for the access time per patient type or per priority (which are determined based on less patients), we expect that a larger number of runs is required. Further research is needed to determine the required number of runs, such that strong conclusions can be drawn on the access times per patient type.

6.2 Validation of the models

Verification is concerned with determining whether the conceptual simulation model (model assumptions) has been correctly translated into a computer program, that is, debugging the simulation computer program. This was done for both models during the programming process, by writing and debugging parts of the program and running the simulation under a variety of settings, followed by a check to see if the output is reasonable.

Validation is the process of determining whether a model (as opposed to the computer program) is an accurate representation of the real system, for the particular objectives of the study. The most definitive test of a models validity is to establish that its output data closely resembles the output data what would be expected from the actual (proposed) system.

6.2.1 ILP model

For the ILP model, there is no historical data available on the lower bounds to validate the model. The only validation that was possible, is a walkthrough with the staff of the department to determine whether the process and scheduling methods we used are indeed realistic.

6.2.2 Simulation model

The validation of the simulation model is done in two steps. At first, we investigated the access times for one patient that arrives at the department, while there are no other patients. This result can be compared to the lower bounds as calculated by the ILP model, for all patient types, arriving at all referral days on both treatment locations. To do this, we used the current doctors' scheme and the basic values of the ILP and simulation model. A sample of the results can be found in Table 6.3. Several differences could be observed:

- The difference for the 'mamma with surgery' patients (AMC) on Friday is due to the fact that in the simulation, another doctor was allocated to the patient than in the ILP model. These doctors have consultation hours in the same time slot and in the simulation model one of the first available doctors is chosen, without taking into account when each doctor has a contouring moment. So in this case, choosing the 'right' doctor would have saved the patient five days in his access time.

Patient type	Location	Referral day	ILP model	Simulation
Mamma with surgery	AMC	Mon	10	10
Mamma with surgery	AMC	Tue	16	16
Mamma with surgery	AMC	Wed	15	15
Mamma with surgery	AMC	Thu	14	14
Mamma with surgery	AMC	Fri	17	12
Mamma with surgery	Flevo	Mon	14	14
Mamma with surgery	Flevo	Tue	13	13
Mamma with surgery	Flevo	Wed	19	19
Mamma with surgery	Flevo	Thu	14	14
Mamma with surgery	Flevo	Fri	17	17
GE with beads	AMC	Mon	17(+7)	24
GE with beads	AMC	Tue	23(+7)	30
GE with beads	AMC	Wed	22(+7)	29
GE with beads	AMC	Thu	21(+7)	28
GE with beads	AMC	Fri	19(+7)	26
GE with Pet-CT	AMC	Mon	17	17
GE with Pet-CT	AMC	Tue	22	16
GE with Pet-CT	AMC	Wed	21	15
GE with Pet-CT	AMC	Thu	20	14
GE with Pet-CT	AMC	Fri	17	12

Table 6.3: Comparing lower bounds as computed by the ILP model and realized in the simulation model, in calendar days

- For the GE with beads patients, the difference of seven days is due to the fact that in the ILP model we assumed that each stage was available immediately, but in the simulation model we assumed that the beads implementation always has a waiting time of seven days.
- In the simulation model we did not take the restriction into account that only one activity can take place in one day part. For the GE with PET-CT patients arriving on Tuesday until Friday, the PET-CT, the CT-scan and the contouring took place at one day, resulting in a fair reduction of the access time compared to the lower bound.

Since most of the results of the two models correspond with each other and the differences could be explained, we conclude that the simulation model is working properly.

Second, we investigated if the model simulates the day-to-day practice of the department. For this, we used historical data of the Radiotherapy department of the AMC. We compared the access time of our model to the historical output data of the actual system. To do this, we used the basic settings of the simulation model. The results can be seen in Figures 6.1 and 6.2.

As we can see in Figure 6.2, the average access times from the simulation model and the real system are not at all similar. From this we conclude that the validation was not successful at this stage. In Section 7.2 we will identify potential causes for this and state the expected consequences of each cause. Although the simulation model does not represent the real system properly at the moment, we will still proceed to continue the model for indication purposes. As stated by Lowery (1996): 'While formal statistical tests may lead to the conclusion that a model is not an accurate representation of the real world system under investigation, the model may still be valid for the purpose for which it is intended. This is especially ture for models that are designed primarily for comparing alternatives instead of predicting absolute answers.' In Chapter 7.3 we will give recommendations to improve the model's validity.

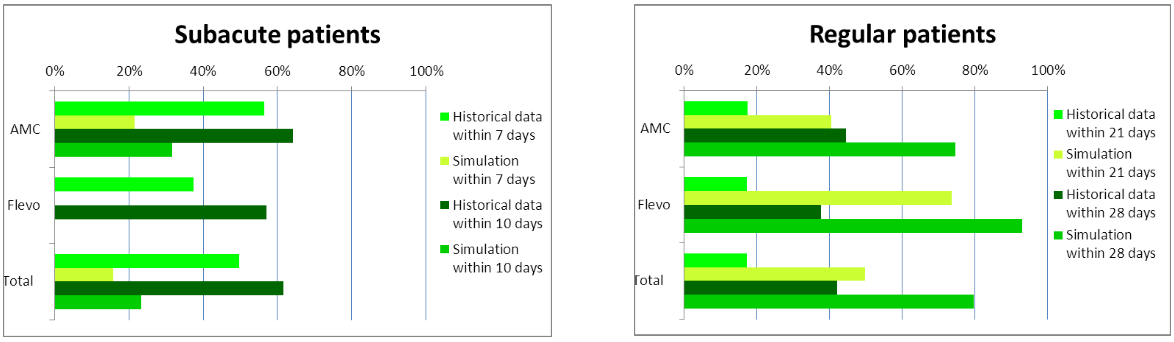


Figure 6.1: Comparing the norm evaluation of the simulation model with historical data

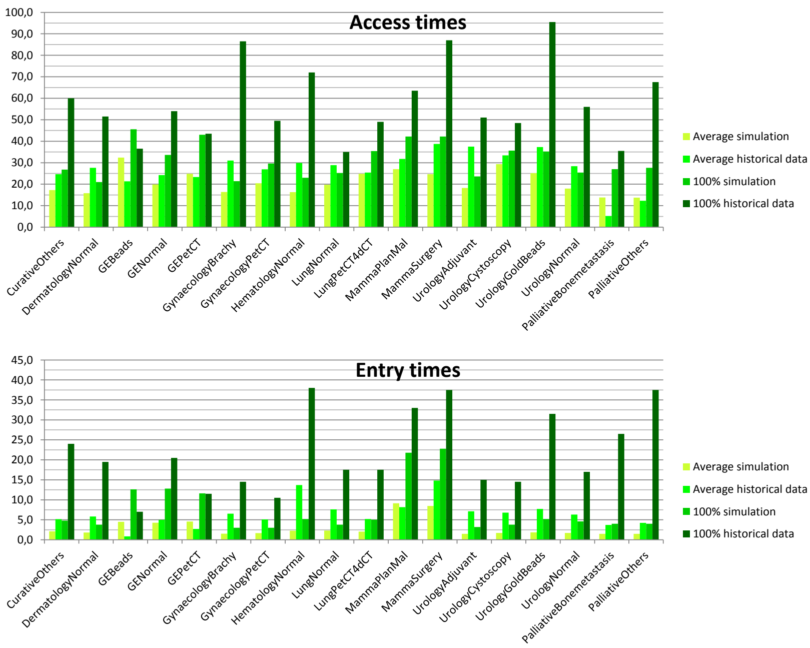


Figure 6.2: Comparing the entry and access times of the simulation model with historical data

6.3 Investigated interventions

In cooperation with the department, we made a selection of interesting interventions to be investigated with the models. An overview is given in Table 6.4 and each intervention is explained below. The interventions are divided in changes in patient-to-doctor allocation and patient routing (A) and extending the facility's capacity (B). In each situation the simulation model uses a scheme created by the ILP model, except for the 'current situation' and intervention B1 where the existing scheme is used. The basic settings of the ILP model (described in Section 6.1.1) and the basic settings of the simulation model (described in Section 6.1.2) are used, unless stated otherwise.

Situation	**Description**
Current	Current situation in the department with the doctors' scheme of December 2012
A1	Current situation in the department
A2	All doctors treat breast and prostate patients
A3	All doctors treat all patients
A4	Consultation and CT-sim at same day
A5	Contouring is done immediately after CT-sim
B1	Opening hours CT-sim and linacs 7am-8pm, doctors' scheme of December 2012
B2	Opening hours CT-sim and linacs 7am-8pm
B3	Opening hours linacs extended; maintenance and tests outside opening hours
B4	Number of linacs in the AMC reduced from four to three
B5	Number of consultations in the AMC increased from 34 to 40
C1	Combination of interventions A2, B3 and B5

Table 6.4: Overview of situations investigated in the experiments

- Current situation: here the basic settings of the simulation model are used and the scheme as it was in December 2012. This is a representation of the treatment process in the department as it is operating at the moment.
- Intervention A1: in this situation, the basic settings of the simulation model are used, but now with a doctors' scheme as input that was created by the ILP model with basic settings. Nothing has changed, except that the time slots in which doctors have consultations and contouring might be on other days of the week.
- Intervention A2: in the data analysis and the simulation, large entry times for breast patients were observed. The management of the department was wondering what the difference would be if the two largest patient groups, breast and prostate, could be treated by all doctors in the AMC (in the Flevo hospital, this was already the case). At first a doctors' scheme was created with the basic settings but a changed doctor-patient allocation table (d_{pal}) and the scheme was used as input for the simulation model, that also used the basic settings but with the adaptation that all doctors could treat breast and prostate patients.
- Intervention A3: analogous to intervention A2, but now with the allowance for all doctors to treat all patient types in the AMC (this is already the case in the Flevo hospital).
- Intervention A4: in the department, a discussion is going on whether or not the CT-sim appointment should be scheduled at the same day of the consultation. The effects of this situation (physicians' meeting is skipped, time constraint between consultation and CT-sim

is left out) on the doctors' scheme are investigated by using the basic settings in the ILP model with adapted v_{pst} (denoting the stages and the order) and q_{pstl} (time constraints between stages). The effects on the access times performance are investigated by using the resulting scheme in the simulation model with basic settings and above adaptations.

- Intervention A5: in some oncological centers, contouring is not done according to a weekly scheme, but the physicians do the contouring in between their other activities. We investigate the situation where physicians do the contouring immediately after a scan is made (but within their working hours). Although this is not a very realistic situation, since physicians might have other obligations keeping them from contouring immediately, the avoided delay can be calculated by comparing the outcome with the situation where contouring is done according to a scheme. In the ILP model, constraint 2 is adapted and constraint 9 is replaced by constraint 10 for the contouring stage; in the simulation model, each doctor is available for contouring between 9:00 and 17:00 o'clock except during their consultations.

- Intervention B1 and B2: for creating schemes with the ILP model, it is assumed that there is no waiting time for the machines and the consultations. We therefore expect that if the CT-sim and linac opening hours are extended to 7:00-20:00 o'clock each working day (which implies low waiting time for the machines), the scheme created by the ILP model would function best, resulting in large differences in access times between using the current scheme (intervention B1) and the scheme created by the ILP model (intervention B2). Although these opening hours extensions are not very realistic, it is theoretically interesting to observe the differences. Except for the opening hours of the machines, the other settings are basic settings.

- Intervention B3: in Section 4.3 we learned that the queueing effects at the linacs influence the access time significantly. One possibility for extending the opening hours of the machines is that the maintenance work and tests are moved outside working hours, such that the linacs can operate each working day from 8:00 until 17:30 o'clock in the AMC and 8:00 until 16:30 o'clock in the Flevo hospital.

- Intervention B4: in the situation of end 2012, only three linacs were operating in the AMC, resulting in very high utilization rates. The basic settings of the ILP model and the simulation model are used, so the situation is similar to intervention A2 but with three linacs in the AMC.

- Intervention B5: besides adapting the opening hours of the machines, extending the facility's capacity can also be done by extending the weekly number of consultations. ILP model, the basic settings are used but g_{al} (the weekly number of consultations per doctor) is adapted such that there are 40 consultations in the AMC each week. In the simulation model, the basic settings are used.

- Intervention C1: based on the outcomes of above interventions, we decided to intestigate a combination of three interventions that looked promising: interventions A2, B3 and B5. In the ILP model, the basic settings are used, but the number of consultations is extended and breast and prostate patients can be seen by all doctors. In the simulation model, additional to the rule that breast and prostate patients can be treated by all doctors, the opening hours are extended such that maintenance and tests are done outside opening hours.

6.4 Experimental results

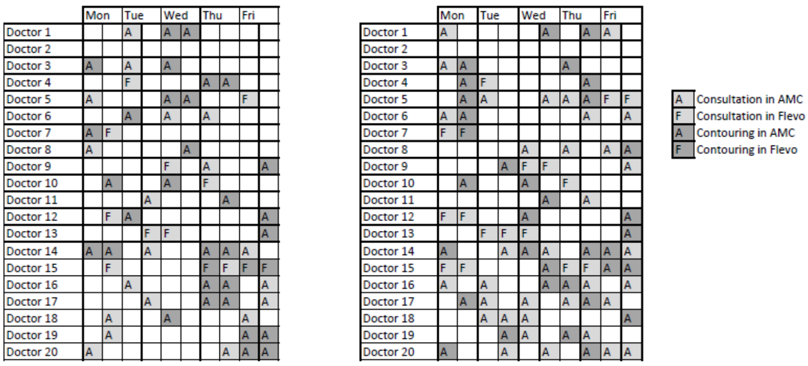
In this section, the results of the different interventions are given. The results are subdivided in the doctors' schemes created by the ILP model and the access time evaluation by the simulation model.

6.4.1 Doctors' schemes created by the ILP model

In this section, the resulting doctors' schemes created by the ILP model are given. In Figure 6.3, the used scheme of December 2012 ('current' situation) and the scheme created by the ILP model (intervention A1) are shown. The schemes for interventions A2 (breast and prostate patients are treated by all doctors) and A3 (all patient types can be treated by all doctors) turned out to be the same as that of intervention A1. In Figure 6.4, the schemes for interventions A4 (consultation and CT-sim on the same day) and A5 (immediate contouring) are given. The schemes for interventions B1-B4 are the same as that of intervention A1, because the same settings are used for the ILP model. In Figure 6.5, the scheme of intervention B5 (more consultations) is displayed.

Remarks on the schemes:

- Note that in the current scheme, there are less consultation and contouring moments than in the other schemes. In the ILP model at most one consultation is scheduled at one day part, as in reality more consultations can take place on the same part of the day.
- For intervention A5, no contouring moments are scheduled because the contouring takes place immediately, and not according to a scheme.



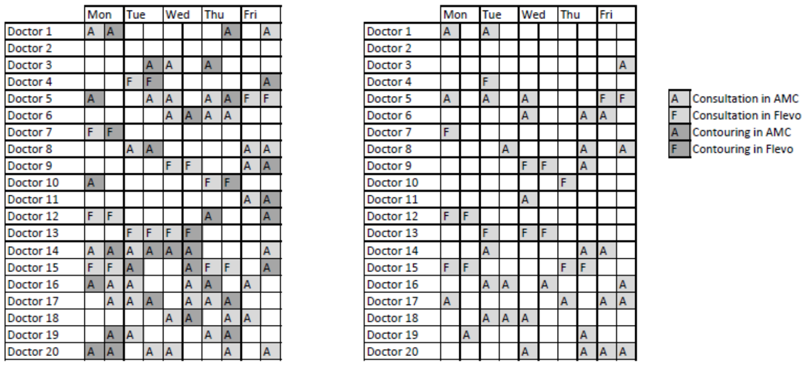
	Mon	Tue	Wed	Thu	Fri	Tot
Consultations AMC	5	6	1	3	4	19
Consultations Flevo	3	2	2	2	1	10
Contouring	5	2	8	10	9	34

Scheme of December 2012

	Mon	Tue	Wed	Thu	Fri	Tot
Consultations AMC	4	7	7	7	9	34
Consultations Flevo	5	3	3	3	2	16
Contouring	9	2	7	9	7	34

Interventions A1-A3, A5 and B2-B4

Figure 6.3: The scheme of December 2012 and the scheme created by the ILP model for interventions A1-A3 and B2-B4



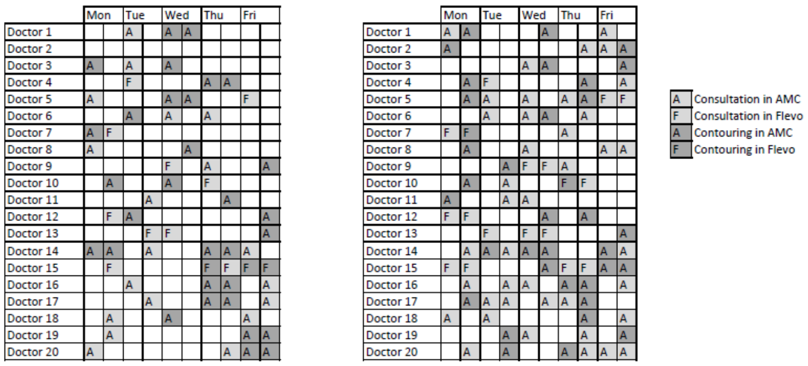
	Mon	Tue	Wed	Thu	Fri	Total
Consultations AMC	4	7	7	7	9	34
Consultations Flevo	5	3	3	3	2	16
Contouring	9	6	6	8	5	34

Intervention A4

	Mon	Tue	Wed	Thu	Fri	Total
Consultations AMC	4	8	6	7	9	34
Consultations Flevo	5	2	4	3	2	16
Contouring	-	-	-	-	-	-

Intervention A5

Figure 6.4: The scheme created by the ILP model for interventions A4 and A5



	Mon	Tue	Wed	Thu	Fri	Total
Consultations AMC	5	6	1	3	4	19
Consultations Flevo	3	2	2	2	1	10
Contouring	5	2	8	10	9	34

Scheme of December 2012

	Mon	Tue	Wed	Thu	Fri	Total
Consultations AMC	5	9	8	8	10	40
Consultations Flevo	5	2	4	3	2	16
Contouring	9	4	7	9	7	36

Intervention B5

Figure 6.5: The scheme of December 2012 and the scheme created by the ILP model for intervention B5

- The time slots for consultations in the Flevo hospital are almost equal in all situations. This can be explained by the fact that the availability of doctors in the Flevo hospital is limited, so there are not many possibilities for shifting to other time slots.
- It can be observed that the consultations and contouring moments for one doctor are not necessarily spread out over the week. For the patient flow it is not important to spread consultations and contouring per doctor over the week, as long as the possibilities for a consultation on each day for each patient type are spread out over the week.
- In this case, there are no obvious patterns to be seen in the ‘distance’ between consultations and contouring moments of each doctor. This can be explained by the fact that the number

of consultations and contouring moments for each doctor are not always equal in this case and the scheme is constrained by the availability of the doctors on both locations. This 'distance' for each doctor is expected to depend on his most common patient type: for patient types that do not require additional stages, 1.5-2 day between the consultation and contouring would be expected to be optimal (because the physicians' meeting and CT-sim have to take place in between).

The corresponding lower bounds of the access times for these situations are given in Table 6.5. The numbers are an average over all referral days. The lower bounds for the entry times are in all interventions equal to 1.4 days, which reflects an entry time of one day when arriving on Monday until Thursday and three days (due to the weekend) when arriving on Friday. The entry times of the 'current' situation can be found in Tables 4.12 and 4.13.

Lower bounds of the access time	**Current scheme**		**Interventions A1-A3, A5, B2-B5**		**Intervention A4**	
Patient group	AMC	Flevo	AMC	Flevo	AMC	Flevo
Dermatology normal	14.2	15.4	11.6 (-18%)	13.0 (-16%)	9.0 (-37%)	10.6 (-31%)
GE normal	13.8	15.4	11.6 (-16%)	13.0 (-16%)	9.0 (-35%)	10.6 (-31%)
GE with Pet-CT	20.6	20.0	16.4 (-20%)	17.2 (-14%)	16.4 (-20%)	17.6 (-12%)
GE with beads	19.4	19.6	15.0 (-23%)	19.0 (-3%)	15.0 (-23%)	19.0 (-3%)
Gynaecology with brachy	15.8	-	11.6 (-27%)	-	9.0 (-43%)	-
Gynaecology with Pet-CT	18.6	-	15.0 (-19%)	-	15.0 (-19%)	-
Hematology normal	14.2	15.4	11.6 (-18%)	13.0 (-16%)	9.0 (-37%)	10.6 (-31%)
Lung normal	16.2	15.4	11.6 (-28%)	13.0 (-16%)	9.0 (-44%)	10.6 (-31%)
Lung with Pet-CT & 4d-CT	19.0	19.6	15.0 (-21%)	19.0 (-3%)	15.0 (-21%)	19.0 (-3%)
Mamma with surgery	13.8	15.4	11.6 (-16%)	13.0 (-16%)	9.0 (-35%)	10.6 (-31%)
Mamma with plan/mal	15.2	-	13.0 (-14%)	-	10.4 (-32%)	-
Urology normal	14.6	15.4	11.6 (-21%)	13.0 (-16%)	9.0 (-38%)	10.6 (-31%)
Urology with gold beads	21.4	21.0	20.4 (-5%)	20.6 (-2%)	20.4 (-5%)	20.6 (-2%)
Urology with cystoscopy	17.4	18.2	14.2 (-18%)	16.0 (-12%)	14.2 (-18%)	16.4 (-10%)
Urology adjuvant	14.6	15.4	11.6 (-21%)	13.0 (-16%)	9.0 (-38%)	10.6 (-31%)
Curative others	14.4	15.4	11.6 (-19%)	13.0 (-16%)	9.0 (-38%)	10.6 (-31%)
Palliative bonemetastasis	13.4	14.8	11.0 (-18%)	12.4 (-16%)	8.4 (-37%)	10.0 (-32%)
Palliative others	13.4	14.8	11.0 (-18%)	12.4 (-16%)	8.4 (-37%)	10.0 (-32%)
Average	16.1	16.7	13.1 (-19%)	14.7 (-13%)	11.3 (-31%)	13.2 (-23%)

Table 6.5: Lower bounds of the access times in calendar days, for the current situation and for the interventions. The percentages denote the difference with the current situation.

Some remarks on the lower bounds:

- For the subacute patients (palliative groups), the lower bound in Table 6.5 is in case of a standard consultation. In practice the access time for these patients can be lower since if they are treated in OSS consultation.
- The patient types 'gynaecology with brachy', 'gynaecology with Pet-CT' and 'mamma with plan/mal' can not have the entire treatment in the Flevo hospital, because they require additional stages that are only carried out in the AMC.

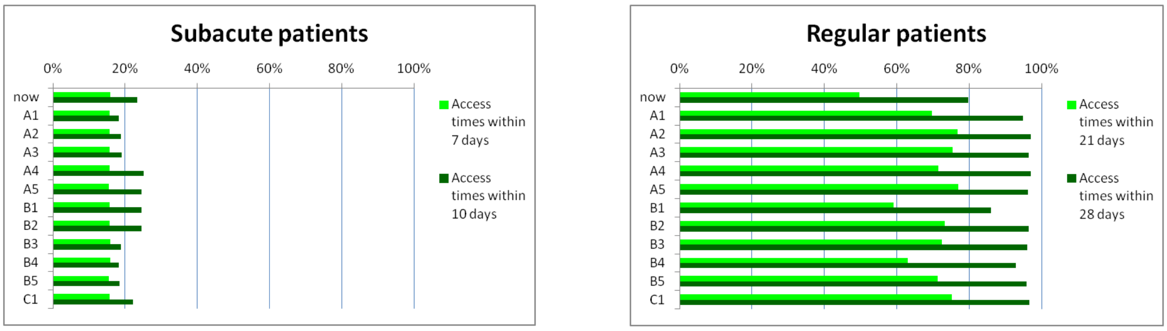


Figure 6.6: Norm evaluation in all situations for subacute and regular patients

- The doctors' scheme for intervention A1 reduces the lower bound of the access time with three days in the AMC and two days in the Flevo hospital. The smaller reduction in the Flevo can be explained by the fact that there are less possibilities to plan consultations and contouring in the Flevo hospital (because of the limited doctor's availability in that location).
- The scheme for intervention A4 reduces the lower bound with another two days in the AMC and 1.5 days in the Flevo hospital. This is as expected, since the 1.5-2 days that were needed before between consultation and CT-sim are now skipped.
- It can be observed that the increased number of consultations of intervention B5 did not further reduce the lower bound of the access times. However, it is expected that in the simulation, where waiting times can arise, a higher number of consultations will turn out to be beneficial for the access times.

6.4.2 Results simulation model

In this section, the results of the simulation model with the different interventions are given. The schemes from previous section are used as input in the simulation model. Recall that the validation of the simulation model was not successful, so the exact numbers do not correspond to the real radiotherapy treatment process, but only an indication of the working could be derived.

In Figure 6.6 the norm evaluation for the different situations is displayed (the numbers can be found in Appendix A.6). Recall that the national standard prescribes that 80% of the subacute patients is treated within seven days and 100% within ten days. Regular patients should all be treated within 28 days and 80% within 21 days.

Some remarks:

- From the figure it can be seen that the norm for subacute patients is not met in all cases. This can be explained by the fact that the scheduling rule of five (AMC) or six (Flevo) working days between contouring and start of the treatment implies that a subacute patient is never treated within seven calendar days and not often within ten days. Only patients treated in a OSS consultation have an access time within seven days.

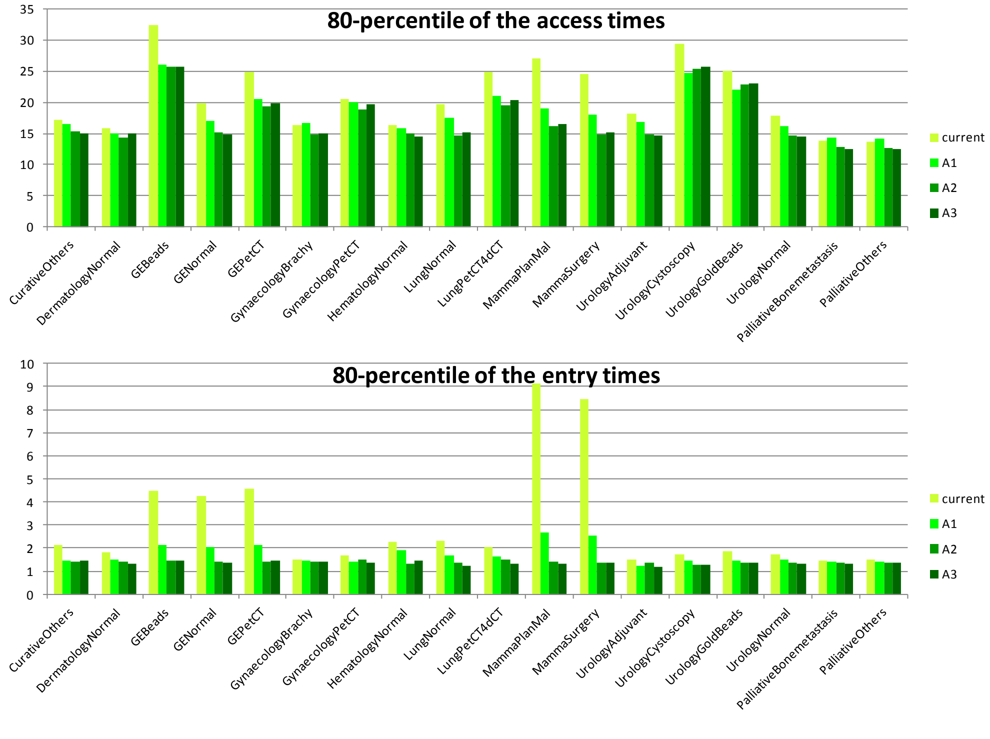


Figure 6.7: Access and entry times per patient type, in the current situation and interventions A1-A3

- For regular patients, the percentage of patients treated within 21 days increases with 20% when changing the current scheme to a scheme created by the ILP model (A1). Another improvement of 8% is observed when breast and prostate patients can be treated by all doctors. Immediate contouring (intervention A5) has a larger effect than consultation and CT-sim on one day (A4).
- In the simulation model, the percentage of patients treated within 21 days is increased more by changing the scheme (A2) than by extending the opening hours of the CT-sim and linacs to 7:00-20:00 o'clock (B1).
- It is remarkable to see that intervention C1 does not give a better result than the individual interventions it consists of.
- In all situations, the norms are not met in the simulation model.

For the situations where we changed the doctor-to-patient allocation, we are interested in how the access and entry times of the separate patient types are influenced. In Figure 6.7, it can be seen within how many days 80% of the patients of a certain type have the first consultation and the linac sessions.

- From the figure we can see that the entry times for breast patients are reduced much when the scheme created by the ILP model is used, and slightly more if the doctor-patient allo-

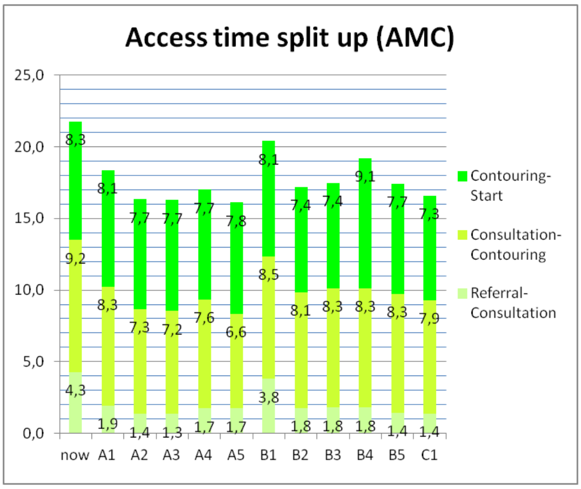


Figure 6.8: Average access times split up in different components, in all situations

cation is changed (A2 and A3). The access times almost stay the same after interventions A2 and A3: the largest improvement can be seen for the breast patients (two days).

- For intervention A3 we see that the entry times are almost equal for all patient types, which is logical since they can all be seen in the first available time slot of any doctor. The access time still vary in that case, but this is due to the different treatment pathways for different patient types.

In Figure 6.8, the average access times in all situations are split up in different components.

- It can be observed that the entry times reduce significantly by using doctors' schemes created by the ILP model. The entry time is the lowest when all patients can be seen by all doctors (intervention A3).
- The time between consultation and contouring is also reduced by using doctors' schemes created by the ILP model, but the improvement is small. If the contouring takes place immediately after the CT-sim appointment (intervention A5), the time between consultation and contouring is the smallest of all situations.
- The time between contouring and start of the treatment is the smallest in the situations B2 and B3, where the machine opening hours were extended to 7:00-20:00 o'clock, and the largest in the situation of three linacs in the AMC. This is as expected, because the linac availability influences the waiting times for the start of the treatment.

In Table 6.4.2, the utilization of the consultation time slots, CT-sims and linacs are given in the situations A1 and B4. The only difference between these situations is the number of linacs in the AMC: four in situation A1 and three in situation B4. From Figure 6.8 we see that when the utilization of the linacs in the AMC increased from 78% to 88%, the average access time increased with one day on average for all patients in the simulation model. Note that since the validation of the model was not succesful, these numbers are not very reliable; especially because we made a simplification for the linacs (in the simulation model all linac sessions are carried out at once instead of spread over the days and the linacs are interchangeable) which is expected to influence the linac performances significantly.

Resource	**Situation A1**	**Situation B4**
Consultation time slots AMC	80%	80%
Consultation time slots Flevo	71%	71%
CT-sim AMC	60%	60%
CT-sim Flevo	40%	40%
Linacs AMC	78%	88%
Linacs Flevo	55%	55%

Table 6.6: Utilization of the simulation model, in the situation with four linacs in the AMC (interventionA1) and in the situation with three linacs in the AMC (intervention B4)

Chapter 7

Conclusion and recommendations

The conclusions of this research is given in Section 7.1 and the results are discussed in Section 7.2. In Section 7.3 the recommendations for further development of the models, recommendations for the management of the Radiotherapy department and ideas for further research are described.

7.1 Conclusion

The aim of this research is to identify logistic interventions that can reduce the access times for regular and subacute patients, treated on linear accelerators, by making use of the available resources in an efficient way. The following conclusions can be drawn.

7.1.1 Current performance and bottlenecks

- In the current situation of the Radiotherapy treatment process, the national standards are not met by far: for regular patients, the percentage of patients treated within the required number of calendar days is lower than for subacute patients. Especially urology and breast patients have long access times (more than 30 days on average).
- From the utilization rates of the consultations, CT-sim and linacs and their specific service process, it can be concluded that the delay at the linacs, due to queueing effects is the largest of these three stages and congestion is likely. If only three linacs are operating in the AMC, an access time build-up is expected that keeps growing: this situation should be avoided. The queueing effects for the consultations would be reduced if the variety in the number of weekly consultation slots would be reduced.
- Not only the overall capacity of stages in the treatment process is a crucial factor for the access times, also the capacity allocation, especially the moments in the week at which stages take place, is important. The doctors' schemes have a substantial influence on the access times.
- From the process analysis and bottleneck analysis we have learned that the optimal allocation of time slots for consultations and contouring for a doctor depends on several factors, amongst others the patient type a doctor may treat, the schemes of other doctors that may treat the same patient types, on the overall patient mix and arrival distribution, on the availability of all other stages and on the objective in terms of access times.

7.1.2 Experiments

Although the validation of the simulation model was not succesful, the results give a global indication of the impact of the investigated interventions. From the results, the following conclusions can be drawn:

- Changing the current doctors' scheme to a scheme created by the ILP model and keeping the other settings (including number of consultations and contouring moments) the same, has a large effect on the percentage of regular patients treated within the required number of calendar days. (The percentage treated within 21 days increased from 50% to 80% and the percentage of regular patients treated within 28 days increased from 80% to 95% in the simulation program.)
- In the current situation, breast patients have a relatively long entry time. When a scheme created by the ILP model is used instead of the current scheme, a large reduction is recorded in the entry times for breast patients. Introducing the rule that all doctors can treat breast and urology patients, implies a further improvement for breast patients: 80% has an entry time within two days instead of twelve days in the original situation. The allowance for doctors to treat more patient types cause the queueing effects to be distributed along more patient types, such that the peaks are smoothed.
- In the simulation program, the introduction of a scheme created by the ILP model has more effect than any of the other interventions, including the extension of linac opening hours to 7:00-20:00 o'clock on each working day. However, since in the simulation model the waiting time for the linacs is expected to be shorter than in reality (which will be explained in Section 7.2), this result might not hold for the real situation where the extension of the opening hours is expected to have a larger effect.
- To improve the percentage of subacute patients treated within the required number of calendar days, the investigated interventions are not useful. This is due to the fact that the prescribed five or six days between contouring and the start of the sessions are still taken into account for patients that are not treated in a OSS consultation.

7.2 Discussion

A famous statement of statistician G. Box is: 'All models are wrong, but some are useful'. How wrong and useful the results and the conclusions are, is evaluated in this section.

7.2.1 Limitations of the simulation model

As stated in Section 6.2, the validation of the simulation model with the historical data was not successful. The potential causes for this will be discussed here. First, we have made some assumptions and simplifications in modelling, that are expected to have a significant influence on the working of the system and the average access times.

- Doctors' schemes are not adapted to holidays and conferences. In reality, about 15% of the consultations in the scheme are canceled because of these reasons. In the simulation model, we did not take this into account. Effect: the access times in the simulation are shorter than in reality.
- In reality, the doctors' schemes can be adapted monthly. Especially physicians in education do not stay long and physicians' other activities (education) might change during the year. The scheme of December 2012 has been confirmed to be quite representative in terms of number of consultations, but the number of consultations in the Flevo hospital is higher than average. Effect: in reality, the access times in Flevo might be higher than in the simulation model.
- In the simulation, all linac sessions are carried out at once instead of spread over the days and the linacs are interchangeable. In practice, this is not the case, and more time constraints play a role. Therefore the utilization of the linacs can reach higher values in the simulation model than what is possible in reality. Effect: the access times in the simulation are shorter than in reality.
- In reality, the doctor allocation to patient types is not as strict as in the model. Sometimes patients are allocated to a specific doctor, or patients that face a long entry time are assigned to doctors that do not treat their patient type, such that very long entry times are avoided. Effect: unknown, but might be substantial.
- Patients may require additional consultations or scans, for example when the first one was not sufficient, or stages that are not described in a protocol, for example an MRI scan or a mould. Effect: access times in the simulation are lower than in reality.
- Acute patients are not modeled. If the OSS queue is too long, patients would be served as acute patients in reality, but not in the simulation model. Effect: OSS access time might be too high in the simulation compared to data.
- In reality, the department might take temporary measures in case the access times get too high, for example introducing additional consultation hours or extending the machine capacity. We assumed this is not the case in the simulation model.
- In reality, appointments are scheduled beforehand, but in the simulation a patient joins a 'queue' when he finished the previous stage. Some differences between the two can arise with respect to the order in which patients are treated. Effect: patients that have a long preparation phase (additional stages) might have a longer access time in the simulation and patients with short preparation phases might have a shorter access time.

- Patients might choose their treatment location based on the current expected access time.

Second, some historical data is unknown, which complicates accurate modelling and the determination of parameter values.

- For 16% of the patients treated on a linac, no course name is registered and therefore we do not know the trajectory (steps) these patients go through in the treatment process. Effect on the average access times: unknown, but small.
- There was no historical data available on the number of patients eligible for OSS consultation, the time needed for contouring, the distribution of waiting times for bead implementation, a Pet-CT scan or cystoscopy. The estimations for these parameters could therefore be inaccurate.

To evaluate the current access time performance with respect to the norms, historical data was used. This norm evaluation might deviate from the real situation on some points:

- As stated in Section 4.1.1, it is not registered which patients are acute. Therefore the historical data for subacute patients contains all the acute patients and this may cause higher percentages of subacute patients to be treated within the prescribed number of days in the historical data than experienced in the real system. Further, we assumed that palliative patients were subacute and curative patients were regular, but this division is not exactly right.
- Registration of patients that voluntarily start their treatment later because of their own availability (holidays) or preference (location) or because of medical reasons (surgery recovery) is incomplete. In the norm evaluation we have taken patients with an entry time more than 40 days or a preparation time more than 90 days out of the data set, but this might not cover all elective cases. Effect: unknown.
- To evaluate the access time of each patient, data from X-Care and Mosaiq had to be matched, but this process is prone for errors. Effect: unknown.

7.2.2 Limitations of the ILP model

As stated in Section 5.1, an ILP model might not be the best tool to optimize the doctors' schemes, as it does not optimize the scheme subject to all factors that influence the access time. Apart from that, the ILP model we constructed also has some disadvantages in the modelling itself:

- In the model, only one consultation per time slot can take place, so in our case this means that all consultations are scheduled in different parts of the day.
- The current scheduling rule of assigning a patient to the first available doctor is represented in the objective function now, but it would be better to use a constraint for this. Also, in reality, if two doctors have consultations at the same moment, a patient can be allocated to either of the doctors, but in the model the patient is allocated to the doctor where the access time is the shortest.
- At this moment, there is no limit of the number of patient types allocated to a doctor. This can imply that there are 'popular' doctors, such that in reality these patient types can not reach the lower bound, and some doctors might not be allocated to any patients, such that an arbitrary scheme is constructed for them.

7.3 Recommendations

In this section, the recommendations are described, divided in recommendations to researchers for further development of the models of this research, recommendations to the management of the Radiotherapy department and recommendations for further research in the department on minimizing the access times for radiation treatment.

7.3.1 Further development of the models

The following recommendations are given for further development of the models. First, the most important recommendation for the simulation is to investigate why the model validation was not successful and to validate it again, such that the model represents the working of the treatment process more accurately. In this way, stronger conclusions can be drawn from the output, such as which interventions ensure the national standards will be met. The following actions can be taken to improve the validity:

- Carry out another detailed walk-through with doctors and planning personnel where the largest deviations between the model and the reality are discussed, such that the scheduling rules and patient groups are verified to represent the current situation at the department.
- Develop the simulation model such that less of the simplifications described in Section 7.2 are needed.
- Since some parameter values had to be estimated, it would be useful to carry out a sensitivity analysis to see the effects of the parameter values on the output.

Second, for creating the 'best' doctors' scheme, the ILP model was a good start. However, the optimization would be more accurate if more parameters that influence the access time would be taken into account. A first step forward could be, to adapt the model such that it assigns actual patients to appointments for several arrival patterns, such that the access times for several realistic scenarios can be calculated instead of only the lower bounds.

However, at the moment the computation time for solving the ILP model with the basic settings as described in Section 6.1.1, is about two hours. The before mentioned adaptation would increase the number of variables and therefore the computation time significantly, so the program should have to be improved in order to maintain a workable computation time.

7.3.2 Recommendations to the Radiotherapy department

The first recommendation to the management of the Radiotherapy department is, in case there are still only three linacs able to operate in the AMC, to extend the opening hours of these linacs or to advise more patients to switch to the Flevo hospital. Otherwise the access times will only build up over time.

Further, we have seen that a doctors' scheme based on patient flow instead of doctor preferences has a beneficial effect on the access times. Although the developed schemes are not necessarily the best possible doctors' schemes, they perform much better than the original one. We therefore recommend to change the doctors' scheme to a scheme such as created by the ILP model. The developed ILP model can be useful for that (and the simulation model for evaluating the consequences), but as the schemes might change during the year and these models might not available to the department at all times, some guidelines are set to support the (manual) development of a doctors' scheme, derived from characteristics of schemes created by the ILP model:

1. Spread the first possibilities for a consultation for each patient type over the week (for example, try to avoid that the only two consultation slots suitable for dermatology patients are on Friday). This is slightly more important for patient types that are common (breast, prostate) and for subacute patients.
2. Try to match the total number of consultation time slots on a working day with the average number of arriving patients on the previous working day.
3. Take into account that contouring on Thursday instead of Friday for AMC patients and contouring on Wednesday instead of Thursday for Flevo patients, saves three days of access time for regular patients (due to the required five or six days between contouring and start of the treatment and the fact that regular patients can not start treatment on Friday).

Other recommendations to the department are:

- Improve the data registration of the patient's priority (acute, subacute or regular) and whether or not a patient encounters elective delay. This data can provide more insight in the treatment process and it would make the norm evaluation and the results of the simulation model more accurate.
- Consider implementation of the interventions investigated in this research, especially the rule where all doctors can see breast and prostate patients.
- An optimized scheme alone is not enough to reach the norm for subacute patients and for patients types with additional stages, because there is always this prescribed five or six days between contouring and the start of the sessions. Other interventions, such as priority rules or capacity reservation, should therefore be considered for this group.
- For the scheduling procedure of the consultations: if scheduling a first consultation only happens after a doctor has come by to assign the patient to a specific doctor, this does not only delay the scheduling of the first consultation, but moreover, assigning patients to a specific doctor cause unnecessary delay. Assigning patients to a focus area generally implies shorter entry times.

7.3.3 Further research

In this research we have seen that the Radiotherapy treatment process is a complex system, since different patient types, priorities, treatment locations and various interdependent stages are involved, and variability further complicates the treatment process. This research only touched upon a few of the many logistic decisions that the Radiotherapy department is faced with. Further research can be carried out on each of the decisions in Table 3.1 and especially the questions that have not been considered in literature before.

A more specific suggestion is to investigate priority rules or capacity reservation for certain groups of patients, for example (sub)acute patients and patient types with additional stages. In this research we have seen that the norm can not be met for both priorities and all patient groups, when the same scheduling rules are used for all patients. The OSS consultation is an example of capacity reservation for specific patient groups; this type of capacity reservation could be a starting point for further investigation.

Another suggestion is to consider temporary measures that could be taken by the management of the department when timeliness of the treatment is endangered. The treatment process is affected by variability and some levels of fluctuation are unpredictable, but others can be foreseen to some extent. It would be useful to investigate when to adapt which part(s) of the treatment process and how, to achieve an acceptable access time performance at all times.

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Appendix A

Appendix

A.1 Keywords and abbreviations

Keyword	**Dutch**	**Meaning**
Access time	Toegangstijd	No. of calendar days between referral and start treatment
Acute patient	Acute patiënt	Treated immediately, generally once and without appointment
Brachytherapy	Brachytherapie	Treatment of implementing a radioactive source in patient's body
Checking consultation	Dokterscontrole (DC)	Short weekly consultations in the period of linac sessions
Curative	Curatief	Aim to give long-term benefits to the patient (regular patient)
Desk 1	Balie 1	The reception, where referrals are collected and the first consultation is scheduled
Doctor	Arts	See Physician
Entry time	Entreetijd	No. of calendar days between referral and first consultation
External beam radiation	Uitwendige bestraling	Radiation performed with a linac or orthovolt machine
First consultation	Eerste consult (EC)	First appointment at the department with radiotherapist
Follow up consultation	Vervolgconsult (VC)	Consultation several weeks/months after the treatment
GIOCA consultation	GIOCA consult	A fast diagnostics consultation for gastroenterological diseases
Hyperthermia	Hyperthermie	Treatment of heating a certain part of the body
Kwadraet	Kwadraet	Information system used by the Radiotherapy department to store quality documents
Laboratory technician	Laborant	Person qualified to operate linacs and perform treatment planning
Linac/Linear accelerator	Lineaire versneller	Machine to perform external beam radiation
Linear Program (LP)	Lineaire Programmering	Mathematical optimization method for deterministic planning
Lower bound	Ondergrens	(of the access time) Shortest possible access time for a patient in current organizational characteristics
Medical physicist	klinisch fysicus	Person qualified, amongst others, to perform tests on linacs
Multidisciplinary meeting	MDO (multid. overleg)	Meeting of physicians with different specialties
Model	Model	Simplified replica of a planned or real system with its processes
Mosaiq	Mosaiq	Information system used to register dates and times for preparation appointments and linac sessions
Norm/standard	Norm	In this research: national standards for the access time
One stop shop	One stop shop	Appointment with first consultation until treatment in one day
Orthovolt machine	Orthovolt machine	Machine to perform external beam radiation, but from another type of radiation than a linear accelerator
Planning office	Inplanbureau (IP)	Office where preparation and linac appointments are scheduled majority of the patients, 25-39 sessions for curative treatment
Palliative patient	Palliatieve patiënt	Treated for pain relief (subacute patient); 1-10 sessions
Physician	Arts	In this research: physician specialized in radiotherapy

Keyword	**Dutch**	**Meaning**
Physician assistant	Arts-assistent	A physician assistent is qualified to assist a physician
Physician in training	Arts in opleiding	A physician that is in training (in education) to become a physician
Plant Simulation	Plant Simulation	Simulation software program
Preparation time	Voorbereidingstijd	No. of calendar days between first consultation and start linac sessions
Radiotherapist	Radiotherapeut	Doctor specialized in radiotherapy (each doctor in this research)
Regular patient	Overige patiënt	Patient with a regular priority;
Simulation run		The image of the behavior of the system in the simulation model within a specified period
Subacute patient	Subacute patiënt	Treated for pain relief (palliative patient); 1-10 sessions
System	Systeem	Separate set of components which are related to each other; in this research often used instead to refer to ‘treatment process’
Treeknorm	Treeknorm	National standards for the access times of radiation treatments
Waiting time	Wachttijd	In this research: delay at a stage due to queueing effects
X-Care	X-Care	Information system used to register consultation dates and times

Abbrevation	**Meaning**
AMC	Academic Medical Center, Amsterdam
AvL	Antoni van Leeuwenhoek hospital, Amsterdam
CT-sim	CT-simulator, machine used to make CT-scans and to simulate the patient’s position on the linac
DES	Discrete-event simulation
ILP	Integer Linear Program, a linear program where some or all variables are integers
NVRO	Dutch Association of Radiotherapy and Oncology
OLVG	Onze Lieve Vrouwe Hospital in Amsterdam
OR	Operations Research, branch of applied mathematics suitable to support logistic decision making
OSS	One stop shop: appointment that covers first consultation until treatment in one day
VUmc	VU University Medical Center, Amsterdam
ZZZ	Zuiderzee hospital in Lelystad

A.2 More data access time performance

The following table provides information on the division of patient types into groups we used in this study. The entry times (ET), preparation times (PT) and access times (AT) are a supplement to Section 4.1.

Diagnosis	**AMC**				**Flevo**			
Regular patients	No.	ET	PT	AT	No.	ET	PT	AT
Dermatology normal								
Huid Electronen	3	6.7	17.7	25.0	6	4.5	24.7	29.3
Huid Fotonen	6	6.0	21.5	27.8	2	4.0	17.5	21.5
Melanoom Radiotherapie + Hyperthermie	10	5.9	22.0	28.2	1	13.0	14.0	31.0
GE normal								
Anus Primair	12	6.3	20.4	28.1	3	6.3	20.7	27.0
Galgang/Klatskin Preoperatief	22	6.8	22.2	29.5	3	2.3	11.3	14.7
Maag Neoadjuvant NARCIS					1	6.0	26.0	32.0
Maag Postoperatief CRITICS	5	5.2	22.2	28.0				
Rectum Herbestraling + Chemotherapie	1	8.0	17.0	25.0	1	3.0	17.0	20.0
Rectum Herbestraling + Hyperthermie	5	5.4	22.2	29.0				
Rectum Postoperatief	1	5.0	20.0	25.0				
Rectum Preoperatief Kort	39	3.6	18.3	22.3	25	4.6	14.8	20.3
Rectum Preoperatief Lang	39	3.5	19.6	23.4	31	7.1	17.4	24.9
GE with Pet-CT								
Oesophagus Inoperabel	54	2.9	20.4	23.9	9	1.3	18.2	19.9
GE with beads								
Oesophagus Neoadjuvant	67	0.6	19.8	21.3	9	0.1	18.7	18.8
Pancreas Primair	12	2.3	20.1	23.4	3	2.0	18.7	23.3
Gynaecology with brachy								
Brachytherapie Endometrium	1	7.0	32.0	39.0				
Cervix Chemotherapie + Hyperthermie	4	4.3	23.8	28.0				
Cervix Postoperatief	18	5.5	23.9	29.8				
Cervix Primair	16	5.6	23.6	29.9				
Endometrium Postoperatief	26	8.3	22.0	31.6				
Vagina Primair	3	7.0	24.3	31.3				
Vulva Postoperatief	7	5.4	19.4	25.0				
Vulva Primair	6	6.8	34.8	42.5				
Gynaecology with Pet-CT								
Cervix Primair PET-CT	30	5.1	21.4	27.0				
Hematology normal								
Morbus Hodgkin	5	6.0	38.2	45.0	2	3.5	47.0	50.5
Non Hodgkin Lymfoom	8	3.1	12.0	15.3	6	7.0	12.7	19.7
Total Body Irradiation	39	18.4	13.1	31.5				
Lung normal								
Long Kleincellig CREST Studie	2	6.5	30.0	38.0				
Long Kleincellig PCI (hersenen)	4	10.8	20.3	31.3				
Long Niet-Kleincellig Postoperatief	1	6.0	21.0	27.0	3	4.7	15.7	20.3
Lung with Pet-CT and 4d-CT								
Long Kleincellig Primair	2	4.0	26.0	30.0	1	6.0	15.0	21.0
Long Niet-Kleincellig Primair	24	5.1	19.0	24.3	30	3.7	17.1	21.1
Long Stereotaxie	19	7.8	24.9	33.2	2	4.5	23.0	27.5
Mamma with surgery								
Mamma/Thoraxwand	32	10.8	22.8	33.8	52	18.2	24.8	43.4
Mamma/Thoraxwand + oksel	2	21.0	32.5	53.5	12	14.8	25.3	40.8
Mamma/Thoraxwand + oksel LINKS	18	10.5	18.2	29.0	29	16.9	22.4	40.1
Mamma/Thoraxwand + oksel RECHTS	15	10.5	21.0	32.6	32	14.1	23.7	38.3
Mamma/Thoraxwand beiderzijds	1	2.0	33.0	35.0				
Mamma/Thoraxwand Intensief	9	11.6	23.7	35.4	4	9.8	30.0	40.0
Mamma/Thoraxwand Intensief LINKS	7	13.0	22.6	35.9	5	14.4	24.4	39.0
Mamma/Thoraxwand Intensief RECHTS	3	18.3	20.7	41.0	3	16.7	15.0	32.3
Mamma/Thoraxwand LINKS	52	13.7	22.1	36.2	76	15.9	25.3	41.7

Diagnosis	**AMC**				**Flevo**			
	No.	ET	PT	AT	No.	ET	PT	AT
Mamma/Thoraxwand RECHTS	38	12.1	20.1	32.9	70	17.3	24.8	42.9
Mamma with plan/mal								
Mamma/Thoraxwand Herbestr.+Hypert.	24	7.1	22.3	29.5				
Mamma/Thoraxwand Herbestr.+Hypert. LI	42	8.0	23.3	32.5				
Mamma/Thoraxwand Herbestr.+Hypert. RE	25	9.4	23.0	32.7				
Urology normal								
Blaas Preoperatief	2	6.0	21.0	27.0	1	2.0	26.0	28.0
Blaas Totaal	6	5.2	17.2	23.8	2	8.0	22.0	30.0
Prostaat Postoperatief	35	6.0	22.5	28.6	16	8.9	23.5	32.8
Seminoma Testis	3	4.0	20.7	24.7	4	2.3	15.8	18.5
Urology with gold beads								
Prostaat Primair 70 Gy	20	8.0	22.5	31.6	11	8.5	22.5	31.5
Prostaat Primair IMRT	222	7.2	29.5	37.3	77	9.0	29.8	39.5
Urology with cystoscopy								
Blaas FIF	36	6.4	25.7	32.8	5	9.2	27.2	38.4
Urology adjuvant								
Blaas Chemotherapie + Hyperthermie	1	4.0	28.0	33.0				
Brachytherapie blaas	1	4.0	27.0	31.0				
Brachytherapie Prostaat PDR	14	7.9	27.9	39.0	2	5.0	24.0	32.5
Curative others								
Craniospinale As	3	7.3	24.7	34.3	1	5.0	7.0	12.0
Graves Orbitopathie	9	6.3	20.0	27.1				
Hersenen GBM	23	6.5	21.6	28.2	4	1.5	18.3	20.0
Pediatrische Radiotherapie	18	2.6	12.4	15.4	1	0.0	10.0	10.0
Sarcoom met moulage	7	7.6	21.9	29.7	2	7.5	13.5	21.0
Sarcoom zonder moulage	14	5.2	23.3	29.4	4	4.0	16.0	21.0
Subacute patients								
Palliative bonemetastasis								
Palliatie Botmetastase 1x8 Gy OSS	186	3.6	0.7	4.3	51	4.2	3.6	8.5
Palliative others								
Hersenen Palliatief/Electief	56	5.8	14.9	21.2	19	3.5	11.2	15.0
Palliatie Overig	263	4.0	6.7	11.1	161	4.1	6.3	10.8
Unknown								
LEEG!	264	5.0	11.6	17.0	202	6.1	13.2	19.8
Total	1942	6.0	16.8	23.3	984	8.6	17.1	26.3

A.2.1 Entry time

To compute the entry times, we used information from X-Care about the referral date and the date of the first consultation. For the computations we omitted incomplete entries, negative entry times (caused by acute patients who are booked after their treatment) and entry times of more than 40 days, following the department's assumption that these entries have an elective reason. Elective delays or delays caused by the unavailability of patients are hardly registered. The priority of the patients is not recorded in X-Care.

In Table A.1 the average entry times for all locations for the years 2011 and 2012 are listed. These numbers contain (a substantial part of the) acute, subacute and regular patients. In practise, not all acute patients are registered.

		Entry time	**No. of patients**
2011	AMC	5.5	1384
	Flevo	6.0	507
	ZZZ	6.5	131
	OLVG	8.7	36
	Total	5.7	2058
2012	AMC	6.1	1335
	Flevo	6.1	504
	ZZZ	7.0	142
	OLVG	6.0	4
	Total	6.2	1984

Table A.1: Average entry times (in calendar days) per location (Source: X-Care)

From Table A.1 it can be seen that the mean entry times of the AMC and Flevo hospital were higher in 2012 than in 2011. This can most likely be explained by the decreased number of patients requiring a second treatment; these patients are normally subacute.

Fluctuations in entry time

Since the number of available first consultations does not depend on the patient's arrival rate, the number of referrals is expected to influence the mean entry time. In Figure A.1, the relation between the mean entry times and the number of referrals in the same month is shown, as well as the relation with the month before. Some correlation can be observed between the number of referrals and the entry times but the entry times do not follow the number of referrals exactly.

It is also possible that the mean entry times influence the number of referrals, because patients are free to choose to be treated in another institute if the entry time is too long in their opinion. However, according to the department this rarely occurs.

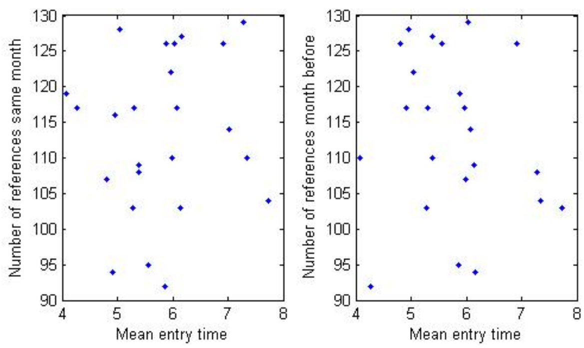

Figure A.1: Relation between number of referrals and average entry times in 2011 and 2012 per month (Source: X-Care)

Treatment type	No. of patients
Mamma (breast)	348
Bonemetastasis	204
Prostate	194
Oesophagus	122
Rectum	100
Brain	67
Lung	51
Cervix	41
Bladder	39
Palliative others	296
Curative others	164
Unknown	394
Total	2020

Table A.2: Most common patient types for treatments in 2012 (Source: Mosaiq)

A.2.2 Preparation time

To compute the preparation times, we used information from Mosaiq about the course date (we assume this is the day after the first consultation, except for OSS consultations where it is the same day) and the start date of the treatment. We omitted the treatments on orthovolt machines, and with brachytherapy and hyperthermia. The number of the most common performed treatments are given in Table A.2. Note that for 20% of the treatments the patient type is unknown: this means the treating physician omitted filling in the treatment type in Mosaiq.

In Table A.3 and A.4 the average preparation times can be seen for patients of different priorities. The preparation times more than 90 days are omitted, following the department's assumption these patients have delays for elective reasons or because they need surgery or chemotherapy before the start of the radiotherapy treatment. Also incomplete data is not taken into account.

Note that there is no subdivision of acute and subacute patients in this data. From interviews in the department we know that at most 5% of the patients is acute and most of them are treated in the weekend, outside working hours or in a OSS consultation. Compared to the influence of other irregularities, the influence of acute patients on the data is negligible and therefore it is pretended here that acute patients are not in the data set.

	AMC		**Flevo**	
Priority	Mean	No. patients	Mean	No. patients
Regular	23.4	714	22.4	362
Subacute	4.7	347	6.2	202
* Standard	7.4	209	-	-
* OSS	0.7	138	-	-
Unknown	11.2	222	11.5	173
Total	16.2	1283	15.4	737

Table A.3: Mean preparation times (in calendar days) in 2012 (Source: Mosaiq)

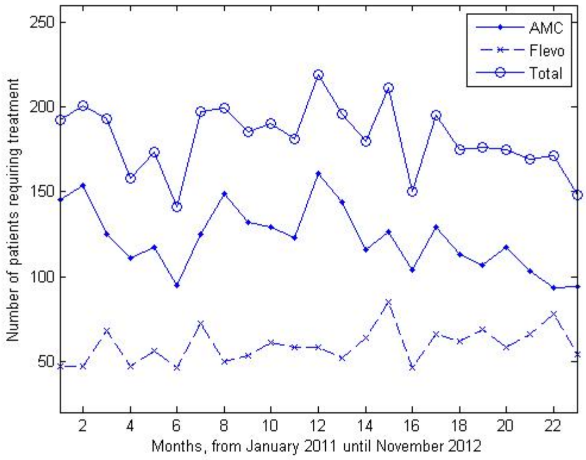

Figure A.2: Number of treatment requests per month in 2011 and 2012 (Source: Mosaiq)

	Weeks 1-36 (6 linacs)				**Weeks 37-52 (5 linacs)**			
	AMC		**Flevo**		**AMC**		**Flevo**	
Priority	Mean	No. patients	Mean	No. patients	Mean	No. patients	Mean	No. patients
Regular	24.0	551	23.7	232	21.3	163	20.1	130
Subacute	5.5	237	6.1	151	3.2	110	6.2	51
* Standard	8.2	150	-	-	5.5	59	-	-
* OSS	0.8	87	-	-	0.5	51	-	-
Unknown	10.9	168	11.4	119	12.0	54	11.8	54
Total	17.1	956	15.5	502	13.7	327	15.2	235

Table A.4: Mean preparation times in the situation with four and three linacs in the AMC in 2012 (Source: Mosaiq)

Fluctuations in preparation time

In Figure A.2 the number of requested treatments per month for 2011 and 2012 can be seen.

In Figure A.3 the relation between the mean preparation times and the number of treatment requests in the same month is shown, as well as the relation with the month before. No strong correlation can be observed, which might be an indication that the number of patients is not the only important factor influencing the preparation times.

Preparation phase in detail

The preparation phase consists of different steps. The mean number of days between several steps is displayed in Table A.5. Patients are subdivided in groups following equal trajectories; that is, the stages they need to go through in their treatment process according to their protocol are equal. Patients who follow only a part of the trajectory are not taken into consideration, neither are patients whose trajectory is (partly) unknown. The latter patients are the reason that the total number of patients in this table is less than the number of patients following the treatment path from referral to treatment, described in Table 4.2.

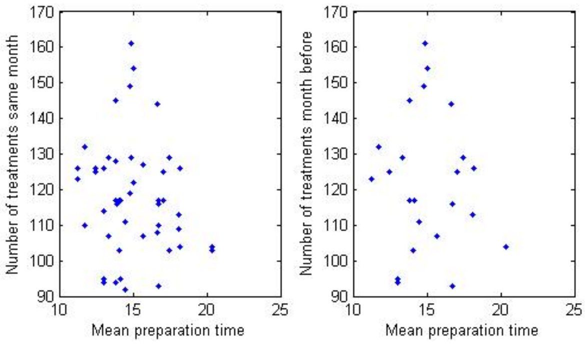

Figure A.3: Relation between number of referrals and mean entry times in 2011 and 2012 (Source: X-Care)

Note that the group following the 'normal trajectory' is by far the largest group. The mean number of days in other groups is based on a very small number of patients, so their mean is more arbitrary than that of the 'normal trajectory' group.

Unfortunately the dates at which the contouring takes place are not registered in Mosaiq. However, from the table we can still see that the prescribed five (AMC) and six (Flevo) working days between the contouring and the start of the treatment have been maintained in practice. Since the CT-sim is scheduled 10.2 and 10.0 calendar days respectively before the start of the treatment and the treatment planning is carried out 4.1 and 4.4 calendar days respectively before the treatment, this matches with our expectations that the contouring is carried out about seven and eight calendar days before the treatment. The number of days between the plan/mal check and the start of the treatment for trajectories with plan/mal however, does not reflect the prescribed one working day in between. It is not known why this is the case.

A.3 Calculations on utilization and queueing effects

These calculations support Section 4.3. The following formulas are for a M/G/1-queue, which we use to model the CT-sim and the consultations to get a global indication of the mean waiting times at these stages. The mean waiting time can be calculated from the Laplace Stieltjes transform (third form of the Pollaczek-Khinchin formula), but it can also be determined directly with the mean value approach [5]. For this, we need the arrival rate λ, the expected service time E(B) and the standard deviation of the service time σ_B.

The expected waiting time E(W) can be calculated by

$$E(W) = \frac{\rho E(R)}{1-\rho}, \tag{A.1}$$

where $\rho = \lambda E(B)$ and the expected residual waiting time E(R) is given by

$$E(R) = \frac{1}{2}(c_B^2 + 1)E(B). \tag{A.2}$$

The coefficient of correlation (c_B^2) is given by

$$c_B^2 = \frac{\sigma_B^2}{E(B)^2}. \tag{A.3}$$

	Time between stages AMC	Flevo
Normal trajectory	672 patients	469 patients
From referral to consultation	5.8	8.7
From consultation to CT-sim	11.6	8.9
From CT-sim to treatment planning	6.1	5.6
From treatment planning to start	4.1	4.4
Access time	27.6	27.6
Trajectory with Pet-CT	7 patients	2 patients
From referral to consultation	4.0	7.0
From consultation to Pet-CT	10.4	11.0
From Pet-CT to CT-sim	2.3	1.0
From CT-sim to treatment planning	7.1	5.5
From treatment planning to start	4.1	2.0
Access time	27.9	26.5
Trajectory with Pet-CT and 4d-CT	8 patients	10 patients
From referral to consultation	7.0	5.7
From consultation to Pet-CT	8.0	6.7
From Pet-CT to 4d-CT	0.5	3.2
From 4d-CT to treatment planning	9.8	10.1
From treatment planning to start	4.6	5.1
Access time	29.9	30.8
Trajectory with plan/mal	25 patients	1 patient
From referral to consultation	8.5	38.0
From consultation to CT-sim	15.9	16.0
From CT-sim to planning	7.0	5.0
From planning to plan/mal	3.1	2.8
From plan/mal to start	3.0	4.0
Access time	37.5	65.8

Table A.5: Number of calendar days between steps in the treatment process in 2012, obtained by matching data from Mosaiq

The numbers for the calculations are determined based on the data of 2012. An overview of the input data can be found in Table A.6.

	Consultations		CT-sim	
	AMC	Flevo	AMC	Flevo
Arrival rate λ (week^{-1})	25.6	9.7	35.2	13.6
Service rate (week^{-1})	31.9	11.8	46.8	23.4
Service time E(B) (min)	-	-	23.1	25.7
Service time E(B) (week)	0.0313	0.0847	0.0214	0.0428
Opening per week (hours)	-	-	18	10
ρ	80%	82%	75%	58%
σ_B^2	3.9	0.9	163.0 (min)	201.4 (min)
c_B^2	0.015	0.006	0.306	0.305
E(W) (week)	0.064	0.194	0.042	0.039

Table A.6: Data for the calculations for the mean waiting time in a M/G/1-queue

In the AMC, the CT-sim is opened eighteen hours per week (see Table 4.8) and the mean duration for a CT-sim appointment is 23.1 minutes (see Tables A.7), so the mean service rate is 18/(23.1/60) = 46.75 patients per week and the expected service time is $E(B) = 1/46.75 = 0.0214$ week. In this case, $\rho = 0.75$, quite similar with the utilization in Table 4.9. The result is $E(W) = 0.0419$ week, corresponding to twice the average duration of an appointment. So we can say the expected service time in the AMC is much smaller than one day, indicating that the capacity of eighteen hours a week in the AMC is in general enough to serve patients within one day.

For the Flevo hospital, the CT-sim is opened for ten hours per week (see Table 4.8) and the mean duration for a CT-sim appointment is 25.7 minutes (see Tables A.7), so the mean service rate is 10/(25.7/60) = 23.35 patients per week and the expected service time is $E(B) = 1/23.35 = 0.0428$ week. The utilization turns out to be $\rho = 0.58$, quite similar with the utilization in Table 4.9. The result is $E(W) = 0.0382$ week, less than the average duration of an appointment. So the expected service time in the Flevo is also much smaller than a day, which means that also the capacity of ten hours a week in the Flevo hospital is enough to generally serve patients without delay.

For the consultations in the AMC, the average number and standard deviation of consultation time slots (service) can be found in Table 4.6 for both locations. The calculations result in a waiting time of $E(W) = 0.064$ week in the AMC and $E(W) = 0.039$ in the Flevo hospital. This waiting time is similar to that of the CT-sim, calcuated above. So, the expected service time in the outpatient department is smaller than one day at both locations, indicating that the capacity of 31.9 and 11.8 consultation time slots a week is in general enough to serve patients within one day.

	AMC		**Flevo**	
	Mean	Stdev	Mean	Stdev
No. of new patients	35.9	5.5	13.9	3.4
Total duration (min)	829.4	144.0	357.4	102.6
Session duration (min)	23.1		25.7	

Table A.7: Weekly CT-sim use in 2012 (Source: Mosaiq)

	AMC		Flevo	
	Mean	Stdev	Mean	Stdev
No. of sessions per week	383.0	58.3	190.8	44.4
Total duration (min)	6041	803	2965	714
No. of new patients per week	23.4	10.1	12.3	6.1
No. of sessions per person	16.4		15.6	
Session duration (min)	15.8		15.5	

Table A.8: Weekly linac use in 2012 (Source: Mosaiq)

	Weeks 1-36 (6 units)				Weeks 37-52 (5 units)			
	AMC		Flevo		AMC		Flevo	
	Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev
Total duration (min)	6419	655	2598	460	5190	288	3789	446
No. of sessions per week	412.8	43.5	168.7	29.8	315.8	16.0	240.4	29.4
No. of new patients per week	26.1	10.8	11.8	6.9	17.0	4.2	13.31	3.3
No. of sessions per person	15.8		14.3		18.2		18.1	
Session duration (min)	15.6		15.4		16.4		15.8	

Table A.9: Weekly linac utilization in 2012, in the situation with 6 and 5 linacs (Source: Mosaiq)

A.4 Calculations on experimental setup

The warm up period can be determined by a graphical procedure due to Welch, as described in [26]. Its specific goal is to determine a time index in which the system reaches the steady-state, such that by deleting the warm up period, the consequences of starting in the initial state are minimized. Welch's procedure is based on making n independent replications of the simulation with a length m that is large enough to allow infrequent events to occur a reasonable number of times. In these runs, the considered performance measures are observed in each time period. We have made five replications of three years (1095 days). The average access time per month i, denoted by Y_i, was calculated based on all the runs. To smooth out the high-frequency oscillations in the averages, we used the moving average $Y_i(w)$ where w, the window, is taken as 1. $Y_i(w)$ is then the average of $2w+1$ observations of the averaged process centered at observation i. In Figure A.4, $Y_i(w)$ is plotted. The warm up period should be chosen as the value of i beyond which the series $Y_i(w)$ appears to have converged. In our case, the access time seems to converge after a year, although a longer simulation run should be carried out to see if it really converges. Due to practical limitations with the simulation model, we choose the warm up period to be three months.

For determining the number of replications required to estimate the average access time with a specified precision, we used a procedure described in [26]. An approximate expression for the number of replications, $n_r^*(\gamma)$ required to estimate the average access time with relative error γ, is given by

$$n_r^*(\gamma) = min\{i \geq n : \frac{t_{i-1,1-\alpha/2}\sqrt{S^2(n)/i}}{|\bar{X}(n)|} \leq \gamma'\}, \tag{A.4}$$

where $\bar{X}(n)$ is the sample mean for the average access time over n runs and $S^2(n)$ the sample variance for the average access time over n runs. $t_{n-1,1-\alpha/2}$ denotes the upper $1-\alpha/2$ critical point for the Student's t distribution with $n-1$ degrees of freedom. $\gamma' = \gamma/(1+\gamma)$ is the

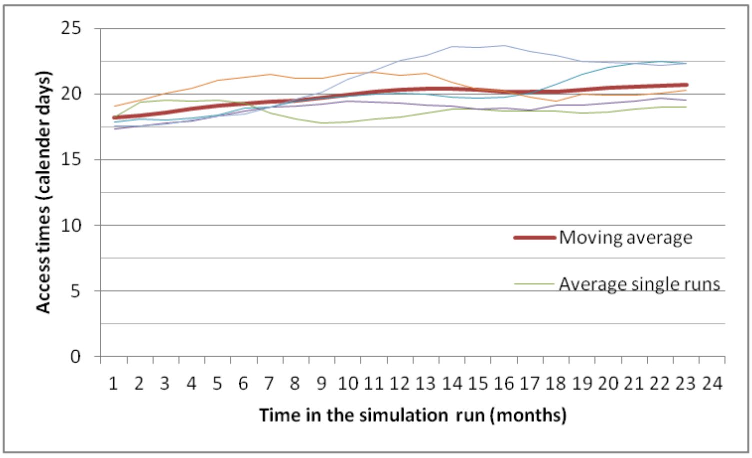

Figure A.4: Choosing a warm up period based on Welch's procedure

'adjusted' relative error needed to get an actual relative error of γ. The colon ':' is read 'such that'. In our case, it turned out that the number of replications $n = 5$ was enough to reach a relative precision of $\gamma = 0.1$.

A $100(1-\alpha)$%-confidence interval for the average access time in a run is given by

$$\bar{X}(n) \pm t_{n-1,1-\alpha/2}\sqrt{\frac{S^2(n)}{n}}. \tag{A.5}$$

This means that if $X(n)$ would be a correct estimation for the average access time (which, according to the validation, is not the case here), then we could claim that with $100(1-\alpha)$% confidence the average access time is contained in above interval.

We determined the number of replications for the basic settings of the simulation model with the current doctors' scheme. From equation A.4 and A.5 we see that the c.i. half width/mean should be smaller than γ'. When we specify $\gamma = 0.1$ we see that in this case, the last column is already smaller than $\gamma' = 0.09$ for two runs. So for the average access time, five runs per experiment is enough; however, for the access time per patient type and per priority (which are determined based on less patients), we expect that a larger number of runs is required. Further research is needed to determine the required number of runs, such that strong conclusions can be drawn on the access times per patient type.

	Access time	Mean	Stdev	Student distr	c.i. half width	c.i. half width/mean
1	18.7	18.7	-	-	-	-
2	19.1	18.9	0.28	12.71	2.54	0.13
3	19.3	19.0	0.31	4.30	0.76	0.04
4	20.0	19.3	0.54	3.18	0.87	0.04
5	21.5	19.7	1.10	2.78	1.37	0.07

Table A.10: Determining the number of replications, current situation

	Access time	Mean	Stdev	Student distr	c.i. half width	c.i. half width/mean
1	18.4	18.4	-	-	-	-
2	18.7	18.6	0.18	12.71	1.58	0.11
3	18.5	18.5	0.13	4.30	0.32	0.02
4	18.7	18.6	0.15	3.18	0.23	0.01
5	18.1	18.5	0.25	2.78	0.31	0.02

Table A.11: Determining the number of replications, intervention A1

In this case, the 90% confidence interval of the average access time in the current situation is $[18.3, 21.1]$ and in the situation of intervention A1 $[18.2, 18.8]$. However, since the validation of the simulation model is not completed, the level of confidence of the results is not very high in general; therefore the precision is not of much importance at this moment.

A.5 Basic settings of the models

An overview of the basic settings for the simulation model and the ILP model is provided in the following tables. Table A.5 is also used in the bottleneck analysis of Section 4.4. Here 'x' means that a patient type can be treated by the considered doctor. The opening hours in Table A.6 are in case of four operating linacs in the AMC. These hours are also described in Section 4.2.

Patient group	Percentage
Dermatology normal	1.6%
GE normal	5.8%
GE with Pet-CT	3.0%
GE with beads	4.5%
Gynaecology with brachy	2.4%
Gynaecology with Pet-CT	3.0%
Hematology normal	2.8%
Lung normal	0.5%
Lung with Pet-CT and 4d-CT	3.1%
Mamma with surgery	14.7%
Mamma with plan/mal	3.6%
Urology normal	2.1%
Urology with gold beads	10.6%
Urology with cystoscopy	1.0%
Urology adjuvant	0.5%
Curative others	2.8%
Palliative bonemetastasis	12.3%
Palliative others	27.4%

Table A.12: Input data simulation model

Location	Percentage
AMC	73.0%
Flevo	27.0%
Type of consultation	Percentage of subacute patients in AMC
Standard	78.0%
OSS	22.0%
Referral day	Arrival rate (no. of patients)
Monday	7.91
Tuesday	8.31
Wednesday	7.91
Thursday	8.57
Friday	6.86

Table A.13: Input data simulation model

	Stages	**Patient groups**
1	Arrival	Dermatology normal
2	Consultation	GE normal
3	Beads	GE with Pet-CT
4	Gold beads	GE with beads
5	Pet-CT	Gynaecology with brachy
6	4d-CT	Gynaecology with Pet-CT
7	Cystoscopy	Hematology normal
8	CT-sim	Lung normal
9	Contouring	Lung with Pet-CT and 4d-CT
10	Plan/mal check	Mamma with surgery
11	Start treatment	Mamma with plan/mal
12		Urology normal
13		Urology with gold beads
14		Urology with cystoscopy
15		Urology adjuvant
16		Curative others
17		Palliative bonemetastasis
18		Palliative others

Table A.14: Settings of the ILP model

AMC

Doctor:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Dermatology normal	x				x									x	x		x	x		
GE normal	x	x	x	x						x							x	x	x	
GE with beads	x	x	x	x						x							x	x	x	
GE with Pet-CT	x	x	x	x						x							x	x	x	
Gynaecology with brachy	x							x								x	x	x		x
Gynaecology with Pet-CT	x							x								x	x	x		x
Hematology normal	x				x												x	x		
Lung normal	x								x								x	x		
Lung with Pet-CT and 4d-CT	x								x								x	x		
Mamma with surgery	x			x			x				x	x	x				x	x	x	
Mamma with plan/mal	x			x			x				x	x	x				x	x	x	
Urology normal	x	x	x			x											x	x		x
Urology with gold beads	x	x	x			x											x	x		x
Urology with cystoscopy	x	x	x			x					x	x	x				x	x		x
Urology adjuvant	x	x	x			x											x	x		x
Curative others	x	x	x	x	x	x	x	x	x	x										
Palliative bonemetastasis	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Palliative others	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

FLEVO

Doctor:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Dermatology normal				x	x		x		x	x		x	x		x					
GE normal				x	x		x		x	x		x	x		x					
GE with beads				x	x		x		x	x		x	x		x					
GE with Pet-CT				x	x		x		x	x		x	x		x					
Gynaecology with brachy				x	x		x		x	x		x	x		x					
Gynaecology with Pet-CT				x	x		x		x	x		x	x		x					
Hematology normal				x	x		x		x	x		x	x		x					
Lung normal				x	x		x		x	x		x	x		x					
Lung with Pet-CT and 4d-CT				x	x		x		x	x		x	x		x					
Mamma with surgery				x	x		x		x	x		x	x		x					
Mamma with plan/mal				x	x		x		x	x		x	x		x					
Urology normal				x	x		x		x	x		x	x		x					
Urology with gold beads				x	x		x		x	x		x	x		x					
Urology with cystoscopy				x	x		x		x	x		x	x		x					
Urology adjuvant				x	x		x		x	x		x	x		x					
Curative others				x	x		x		x	x		x	x		x					
Palliative bonemetastasis				x	x		x		x	x		x	x		x					
Palliative others				x	x		x		x	x		x	x		x					

Figure A.5: Compatibility of patient groups to physicians in the AMC and Flevo hospital, based on the physician's scheme of December 2012

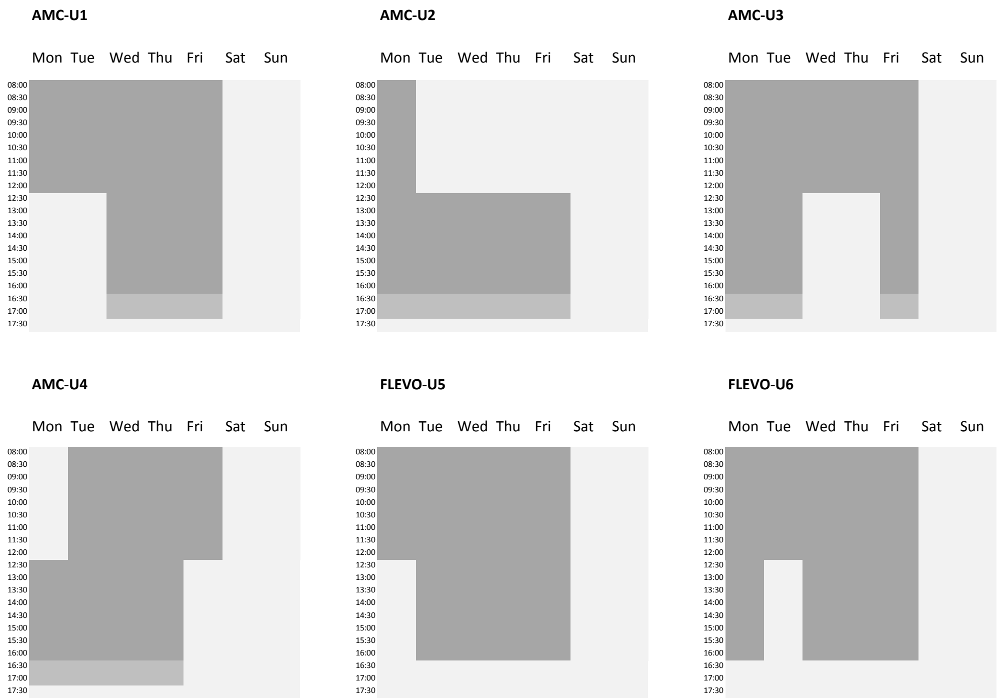

Figure A.6: Weekly opening hours of the linacs in the AMC and the Flevo hospital in the beginning of 2012

Basic settings

		n_prl	
p	r	l=1	l=2
1	1	0,07	0,04
1	2	0,08	0,04
1	3	0,07	0,04
1	4	0,08	0,04
1	5	0,07	0,03
2	1	0,49	0,25
2	2	0,51	0,26
2	3	0,49	0,25
2	4	0,52	0,27
2	5	0,43	0,22
3	1	0,31	0,05
3	2	0,32	0,05
3	3	0,31	0,05
3	4	0,33	0,05
3	5	0,27	0,04
4	1	0,21	0,04
4	2	0,22	0,04
4	3	0,21	0,04
4	4	0,23	0,04
4	5	0,19	0,03
5	1	0,31	0,00
5	2	0,33	0,00
5	3	0,31	0,00
5	4	0,34	0,00
5	5	0,27	0,00
6	1	0,12	0,00
6	2	0,12	0,00
6	3	0,12	0,00
6	4	0,13	0,00
6	5	0,10	0,00
7	1	0,19	0,03
7	2	0,20	0,03
7	3	0,19	0,03
7	4	0,21	0,03
7	5	0,17	0,03
8	1	0,03	0,01
8	2	0,03	0,01
8	3	0,03	0,01
8	4	0,03	0,01
8	5	0,02	0,01
9	1	0,18	0,13
9	2	0,18	0,14
9	3	0,18	0,13
9	4	0,19	0,14
9	5	0,15	0,11

		n_prl	
p	r	l=1	l=2
10	1	0,69	1,09
10	2	0,72	1,14
10	3	0,69	1,09
10	4	0,75	1,17
10	5	0,60	0,95
11	1	0,36	0,00
11	2	0,37	0,00
11	3	0,36	0,00
11	4	0,39	0,00
11	5	0,31	0,00
12	1	0,18	0,09
12	2	0,18	0,09
12	3	0,18	0,09
12	4	0,19	0,10
12	5	0,15	0,08
13	1	0,94	0,33
13	2	0,99	0,35
13	3	0,94	0,33
13	4	1,02	0,36
13	5	0,83	0,29
14	1	0,14	0,02
14	2	0,14	0,02
14	3	0,14	0,02
14	4	0,15	0,02
14	5	0,12	0,02
15	1	0,06	0,01
15	2	0,07	0,01
15	3	0,06	0,01
15	4	0,07	0,01
15	5	0,05	0,01
16	1	0,29	0,05
16	2	0,30	0,05
16	3	0,29	0,05
16	4	0,31	0,05
16	5	0,25	0,04
17	1	0,73	0,20
17	2	0,76	0,21
17	3	0,73	0,20
17	4	0,79	0,22
17	5	0,64	0,17
18	1	1,25	0,71
18	2	1,31	0,74
18	3	1,25	0,71
18	4	1,35	0,76
18	5	1,09	0,62

Basic settings

	g_al	
a	**l=1**	**l=2**
1	2	0
2	0	0
3	1	0
4	0	1
5	3	2
6	3	0
7	0	1
8	3	0
9	1	2
10	0	1
11	1	0
12	0	2
13	0	3
14	3	0
15	0	4
16	4	0
17	4	0
18	3	0
19	2	0
20	4	0

	h_a
a	
1	2
2	0
3	2
4	2
5	2
6	1
7	1
8	1
9	1
10	2
11	1
12	2
13	1
14	4
15	3
16	2
17	2
18	1
19	2
20	2

Intervention B5

	g_al	
a	**l=1**	**l=2**
1	2	0
2	2	0
3	1	0
4	1	1
5	3	2
6	3	0
7	1	1
8	3	0
9	1	2
10	1	1
11	2	0
12	0	2
13	0	3
14	3	0
15	0	4
16	4	0
17	4	0
18	3	0
19	2	0
20	4	0

	h_a
a	
1	2
2	2
3	2
4	2
5	2
6	1
7	1
8	1
9	1
10	2
11	1
12	2
13	1
14	4
15	3
16	2
17	2
18	1
19	2
20	2

Basic settings

c_adl		d									
l	a	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
1	*1*	1	1	1	1	1	1	1	1	1	1
1	*2*	1	1	1	1	1	1	1	1	1	1
1	*3*	1	1	1	1	1	1	1	1	1	1
1	*4*	1	1			1	1	1	1	1	1
1	*5*	1	1	1	1	1	1	1	1		
1	*6*	1	1	1	1	1	1	1	1	1	1
1	*7*			1	1	1	1	1	1	1	1
1	*8*	1	1	1	1	1	1	1	1	1	1
1	*9*	1	1	1	1			1	1	1	1
1	*10*	1	1	1	1	1	1			1	1
1	*11*	1	1	1	1	1	1	1	1	1	1
1	*12*			1	1	1	1	1	1	1	1
1	*13*	1	1					1	1	1	1
1	*14*	1	1	1	1	1	1	1	1	1	1
1	*15*			1	1	1	1			1	1
1	*16*	1	1	1	1	1	1	1	1	1	1
1	*17*	1	1	1	1	1	1	1	1	1	1
1	*18*	1	1	1	1	1	1	1	1	1	1
1	*19*	1	1	1	1	1	1	1	1	1	1
1	*20*	1	1	1	1	1	1	1	1	1	1
2	*1*										
2	*2*										
2	*3*										
2	*4*			1	1						
2	*5*									1	1
2	*6*										
2	*7*	1	1								
2	*8*										
2	*9*					1	1				
2	*10*							1	1		
2	*11*										
2	*12*	1	1								
2	*13*			1	1	1	1				
2	*14*										
2	*15*	1	1					1	1		
2	*16*										
2	*17*										
2	*18*										
2	*19*										
2	*20*										

Basic settings v_pst (partly)

v_pst		t										
p	s	1	2	3	4	5	6	7	8	9	10	11
1	1		1						1	1		1
1	2								1	1		1
1	3											
1	4											
1	5											
1	6											
1	7											
1	8									1		1
1	9											1
1	10											
2	1		1						1	1		1
2	2								1	1		1
2	3											
2	4											
2	5											
2	6											
2	7											
2	8									1		1
2	9											1
2	10											
3	1		1	1					1	1		1
3	2			1					1	1		1
3	3								1	1		1
3	4											
3	5											
3	6											
3	7											
3	8									1		1
3	9											1
3	10											
4	1		1			1			1	1		1
4	2					1			1	1		1
4	3											
4	4											
4	5								1	1		1
4	6											
4	7											
4	8									1		1
4	9											1
4	10											
5	1		1						1	1		1
5	2								1	1		1
5	3											
5	4											
5	5											
5	6											
5	7											
5	8									1		1
5	9											1
5	10											
6	1		1			1			1	1		1
6	2					1			1	1		1
6	3											
6	4											
6	5								1	1		1
6	6											
6	7											
6	8									1		1
6	9											1
6	10											
7	1		1						1	1		1
7	2								1	1		1
7	3											
7	4											
7	5											
7	6											
7	7											
7	8									1		1
7	9											1
7	10											

v_pst		t										
p	s	1	2	3	4	5	6	7	8	9	10	11
8	1		1						1	1		1
8	2								1	1		1
8	3											
8	4											
8	5											
8	6											
8	7											
8	8									1		1
8	9											1
8	10											
9	1		1			1	1			1		1
9	2					1	1			1		1
9	3											
9	4											
9	5						1			1		1
9	6									1		1
9	7											
9	8											
9	9											1
9	10											
10	1		1						1	1		1
10	2								1	1		1
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10	8									1		1
10	9											1
10	10											
11	1		1						1	1	1	1
11	2								1	1	1	1
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11	8									1	1	1
11	9										1	1
11	10											1
12	1		1						1	1		1
12	2								1	1		1
12	3											
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12	8									1		1
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13	1		1		1				1	1		1
13	2				1				1	1		1
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13	5											
13	6											
13	7											
13	8									1		1
13	9											1
13	10											
14	1		1					1	1	1		1
14	2							1	1	1		1
14	3											
14	4											
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14	6											
14	7								1	1		1
14	8									1		1
14	9											1
14	10											

Basic settings q_pstl (partly)

q_pstl		t=1	2	3	4	5	6	7	8	9	10	11	1	2	3	4	5	6	7	8	9	10	11
p	s	l=1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2
1	1		0											0									
1	2								3											3			
1	3																						
1	4																						
1	5																						
1	6																						
1	7																						
1	8									0											0		
1	9											13											15
1	10																						
2	1		0											0									
2	2								3											3			
2	3																						
2	4																						
2	5																						
2	6																						
2	7																						
2	8									0											0		
2	9											13											15
2	10																						
3	1		0											0									
3	2			3											3								
3	3								7											7			
3	4																						
3	5																						
3	6																						
3	7																						
3	8									0											0		
3	9											13											15
3	10		0											0									
4	1					3											3						
4	2																						
4	3																						
4	4								0											0			
4	5																						
4	6																						
4	7									0											0		
4	8											13											15
4	9																						
4	10		0											0									
5	1								3											3			
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5	7									0											0		
5	8											13											15
5	9																						
5	10		0											0									
6	1					3											3						
6	2																						
6	3																						
6	4								0											0			
6	5																						
6	6																						
6	7									0											0		
6	8											13											15
6	9																						
6	10		0											0									
7	1								3											3			
7	2																						
7	3																						
7	4																						
7	5																						
7	6																						
7	7									0											0		
7	8											13											15
7	9																						
7	10		0											0									

A.6 More results of the simulation model

In this appendix, more results of the several investigated interventions are given.

Situation	Average AT	≤8 days	≤ 10 days
now	13,8	16%	23%
A1	13,4	16%	18%
A2	12,7	16%	19%
A3	12,5	16%	19%
A4	12,4	16%	25%
A5	11,7	16%	25%
B1	13,4	16%	25%
B2	12,6	16%	24%
B3	12,9	16%	19%
B4	13,2	16%	18%
B5	13,0	16%	18%
C1	12,6	16%	22%

Table A.15: Norm evaluation for subacute patients in the simulation model

Situation	Average AT	≤21 days	≤ 28 days
now	23,5	50%	80%
A1	19,9	70%	95%
A2	18,0	77%	97%
A3	18,1	75%	96%
A4	18,9	71%	97%
A5	18,1	77%	96%
B1	22,2	59%	86%
B2	18,7	73%	96%
B3	18,9	72%	96%
B4	20,6	63%	93%
B5	18,9	71%	96%
C1	18,1	75%	97%

Table A.16: Norm evaluation for regular patients in the simulation model

		now	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	C1
AMC	Referral-Consultation	4.3	1.9	1.4	1.3	1.7	1.7	3.8	1.8	1.8	1.8	1.4	1.4
	Consultation-Contouring	9.2	8.3	7.3	7.2	7.6	6.6	8.5	8.1	8.3	8.3	8.3	7.9
	Contouring-Start	8.3	8.1	7.7	7.7	7.7	7.8	8.1	7.4	7.4	9.1	7.7	7.3
Flevo	Referral-Consultation	1.4	1.4	1.4	1.4	1.6	1.5	1.4	1.4	1.4	1.4	1.4	1.4
	Consultation-Contouring	7.4	7.7	7.3	7.4	7.0	6.7	7.4	7.6	7.8	7.8	7.2	7.3
	Contouring-Start	9.9	9.3	9.4	9.4	9.5	9.0	9.7	8.6	8.6	8.6	9.4	9.1
Total	Referral-Consultation	3.5	1.7	1.3	1.3	1.6	1.6	3.1	1.6	1.6	1.6	1.4	1.3
	Consultation-Contouring	8.4	7.8	7.0	6.9	7.2	6.4	7.9	7.6	7.9	7.9	7.7	7.4
	Contouring-Start	8.3	8.1	7.8	7.8	7.8	7.7	8.1	7.4	7.4	8.6	7.8	7.4

Table A.17: Average access times in the simulation model. split up in different phases

Patient type	now	A1	A2	A3
CurativeOthers	17.3	16.6	15.4	15.0
DermatologyNormal	15.8	15.1	14.4	15.0
GEBeads	32.4	26.1	25.8	25.7
GENormal	19.9	17.1	15.1	14.9
GEPetCT	24.8	20.5	19.3	19.9
GynaecologyBrachy	16.4	16.8	14.9	14.9
GynaecologyPetCT	20.5	20.0	18.9	19.7
HematologyNormal	16.3	15.8	15.1	14.5
LungNormal	19.7	17.5	14.7	15.2
LungPetCT4dCT	24.9	21.1	19.5	20.4
MammaPlanMal	27.0	19.0	16.1	16.5
MammaSurgery	24.6	18.0	14.9	15.1
UrologyAdjuvant	18.2	16.8	14.8	14.7
UrologyCystoscopy	29.3	24.8	25.3	25.7
UrologyGoldBeads	25.1	22.0	23.0	23.1
UrologyNormal	17.9	16.2	14.6	14.6
PalliativeBonemetastasis	13.8	14.3	12.8	12.4
PalliativeOthers	13.7	14.2	12.6	12.5

Table A.18: 80-percentile of the access times per patient group in the simulation model

Patient type	now	A1	A2	A3
CurativeOthers	2.1	1.4	1.4	1.4
DermatologyNormal	1.8	1.5	1.4	1.3
GEBeads	4.5	2.1	1.5	1.4
GENormal	4.3	2.0	1.4	1.4
GEPetCT	4.6	2.1	1.4	1.4
GynaecologyBrachy	1.5	1.4	1.4	1.4
GynaecologyPetCT	1.7	1.4	1.5	1.4
HematologyNormal	2.2	1.9	1.3	1.4
LungNormal	2.3	1.7	1.4	1.2
LungPetCT4dCT	2.0	1.6	1.5	1.3
MammaPlanMal	9.1	2.7	1.4	1.3
MammaSurgery	8.4	2.6	1.4	1.4
UrologyAdjuvant	1.5	1.2	1.3	1.2
UrologyCystoscopy	1.7	1.5	1.3	1.3
UrologyGoldBeads	1.8	1.5	1.4	1.4
UrologyNormal	1.7	1.5	1.4	1.3
PalliativeBonemetastasis	1.5	1.4	1.3	1.3
PalliativeOthers	1.5	1.4	1.4	1.4

Table A.19: 80-percentile of the entry times per patient group in the simulation model