Designing a blueprint schedule for the brachytherapy department using discrete event simulation and linear programming

M.Sc. Thesis

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Management Summary

Problem definition

In 2018, Amsterdam UMC originated from the merger of two academic hospitals, the Academic Medical Centre (AMC) and the VU medical center (VUmc). As a result of the merger, the radiotherapy department will, in the future, primarily be based at the VUmc location. The radiotherapy department offers external beam radiotherapy, brachytherapy, and hyperthermia treatment. The focus of this study will be on the brachytherapy treatment. Brachytherapy is a type of radiotherapy where the radiation source is placed inside the target area. Due to the merger, the brachytherapy department will move to location VUmc in the first quarter of 2025. However, the brachytherapy must first move within the AMC location to a temporary location in July 2023. The time that the brachytherapy takes place at the temporary location is called the bridging phase.

The available resources during the bridging phase differ from the current situation. However, the goal of Amsterdam UMC is to keep the quantity of care at the same level while guaranteeing the quality of care. The expectation is that the demand for operating room (OR) time will increase drastically due to different available facilities and changes in the treatment process during the bridging phase. That is why this research is revolved around answering the following question:

"How to optimally deploy personnel and material resources for the brachytherapy treatment process during the bridging period at the AMC location so that the quality of the treatment is guaranteed and at least the same number of patients are treated?"

Therefore, the objective of this study is to create an appointment and staff-shift schedule for the brachytherapy treatment during the bridging phase, striving to treat the same number of patients as in the current situation within the capacity limitations faced in the bridging phase.

Research approach

After all treatment types of brachytherapy are identified and analyzed, a literature review is conducted to explore the different methods used for multi-disciplinary scheduling and master surgery scheduling. These topics are selected because brachytherapy involves multiple interrelated appointments per patient and one of those appointments is an OR intervention. That is why the appointment and staff-shift schedule that is the purpose of this thesis combines multi-disciplinary appointment scheduling and master surgery scheduling.

Based on the results of the literature review, we decided to integrate a master surgery schedule with multi-discipline appointment scheduling, where a discrete event simulation (DES) model is used as an evaluation tool. A 3-phase approach is proposed. Phase 1 consists of constructing all feasible brachytherapy master surgery schedules for one OR day with the use of a DES model. A schedule is feasible when the interventions in the OR finish on time, and there is enough time and capacity for the required following appointment on a treatment day. Phase 2 creates a complete schedule of all appointment types for each feasible OR schedule with an integer linear programming (ILP) model. In other words, for each combination of surgery types in one OR day, a schedule is made, including preparation appointments and non-OR interventions. Maximizing the number of starting patients that do not require an OR intervention is the objective of this ILP model. These schedules are evaluated using a DES. Phase 3 develops planning rules to identify which schedule to use in which situation using decision trees. The resulting proposed way of working in the bridging phase will again be tested in a DES.

Results

OR days

Based on the current process time and the staff configuration, there are nine feasible brachytherapy master surgery schedules (MSS). One of these schedules consists of three interventions on one day, and five consist of two OR interventions per day. In addition, there are also three combinations that consist of one intervention. Essential for these OR days is that the personnel works in shifts. Otherwise, only three OR combinations fulfill the overtime condition.

From the experiments conducted, it can be stated that reducing the process times influences the range of options available during an OR day and enhances the number of interventions performed on an OR day more than increases the number of personnel. However, if, in the short term, it is not possible to reduce the process times, the addition of one radiotherapy technologist (RTT) also increases the OR day possibilities. When more options are feasible, and these options consist of more OR interventions in one day, this could lead to more flexibility in planning patients, lower access time, and a higher number of treated patients.

Complete week schedules

The output of the ILP model is an appointment schedule and the number of new ring patients that can start treatment that week. It follows that for every week's schedule constructed, at least one HDR ring can start each week. However, around four new ring patients can start each week in most week schedules. Nevertheless, to make these schedules possible, it is essential that the number of RTTs on specific workdays change and thus have a different availability.

Evaluation decision tree for blueprint selection

Decision trees are constructed that indicate what OR combination to use based on the OR combination and week constraints and the number of patients that can be scheduled in the week. The aim of these decision trees is to minimize access time and maximize OR capacity. Compared to the strategy currently used, first-come-first-served, the performance of the decision tree is slightly better regarding the access time, improvement of ∼5 percent (depending on treatment type), and slightly worse regarding OR utilization, ∼1 percent.

Prospective assessment using a DES model

When the number of radiotherapists, RTTs, and the process times stay the same during the bridging phase, and the OR time also stays constant, most patients can be treated if three full OR days in 4 weeks are used and not another configuration. In that case, the average number of treated patients will be 127.3, which is a decrease of 26.4 percent compared to the current situation. Having four full OR days and four morning OR days in four weeks will lead to 161.2 patients, which is a decrease of 6.8 percent.

When the OR capacity stays constant, regardless of the OR capacity configuration, the number of employees, or the improvement of process time, it is impossible to annually treat the same number of patients during the bridging phase as during the current situation. The only setting for which the current number of patients is met is if there is a process time reduction of 25 percent and one full OR day and one half OR day per week is available.

Conclusion

To implement this study into practice, two steps need to be taken. First, developing a scheduling program that automatically states the dates to plan an appointment is important. In addition, it is crucial to monitor the performance of the brachytherapy department to adjust the models when necessary.

However, after implementing this, with the current OR time, it is impossible to treat the same number of patients annually during the bridging phase as during the current situation. Even a process time reduction of 25 percent is not enough to reach that goal. The number of patients treated yearly increases significantly when more OR time is available. However, the only setting for which the current number of patients is met is if there is a process time reduction of 25 percent and one full OR day and one half OR day per week is available. However, when a production loss of 10 percent is considered acceptable, one full OR day per week and one OR morning per two weeks, combined with a process time reduction of 10 percent or an extra RTT, ensures that more than 160 patients can be treated annually.

This thesis offers valuable theoretical insights because, to the best of our knowledge, there is no paper in which a schedule was made for OR interventions where appointments were required before and after the intervention. This study shows how a master surgery schedule was combined with multi-disciplinary scheduling. For practical contribution, this study shows how it could be incorporated in a relatively small department, but it could also be applied within the whole radiotherapy department. In addition, this research's outcome helps simplify the planning process.

Acknowledgements

Dear reader,

I am pleased to finalize my thesis, which marks the completion of my Master's degree in Industrial Engineering and Management at the University of Twente. After finishing my bachelor's at the Eindhoven University of Technology, I transferred to the University of Twente to follow the specialization in Healthcare Technology & Management. That is why Amsterdam UMC was the perfect place to apply the theoretical knowledge from my studies in a practical setting and to learn how it is to work in a multi-disciplinary team. However, I could not have completed this research without the help of several individuals, and I would like to take this opportunity to express my gratitude to them.

First, I want to thank my supervisor at Amsterdam UMC, Danique Barten. Thank you for being so enthusiastic and closely involved in the project. You made me feel super welcome in the brachy team. I would also like to thank my colleague Suzanne van Elst. Thank you for providing me with the data and being a great sparring partner. This has helped me enormously. In addition, I would like to thank all my other colleagues for their contributions and collaboration.

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Lastly, I want to express my gratitude to my friends, family, and especially my boyfriend. Your interest and unwavering support mean so much to me. I apologize for being a bit moody at times due to some stress, but please know that I am grateful to all of you.

Lente Christan
Utrecht, August 2023

Contents

List of Acronyms

AMC	Academic Medical Center
BSP	block scheduling with priority
CI	confidence interval
CT	computed tomography
DA	doctor's assistant
DES	discrete event simulation
EBRT	external beam radiotherapy
F5N	nursing ward F5 North
FCFS	first-come-first-served
HDR	high dose rate
ILP	integer linear programming
KPI	key performance indicators
LDR	low dose rate
MCS	Monte Carlo simulation
MDO	multidisciplinary consultation
MPE	medical physicist expert
MIP	mixed-integer programming
MOPSO	multi-objective particle swarm optimization
MPSM	managerial problem-solving method
MRI	magnetic resonance imaging
MSS	master surgery schedule
NVRO	Dutch Association of Radiotherapy and Oncology
OR	operating room
PDR	pulse dose rate
RTT	radiotherapy technologist
UMC	university medical centers
VUmc	VU Medical Center

Chapter 1

Introduction

This chapter introduces the research on appointment and staff-shift scheduling of the brachtherapy department of Amsterdam university medical centers (UMC) during the bridging phase. Section 1.1 discusses the context description of the research. In Section 1.2 the research motivation is descripted. Section 1.3 continuous with the problem description. Last, in Section 1.4 the research design in discussed.

1.1 Context description

Amsterdam UMC is an academic hospital with more than 16,000 employees who work together to achieve the three core businesses (Amsterdam UMC, n.d.-a). The first core task is to provide high-quality patient care. Second, Amsterdam UMC conducts scientific research to create new treatments for patient care and disease prevention. The third core task is to provide education to ensure the sustainability of healthcare.

One department of Amsterdam UMC is the radiotherapy department. Radiotherapy is a treatment type within oncology and performs treatment with radiation. The radiotherapy department performs three types of treatment: external beam radiotherapy (EBRT), brachytherapy, and hyperthermia. When EBRT is performed, a tumor is irradiated from the outside through the skin. When brachytherapy is performed, the radiation source is placed inside the tumor. That is why brachytherapy is also referred to as internal radiotherapy. Hyperthermia is a treatment where heat is used to kill cancer cells. The focus of this research will be on brachytherapy treatment.

1.2 Research motivation

Amsterdam UMC originated from the merger of two academic hospitals (Academic Medical Center (AMC) and VU Medical Center (VUmc)) in 2018 with the idea of achieving an even higher level of patient care for current and future patients (Amsterdam UMC, n.d.-b).

This merger resulted in a new distribution of different types of care over the two hospital locations. Some departments, including the oncology department, will be concentrated in one area. Clustering a specific patient group in one place will, expectedly, attain a higher quality of patient care. However, only some departments cluster because some departments are necessary for both hospitals. For example, radiology, which uses imaging technology to diagnose and treat disease, will stay at both locations.

One of the departments that will cluster is brachytherapy. The department is now mainly concentrated in the AMC location and will move to the VUmc location because that location is assigned to be the specialized oncology location. The goal is that the brachytherapy moves to location VUmc in the first quarter of 2025. However, the brachytherapy must first move within the AMC location to a temporary location in July 2023. This is because they must make space for another department using their current site. The time that the brachytherapy takes place at the temporary location is called the bridging phase.

During this bridging phase, the department temporarily transitions to other facilities and different equipment availability. However, there is no plan for the new logistics, the planning, and the deployment of personnel and materials. Furthermore, this can endanger the quality of care and cause extra pressure on the personnel.

1.3 Problem description

1.3.1 The organization's problem

The available resources during the bridging phase differ from the current situation. However, the goal of Amsterdam UMC is to keep the quantity of care at the same level while guaranteeing the quality of patient care. The expectation is that the demand for operating room (OR) time will increase drastically due to different available facilities and changes in treatment possibilities. In addition, the pressure on personnel is expected to increase as well. That is why it is crucial to identify which factors influence resource utilization, to what extent, and the duration of the complete treatment process. Those factors are hard to identify because of the mutual dependency between different stadia. These concerns lead to the main question of Amsterdam UMC:

"How to optimally deploy personnel and material resources for the brachytherapy treatment process during the bridging period at the AMC location so that the quality of the treatment is guaranteed and at least the same number of patients are treated?"

1.3.2 Planning and control decisions

Amsterdam UMC wants to know how to deploy its personnel and material resources during the bridging period. In other words, they want to design and organize their processes, also known as planning and control. Planning and control involves setting goals and deciding beforehand what to do, how and when to do it, and who should do it. The goal is already determined: to guarantee the quality of care and keep the quantity of care at the same level. However, the question remains the what, how, when, and who.

Decisions must be made at four hierarchical levels to answer those questions. According to Hans et al. (2012), there are three hierarchical levels: strategic, tactical, and operational. The operational level is split into offline operational and online operational. The planning and control decisions per level are discussed based on the taxonomic classification of planning decisions in health care written by Hulshof et al. (2012). The decisions that need to be made are based on the type of health care service, and brachytherapy is classified as an ambulatory care service. Table 1.1 shows an overview of all the decisions.

Table 1.1: Decisions regarding planning & control

Level	Planning decision	What to decide?	Decision made?
Strategic	Regional coverage	The number, size, and location of facilities in a certain region	Yes
	Service mix	The patient type of consulting	Yes
	Case mix	The volume and composition of patient groups that the facility serves	Yes
	Panel size	The number of potential patients of an ambulatory care facility	Yes
	Capacity dimensioning: - Consultation rooms - Staff - Consultation time capacity - Equipment - Waiting room	The number of available resources	Yes, regarding consultation rooms. staff, equipment, and waiting room No, regarding consultation time capacity
	Facility layout	The positioning and organization of various physical areas in a facility	Yes, however, the only uncertainty is where the patient will stay if they need to spend the night in the hospital
Tactical	Patient routing	The composition and sequence of different stages	No
	Capacity allocation	The subdivision of resources over the patient groups	No
	Temporary capacity change	The possibility to temporarily adjust capacity	Yes
	Access policy	The type of waiting list management	Yes
	Admission control	The rules according to which patients are selected to be admitted from the waiting lists	Yes
	Appointment scheduling	The design of blueprints that can be used to provide a specific time and date for patient consultation	No
	Staff-shift scheduling	The selection of what shifts to work and the number of employees assigned to each shift	No
Offline operational	Patient-to-appointment assignment: - Single appointment - Combination appointment - Appointment series	The appointment at a particular time slot to assign to a particular patient	No
	Staff-to-shift assignment	The date and time that is given to staff members to perform particular shifts	No
Online operational	Dynamic patient (re)assignment	The appointment to reschedule	No
	Staff rescheduling	The adjustment to the staff capacity	No

Note: the decisions marked in orange are the focus of this thesis

Strategic decisions

Strategic planning concerns structural decisions, and it involves defining the organization's mission and translating that mission into the development and design of the process (Hans et al., 2012). These decisions are made over a long planning horizon. According to Hulshof et al. (2012), six strategic planning decisions exist.

The first decision is the regional coverage decision, which determines the number, size, and location of facilities in a particular region. The tradeoff of this decision is between patient accessibility and efficiency. During the bridging phase, this decision is already made. The decision is to have the same as the current levels according to number, size, and location.

Which patient types are consulted, referred to as service mix, is the second decision. The type of patients consulted during the bridging period will not change and thus is the same as the current patient types. In addition, a decision strongly related to the patient types is the decision about the volume and composition of patient groups. This decision, again, will remain the same during the bridging period. The number of potential patients, called panel size, will also stay constant. From the panel size, only a fraction will need care; thus, the panel size is bigger than the number of patients that can be helped.

The fifth strategic decision is regarding the dimensioning of the capacity. For five different resource types, the capacity needs to be dimensioned. These are the number of consultation rooms, the number of staff available, the total consultation time, the number of available equipment, and the dimensioning of the waiting room. The capacity is known during the bridging phase for four resource types, and only the consultation time capacity has yet to be determined. However, this decision is not made at the ambulatory care level but at a higher level and depends on other departments. Hence, the decision still needs to be made; however, it is considered a given in the future.

The last strategic decision concerns the facility layout. This layout states the positioning and organization of various physical areas. Most of the locations of the physical areas are already determined. However, the areas where patients must wait between different treatments/procedures have yet to be decided.

Tactical decisions

One level under the strategic decision-making level is tactical decision-making. These decisions concern the organization of the operations (Hans et al., 2012). However, these decisions are made on a shorter term than strategic decisions on a longer horizon than operational decision-making. Tactical decisions can be interpreted as the decisions that translate strategic decisions into guidelines that then facilitate organizational decisions. There are six types of tactical decisions (Hulshof et al., 2012).

One tactical decision is patient routing. This encompasses the composition and sequence of different stages in the care process. The sequence of stages a patient undergoes is known. However, the composition depends on the facility layout. However, the layout is unknown, so the composition is also unknown. In addition, it is unclear for some steps where in which space to perform it.

The second decision follows from the strategic decision of capacity dimensioning. This decision concerns the allocation of patient groups to available resources. At this point, this decision is not taken. There is no assignment of patient groups to resources or available resources that are subdivided into patient groups. Another decision is if there is a possibility to change the capacity temporarily. This is sometimes possible by asking the gynecology department for some of their OR-time.

In addition, decisions need to be made regarding waiting list management. Different approaches can be chosen. The traditional approach is to have one queue for each doctor. Another policy is to have one joint queue where a patient is treated by the first doctor available. In addition, there is a walk-in policy where patients do not have a scheduled appointment. The last access approach is called advanced access. With this, some of the appointment slots are left open for walk-ins. In this case, there is one joint queue and no walk-ins. Related to the access policy is the decision regarding admission control. This policy involves rules that explain which patients are selected from the waiting list. This is based on general regulations for brachytherapy of the Dutch Association of Radiotherapy and Oncology (NVRO), and according to those regulations, patients are selected.

The fifth tactical decision is regarding appointment scheduling. An appointment schedule is a blueprint that provides specified times and dates for patient consultation. A patient consultation can, for example, be an magnetic resonance imaging (MRI) scan, a doctor visit, or a surgical procedure. The trade-off for appointment scheduling is between patient waiting time and resource idle time. Multiple key decisions can be taken to design an appointment schedule. The critical decisions are the number of patients per consultation session, patient overbooking, length of the appointment interval, the number of patients per appointment slot, sequence of appointments, queue discipline in the waiting room, and anticipation for unscheduled patients. At this point, no decision has been made regarding the appointment schedule.

The last tactical decision is to select what shifts are to be worked and the number of staff required per shift. This decision is based on patient demand. The more attractive a staff-shift schedule, the better job satisfaction and productivity. In addition, it can reduce turnover.

Offline operational decisions

Decisions concerning the execution of the care process are classified as operational decisions (Hans et al., 2012). The difference between online and offline operational decisions is that offline decisions are made in advance. At the same time, online decisions react to unforeseen events but are also concerned with monitoring the process.

Two offline operational decisions need to be made. The first decision is based on the appointment scheduling decision. The blueprint is filled in with patients. The other decision is to assign particular staff to the staff-shift schedule and, thus, to assign staff members to a particular shift. Both decisions are based on the previously mentioned schedules, and because those are not determined, these decisions are also not determined.

Online operational decisions

The decisions made at the offline operational level cannot always be executed because of unforeseen circumstances. That is why patient and staff (re)assignment and rescheduling can be necessary.

The first online operational decision is how to cope with patient rescheduling due to unforeseen circumstances. This can be, for example, equipment breakdown or extended consultation times. Another online operation decision is regarding staff scheduling. Because of absenteeism, rescheduling the staff schedules can be necessary.

1.3.3 Problem cluster

The process of brachytherapy was earlier researched in a Master thesis by de Bruijn (2022). De Bruijn constructed a discrete event simulation (DES) of the current situation, the bridging phase, and the future case in location VUmc. This thesis also contained a problem cluster that still represents the current situation. Figure 1.1 shows this problem cluster.

Based on this thesis, some hypotheses could be refuted. In addition, it showed that DES is an excellent method to use within this department. However, no fundamental changes have been made based on the outcome of the thesis. That is why the problem cluster is used as the starting point.

The brachytherapy team expects that during the bridging period, the problem of too little OR-time in combination with not fully utilizing the OR-time will become a bigger problem. This combination of problems sounds counterintuitive; however, the problem of too little OR-time refers to the number of assigned OR slots spread over the week.

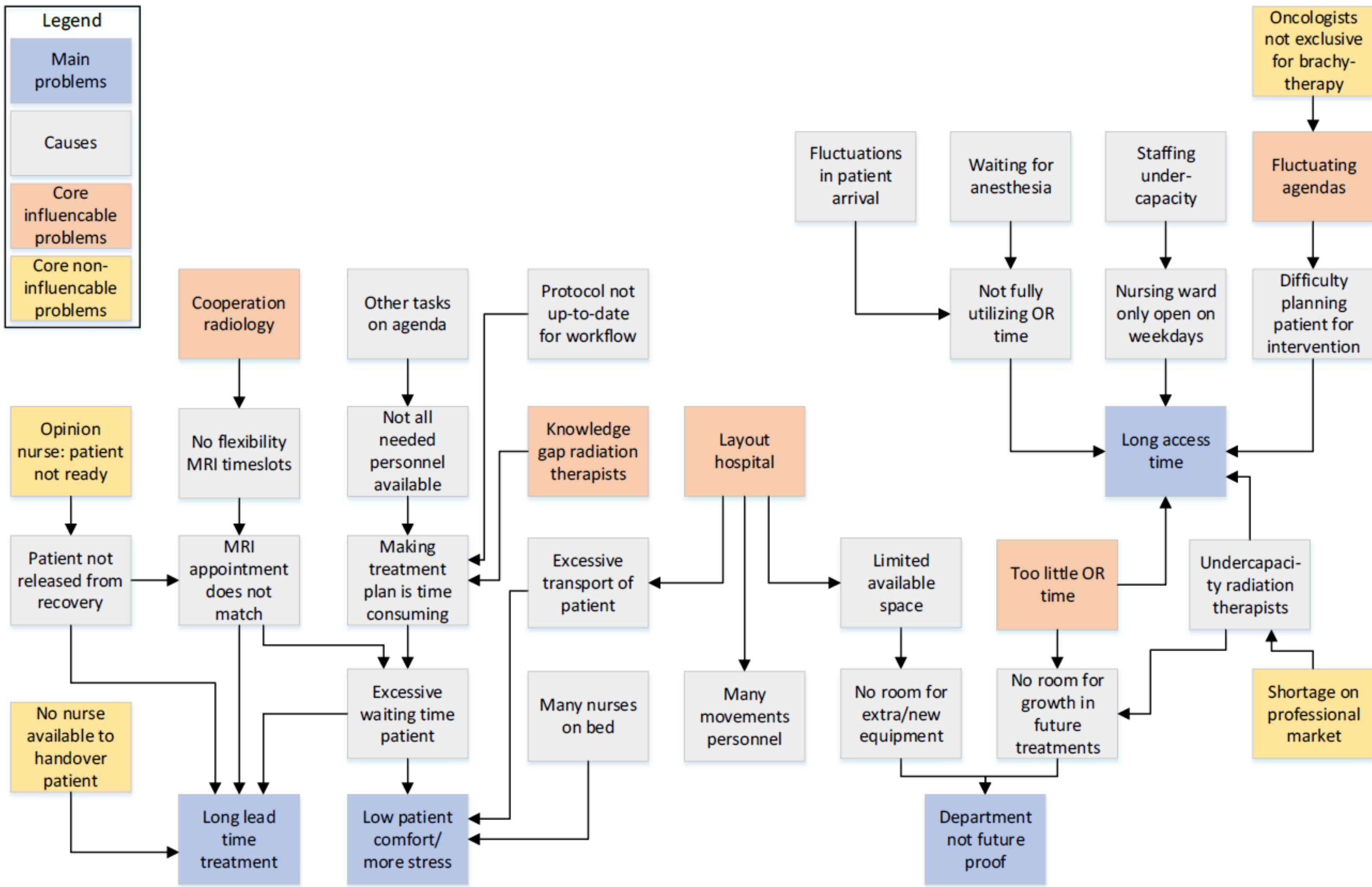


Figure 1.1: Problem cluster (source: de Bruijn, 2022)

Furthermore, the assigned OR-time is not fully utilized because of other factors, like no personnel available or inefficient scheduling within the OR-time. This last cause is not mentioned in the problem cluster of de Bruijn (2022).

In addition, one main problem, not mentioned in the problem cluster, is personnel overtime. Causes of overtime are, among other things, the absenteeism of colleagues, staffing under-capacity, and no proper connection of different process steps that increase the total lead time and cause the care process to be finished after working hours.

1.3.4 Research goal

Based on the decisions concerning control and planning and the problem cluster, we focused on appointment and staff-shift scheduling to optimally utilize material and personnel resources. We expect that these decisions have the most impact on the goal of maintaining the quantity of care and guaranteeing quality. This is because optimally utilizing the resources can ensure that more patients can be treated and that the access time will not increase. In addition, it can also prevent overtime of the personnel. Thus, the research goal is as follows:

To create an appointment and staff-shift schedule for the brachytherapy treatment during the bridging phase striving to treat the same number of patients as in the current situation within the capacity limitations.

1.4 Research design

1.4.1 Problem approach

The managerial problem-solving method (MPSM) is used to solve the core problem (Heerkens and van Winden, 2017). Figure 1.2 shows the different phases of this method. The first step is to define the problem. After that, the approach is formulated. The third step is to analyze the problem and ask questions. Then, the (alternative) solutions are formulated, and one solution is selected. The last two steps are to implement the solution and accordingly evaluate it. The first step, identifying the problem, is already executed. At this point, the problem-solving approach is determined.

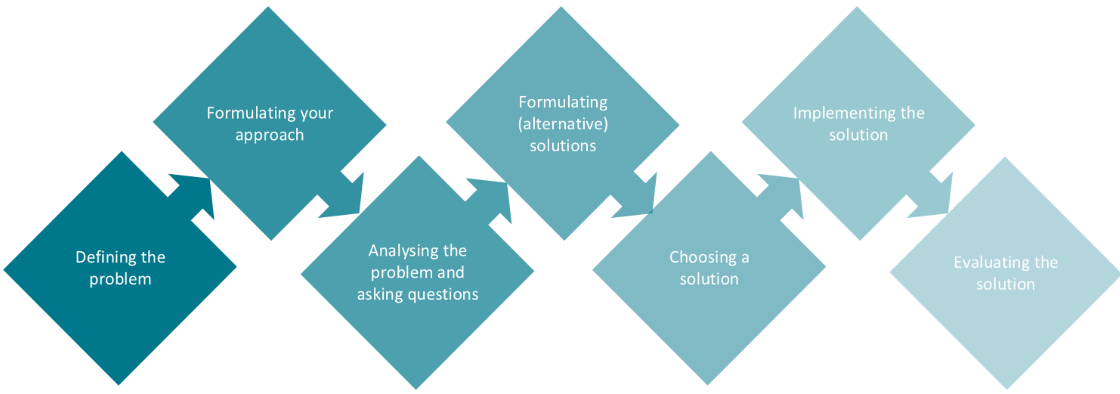


Figure 1.2: Phases of the Managerial Problem-Solving Method

1.4.2 Research questions

First, we want to learn about the current process, its performance, and the changes regarding the process during the bridging phase.

1. What is the current situation regarding the brachytherapy treatment process, and what will change when moving into the bridging phase?
   (a) What kind of treatment types are there within brachytherapy?
   (b) What are the current workflows?
   (c) What are the current patient flows?
   (d) What are the workflow and patient flow changes during the bridging phase?
   (e) How is the scheduling of appointments currently done?
   (f) How is the scheduling of staff shifts currently done?
   (g) What is the current performance of the brachytherapy treatment?

Next, we want to learn possible methods to solve the core problem.

2. Which methods are represented in the literature regarding appointment and staff-shift scheduling?
   (a) Which methods are commonly used for multi-disciplinary scheduling?
   (b) Which methods are commonly used to determine a master surgery schedule?

Based on this information, we want to build a model that can help generate a solution

3. How is the appointment and staff-shift scheduling of brachytherapy treatment be modeled?
   (a) What is the performance of the DES model with the current data?
   (b) What model is used to select feasible OR-day schemes?
   (c) What model is used to create week schedules containing all appointment types?
   (d) What model is used to determine which weekly schedule to utilize?
   (e) Which experiments should be executed?

This model can be used to test different scenarios and gather results.

4. What are the outcomes of the selected experiments, and how does it affect the hospital?

The next step is to discuss how to implement the outcomes in Amsterdam UMC during the bridging phase.

5. What are the steps to implement the chosen solutions?

The last step will be to provide the conclusions and discussions to the thesis.

1.4.3 Structure of the report/research

Based on these research questions, a chapter division is made. Figure 1.3 shows this structure. The first chapter, this chapter, is the introduction. Then, in Chapter 2, the context description is provided. The third chapter contains the literature review. In Chapter 4, the solution design is described. The results and experiments are discussed in Chapter 5. In the final chapter, the implementation of the solution is discussed first, followed by the conclusion and discussion.

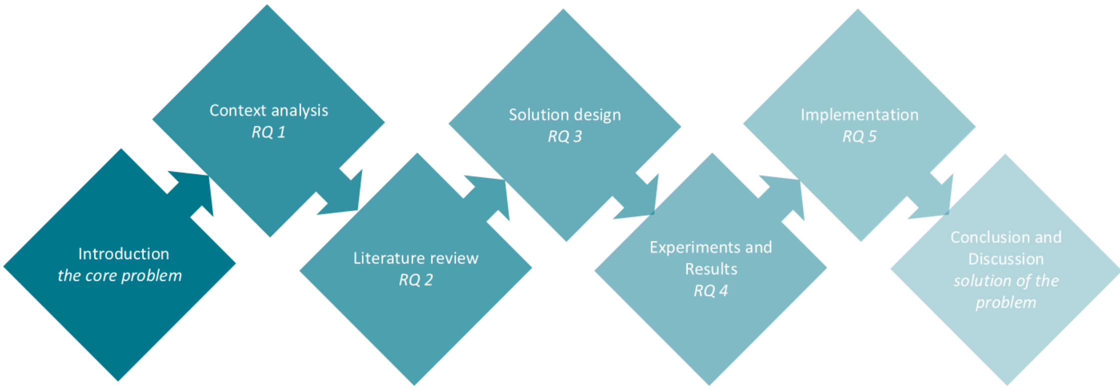


Figure 1.3: Structure of the report

Chapter 2

Context analysis

This chapter aims to answer research question 1. Section 2.1 introduces brachytherapy more thoroughly and explains the different treatment techniques and the main process steps. Section 2.2 describes the various procedures within brachytherapy. Section 2.3 answers research subquestions 1b and 1c, the current work- and a patient flow of the selected processes. Subquestion 1d, the changes towards the bridging phase, is answered in Section 2.4. The current appointment and staff-shift scheduling methods are discussed in Section 2.5. Last, in Section 2.6, the current performance of the brachytherapy treatment is discussed.

2.1 Introduction to brachytherapy

As Section 1.1 states, brachytherapy treatment is internal irradiation. This means the radioactive source is placed close to or in the tumor, and this radioactive material gives off radiation to eliminate cancer cells.

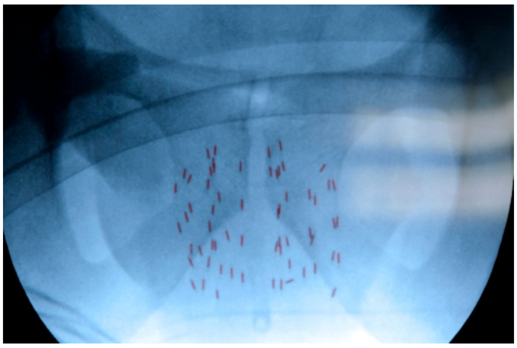
Brachytherapy has two significant advantages. The first advantage is that it is possible to radiate a particular area and thus ensure that the healthy tissue around the tumor is less exposed to radiation and therefore has less risk of damage. The second advantage is that because the treated area can be defined very well, the given doses can be high, which increases efficiency.

2.1.1 Treatment techniques

There are three different treatment techniques within brachytherapy: low dose rate (LDR), high dose rate (HDR), and pulse dose rate (PDR). As the names suggest, the techniques depend on the type of radiation dosing.

LDR is the technique with the lowest radiation doses. If a patient is treated with LDR, the radiation sources, iodine implantations, are permanently placed directly in the tumor. Those implantations are like tiny seeds (see Figure 2.1). Each of those iodine seeds gradually releases radiation before it diminishes. Because of the low dose and the diminishing radiation over time, the sources are not removed from the body.

(a) compared to 1 cent (source: Amsterdam UMC, n.d.-c)



(b) x-ray of the prostate with seeds (source: Urology Associates, n.d.)

Figure 2.1: Iodine seeds

HDR and PDR are more similar techniques than LDR. HDR and PDR sources are temporally placed in the body with the help of hollow needles, which guides the sources to the desired place for a certain amount of time. Via, so-called, transfertubes, the needles are connected to an afterloader. This afterloader contains the radioactive source Iridium-192. Through a cable, the source can be sent from the afterloader via the transfertubes and the needles into the tumor tissue. After the irradiation, the hollow needles are removed if no extra irradiation is needed.

The difference between HDR and PDR is that with HDR, a high dose is given in a relatively short amount of time, approximately 15-20 minutes. When PDR is used, a lower dose than HDR is given, but those pulses are delivered every hour over 24 to 48 hours.

2.1.2 Basic brachytherapy process

Brachytherapy consists of several main process steps. The sequence of these steps and the time it takes depend on the process type. On a treatment day, 4 or 6 steps are performed, depending on the technique used. One of those steps is an intervention. This intervention can be conducted in a treatment room or an OR. The hollow needles or iodine seeds are placed during this intervention.

In addition, another main process step is getting an image of the target area and the surrounding area. This can be done using MRI, computed tomography (CT) scan, or echo. In these images, the critical organs and the target area are contoured. When an applicator is placed, this applicator is reconstructed in the images. Another main process step is making a treatment plan based on the contouring and reconstruction.

All the steps mentioned above are for LDR performed during the OR intervention. Thus, after the patient is placed under general anesthesia, an image is made using an echo. Then the critical organs and target area are contoured, and a treatment plan is made. Based on this treatment plan, the iodine seeds are placed. Figure 2.2 shows the different main process steps of LDR brachytherapy.

When PDR or HDR brachytherapy is performed, the order of steps is reversed (see Figure 2.3). First, the intervention takes place, and the applicator is positioned. Then, an image is made of the applicator and the surrounding area. Next, the critical organs and target area are contoured, the applicator is reconstructed, and a treatment plan is made. The last step is to connect the applicator to the afterloader and irradiate the tumor or target area.

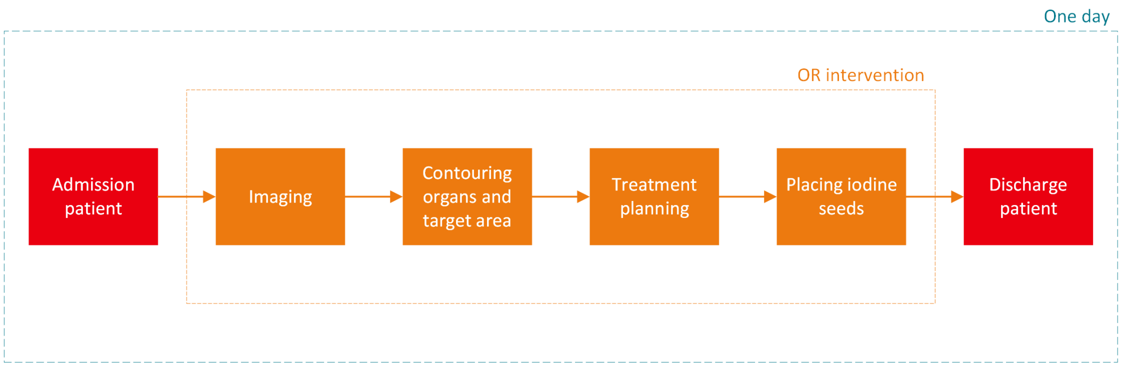


Figure 2.2: Main process steps LDR

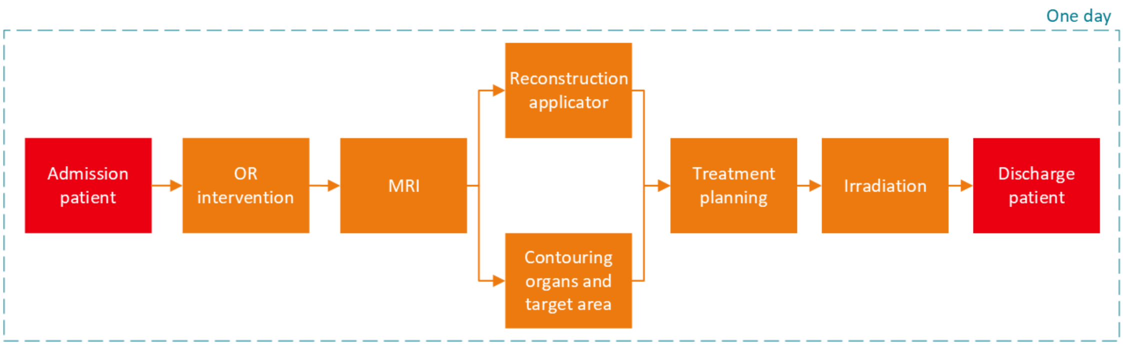


Figure 2.3: Main process steps HDR and PDR

It is important to note that for all mentioned techniques, the same steps apply. Only when LDR is used, those steps take place during the OR intervention, and with HDR and PDR, the other steps are conducted after the OR intervention.

2.2 Processes

To determine the detailed workflows and patient flows, a distinction is made between different treatment types and process types. Based on these process types, the work and patient flows are specified.

2.2.1 Treatment types

How the treatment process looks and how long it takes depend on more than the treatment technique used. The first distinction is made based on the specialty the treatment falls in. Then the treatments are divided based on the target area of the brachytherapy. The target area is the tumor's (former) location. The next step is to see if different techniques are used on one target area. The last step is to check if other differences exist within a treatment technique of a specific target area. In addition, only the treatment types performed in the previous two years, 2021 and 2022, were selected. This eventually led to 12 treatment types (see Table 2.1).

Table 2.1: Treatment types

Specialty	Target area	Brachytherapy technique	Other	Process type
Gynecology (GYN)	Cervix	PDR		E
	Endometrium	PDR		E
	Vagina	PDR		E
	Vaginal cuff	HDR		B
Urology (URO)	Prostate	LDR		A
		HDR	1 fraction	C
			3 fractions	D
	Bladder	PDR		I
Ear, nose, throat (ENT)	AMORE	PDR		H
	Orbit	PDR		H
Keloid	Keloid	HDR		F
Lip	Lip	PDR		M

Note: the treatment types marked in orange are the focus of this thesis

2.2.2 Process types

For each treatment type, the process steps were determined. For some treatment types, the actions taken are the same, and those treatment types have thus the same process type. A process type represents a unique sequence of process steps; however, each step's time differs per treatment type. Table 2.2 shows the different process types. Those processes are further developed into workflow and patient flows.

Table 2.2: Process types

Process	Also referred to as	Non-Clinical	Clinical	HDR	PDR	LDR	MRI	CT	Remark
A	LDR Prostate I-125		✓			✓			
B	HDR Ring	✓		✓				✓	
C	HDR Prostate 1		✓	✓			✓	✓	1 fraction
D	HDR Prostate 3		✓	✓			✓	✓	3 fractions
E	PDR GYN		✓		✓		✓		
F	HDR Keloid	✓		✓					
H	PDR ENT		✓		✓			✓	in ENT OR
I	PDR bladder		✓		✓			✓	in URO OR
M	PDR Lip	✓			✓			✓	

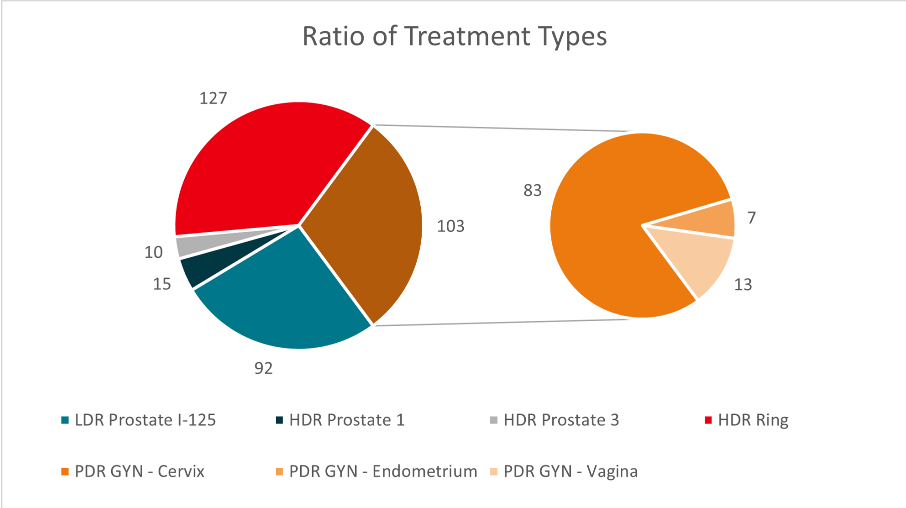


Figure 2.4: Number of treatments per process type separated (*n: 347; T: 2021-2022*)

2.2.3 Data of treatment types and process types

In 2021 and 2022, three process types, H, I, and M, occurred in less than one percent of the cases. Because those processes are rarely performed, it is decided to exclude those process types from this research. In addition, because HDR Keloid needs to be completed in cooperation with a plastic surgeon and thus depends on their availability, HDR Keloid is also excluded. Figure 2.4 shows the ratio of process types that are the focus of this research. For the PDR GYN, a distinction is made based on the target area. Keep in mind that the absolute numbers provided are for a duration of two years.

2.3 Current work- and patient flow

Before diving into the work and patient flow, it is essential to understand the different personnel types and required resources. After those are established, the workflows and patient flows of the process types are discussed. The flows are divided into the workflow of the preparation phase and treatment days' workflow. The treatment day is the day that the patient is radiated. The workflow of the treatment preparation and during the treatment day is graphically depicted in Appendix A. Also, the patient flow during the treatment day is displayed there. The patient flows during the preparation phase are not graphicly shown because this consists primarily of separate appointments.

2.3.1 Personnel and resources

Personnel Types

There are six types of personnel directly involved with the execution of brachytherapy. The first three personnel types discussed are part of the radiotherapy team. Some personnel solely focus on brachytherapy, while others divide their time between the different aspects of radiotherapy. This depends on the staff member and not on the personnel type. The three personnel types discussed last are not part of the radiotherapy team but fall under a different department.

The first personnel type is the radiotherapist. The radiotherapist is a medical specialist who treats patients with ionizing radiation and is the attending physician. The radiotherapist is responsible for the treatment plan and works with other hospital employees to irradiate people with a (non-)malignant condition.

Staff who support the radiotherapists is the radiotherapy technologist (RTT). The main tasks of the RTTs are helping the radiotherapist during the interventions in the OR, reconstructing the applicator and contouring the target area, and setting up the treatment planning. The radiotherapist checks the reconstruction, contouring of the critical organs, and planning afterward. The radiotherapist always contours the tumor.

The third personnel type is an medical physicist expert (MPE). This personnel is a specialist in the field of medical equipment. Within the brachytherapy treatment, the MPE is responsible for checking the reconstruction of the applicator and the treatment plan. However, when there is a shortage of RTTs, an MPE can also perform the reconstruction and planning. This is nonetheless not desired.

The fourth personnel type, not part of the radiotherapy team, is the anesthetist. This is a medical specialist who focuses on giving anesthesia to patients. The anesthetist is responsible for admitting epidural and general anesthesia and controlling the anesthesia during the intervention in the OR.

Another personnel type needed during brachytherapy treatment is a nurse. A nurse provides nursing care like primary care, wound care, observation, and reporting. The sixth personnel type is an employee from patient transport, responsible for transporting a patient from one department to another.

Material resource types

When undergoing brachytherapy, there are three departments in the hospital where the patient may be. The first department is the so-called nursing ward F5 North (F5N). This department is located in building part F on the fifth floor on the north side. F5N is a nursing ward where the brachytherapy bunkers and intervention rooms are located. This department has nursing staff available 24 hours a day during weekdays. The bunkers are used to irradiate patients with the use of an afterloader. There are four bunkers and three afterloaders. This is either an HDR afterloader or an PDR afterloader. There are two PDR afterloaders and one HDR afterloader. In addition to the bunkers, there are intervention rooms in F5N. In those intervention rooms located across from the bunkers, non-clinical interventions are performed.

The second department is the day center. This day center has small ORs and a recovery room. Minor operations are performed at the day center, after which a patient can go home the same day. That is why there is only daycare available. The resources available in the day center are all shared with other departments. Clinical brachytherapy interventions take place in the ORs of the day center. After which, the patient recovers in the recovery room.

The third department is the radiotherapy department. In the radiotherapy departments, the consulting rooms, MRI, and CT are located. It is important to note that the MRI is shared with the radiology department, and the CT is shared with the other treatment types of radiotherapy, hyperthermia, and EBRT.

2.3.2 Flow LDR Prostate I-125

Workflow

Before the treatment can start, some preparatory steps must be taken. It first starts with the registration of the patient by the administration. This happens at desk 1 of the radiotherapy department. Then the doctor's assistant (DA) checks and requests the patient files, after which a consult is planned. Before the consult is planned, the radiotherapist assesses the urgency of the care, also called triage. After the administration plans the consult, the consult takes place with the radiotherapist.

Then, an RTT makes an appointment for volume measurement. When a volume measurement is performed, the volume of the prostate is measured using ultrasound equipment. An RTT or a radiotherapist performs this volume measurement. After this, another consult follows, discussing the results with the patient. After this consult, the RTT schedules the patient's treatment, after which the administration informs the patient. In addition, the anesthetist consults with the patient before the treatment occurs. After the treatment is scheduled, the RTT is also responsible for ordering the iodine sources and the preparation of the iodine before the treatment. The workflow of the preparation is depicted in Appendix A.1, Figure A.1

The first step during the treatment day is the patient's admission at the day center, where a nurse assigns a patient to a bed. This nurse then prepares the patient for the intervention in the OR. After that, the anesthetist arrives and administers an epidural, and takes the patient to the OR. The RTT takes the required materials to the OR during this process. The intervention can occur when the patient and materials are in the OR. A radiotherapist and two RTTs perform this intervention. After the intervention, the anesthetist takes the patient to the day center, and the RTT registers the radiation sources and puts those back in the vault. When the patient is recovered, the nurse discharges the patient. Appendix A.1, Figure A.2 depicts the graphical representation of the workflow during the treatment day. The treatment process for an LDR patient typically lasts around 2.5 hours, not including the recovery period.

Four to six weeks after the treatment day, the patient returns for a consult with the radiotherapist and a CT scan. Based on the CT scan, the treatment is assessed and checked if all radiation sources are still in the prostate. The results are discussed during the consult.

Patient flow

During the preparation, before the treatment, the patient has three appointments. First, the patient has a consult at the radiotherapy department. After this first consult, the volume measurement occurs in the radiotherapy department. After that, the patient is informed of the results and has a consult with anesthesia. These consults are not directly after each other, but take place on different days.

When a patient arrives on the treatment day, the patient is admitted to the day center. The patient is prepared for surgery and transported to the OR. There, or previously in the recovery, the patient gets an epidural. The patient is put under general anesthesia in the OR, and the intervention can start.

After the intervention, the patient returns to the day center. Whereafter the patient can go home after recovering and being discharged. It is important to note that because of the treatment technique LDR, the patient is not irradiated using an afterloader and thus does not go to F5N, but the whole treatment takes place in the day center.

For the follow-up, the patient goes to the radiotherapy department, where a CT scan is made, and the consult takes place.

2.3.3 Flow HDR Prostate

There are two processes of HDR prostate, namely with one fraction and three fractions. The number of fractions refers to the number of irradiations. Because the flows are very similar, both process types are discussed in this subsection, and everything applies to both process types unless otherwise stated.

Workflow

The preparation for HDR prostate is equal to the preparation of the LDR except for two steps. The first difference is that during the volume measurement also, gold markers are placed. Those gold markers are used by EBRT. HDR prostate is always combined with EBRT, and that is why those steps are combined. Because those steps are combined, planning this appointment is done by the planning desk and executed by personnel of EBRT. However, a radiotherapist and RTT must watch during the volume measurement, so they must still be present. The second difference is that the last step in the preparation is not ordering and preparing the iodine seeds but preparing other required materials.

The treatment day of HDR prostate also starts with a nurse's patient admission. However, this time this occurs at F5N. Here, the patient is also prepared for the intervention. Next, the anesthetist administers the epidural, whereafter the anesthetist takes the patient to the OR. At the same time, the RTT brings the necessary materials to the OR. When both patient and the materials are in the OR, the intervention can take place. After the intervention, the anesthetist brings the patient to recovery. When awake, the patient is transported to the MRI scanner by the RTT. The patient is sometimes taken to F5N between recovery and MRI if it takes a while before the MRI can be taken. During the MRI scan, it is checked whether the applicator is still in place. It often happens that the applicator drops down a bit. When this happens, the applicator needs to be pushed back by the radiotherapist, and a new MRI needs to be made. This process iterates until the applicator is in the right place again. Then, the patient is brought to F5N by patient transport.

After the MRI scan, the contouring of the critical organs and reconstruction of the applicator can be executed. Those steps can be done simultaneously or sequentially, depending on the available personnel. The contouring of the critical organs can be performed by either the radiotherapist or the RTT. When the contouring of the critical organs is finished, a radiotherapist contours the target area. Then, the contouring is checked by another radiotherapist. An RTT reconstructs the applicator, but an MPE can also perform the reconstruction. However, the latter is not desirable. After the reconstruction of the applicator is made, this reconstruction is checked by an MPE. After both contouring and reconstruction are checked, an RTT makes a treatment plan. This plan is checked and improved when necessary by a radiotherapist and then also checked by an MPE.

When the treatment plan is almost finished, patient transport transports the patient from F5N to the CT to make a CT scan. After the CT scan, patient transport brings the patient back to F5N. The CT images are overlaid on the MRI images to verify that the applicator is still in place. If necessary, a final change is made to the treatment plan based on the CT images. Then, the plan is sent to F5N, and the patient can be connected to the afterloader. The treatment plan is sent to the afterloader, and the irradiation can start.

From this point on, there comes a difference between 1-fraction and multi-fraction HDR prostate. When a patient receives one fraction, the applicator is removed from the patient when the irradiation is finished, and the patient can go home.

However, when a patient receives more fractions, the applicator is not removed because it is used again during the following fractions. Those patients must stay for the night and receive their second and third fractions the next day. However, a new CT is made before the patient gets another fraction the next day. So the process from the CT until the irradiation described before is repeated, which happens again before the third fraction. So, when a patient has three fractions, three CTs are made. After the last fraction, the applicator is removed, and the patient can go home. It is important to note that this treatment is thus not from the beginning to end in one day but in two days.

Patient flow

The patient flow of the preparation phase of HDR prostate is the same as the preparation of the LDR prostate. However, the only difference is that gold markers are placed in the prostate when the volume measurement occurs.

On the treatment day, the patient was first admitted at F5N. Then, the patient is prepared for surgery in the recovery of the day center. The patient is brought to the OR from recovery. Here, the patient is put under general anesthesia, whereafter the intervention occurs. After the intervention, the patient is brought back to recovery. When awake, the patient is taken to the MRI. And after the MRI, the patient returns to F5N. Then, a CT is made after which the patient again returns to F5N, Here, the patient is connected to the afterloader and is irradiated.

2.3.4 Flow PDR Gynecology

Workflow

The preparation phase starts similarly to the process types mentioned above: registration, triage, planning of the first consult, and the first consult. After the first consult, the RTT schedules the patient, and administration informs the patient. Then, a so-called pre-brachy MRI is performed. The radiotherapist and RTT can make a preliminary plan based on these images. If applicable, an RTT builds a customized applicator. In addition, an RTT collects the required materials.

The workflow of PDR GYN is similar to the workflow of HDR prostate. There are three differences. The first difference is that it is not necessary to adjust the position of the applicator during the MRI. In addition, because the probability of movement of the applicator is small, it is also not necessary to make an CT. Thus, when a treatment plan is made and double-checked, the afterloader can immediately be connected, and the irradiation can start. The third difference is that although PDR always consists of multiple pulses, connecting the afterloader multiple times is unnecessary. The afterloader is connected once to the source conductors, whereafter, every hour irradiation occurs for 24 to

48 hours, so also 24 to 48 pulses. Thus, those pulses also occur during the night. This means the treatment steps before the irradiation can begin are carried out in one day, but the irradiation takes one or two days. After the irradiation, a radiotherapist removes the applicator, and the patient can go home.

Patient flow

Before the treatment day, the patient must be in the hospital three times. The first time is at the radiotherapy department for a first consult. The next appointment is for the pre-brachy MRI. In addition, the patient has a consult with the anesthetist. The patient flow is the same as the patient flow of HDR Prostate. However, no CT is necessary for PDR GYN treatment.

2.3.5 Flow HDR Ring

Workflow

Because the HDR Ring treatment is without anesthesia, the preparation phase is shorter than the other treatment processes. The first steps until the first consult are the same as the other processes. However, after the first consult, the RTT can immediately schedule the treatment, and no other consults or other preliminary tests are necessary.

On the treatment day, the patient is first admitted by a nurse in F5N. Then, the intervention can be carried out by a radiotherapist and an RTT. This intervention does not take place in an OR but in an intervention room in F5N. As the name of the treatment suggests, an applicator in the form of a ring is placed at the so-called vaginal cuff. The uterus of patients receiving the HDR ring treatment is removed, and the ring is put in the vagina where the uterus used to be, the vaginal cuff.

A HDR ring treatment can consist of 1 up to 3 fractions. If the patient did not receive any fraction yet, an CT is made after the intervention. The critical organs are contoured in the CT images, and the applicator is reconstructed. An RTT does both. After that, an RTT also makes the treatment plan. A radiotherapist and an MPE then check this. Then, the patient is connected to an afterloader in a bunker in F5N, after which the irradiation starts. After the irradiation, the applicator is removed by an RTT, regardless of whether there is still a fraction to take place. Those other fractions, namely, take place on another day. The patient goes home in between fractions. When a patient has received a fraction, the treatment process is the same as described above. However, no CT is necessary, and thus no contouring, reconstruction, and treatment planning is necessary. This plan is already made during the first fraction. So, after the intervention, the patient can be directly connected to the afterloader, and the irradiation can start.

Patient flow

During the preparation phase, the patient must be in the hospital just once, during the first consult. After this consult, the patient receives information about the treatment. Patients that undergo HDR ring treatment do not go to the day center. The therapy only occurs at F5N and in the radiotherapy department. First, they are admitted at F5N, whereafter the intervention takes place at an intervention room also at F5N. After the intervention, if it is the first fraction, the RTT brings the patient to the CT. After the CT is transported back to a bunker at F5N. The patient waits until connected to the afterloader, and the treatment starts. When it is not the first fraction, the patient goes from the treatment room directly to the bunker and thus does not leave F5N.

2.4 Changes during bridging phase

The biggest difference during the bridging phase is that the brachytherapy department has to move out of F5N. This has several consequences. The first consequence is that the brachytherapy department will have two instead of three bunkers available. Because the brachytherapy team cannot use the bunkers in F5N, they get two bunkers at the radiotherapy department.

The most significant consequence is that the brachytherapy team does not have 24-hour nursing staff available during the bridging phase. The major result is that treating patients with PDR brachytherapy is no longer possible. Because with PDR, nursing staff must be available at the bunkers day and night. Because the bunkers are during the bridging phase in the radiotherapy department, which is not a nursing ward, this is simply impossible.

Treatment types currently treated with PDR will be treated with HDR during the bridging phase. Those patients will receive four HDR fractions. This does not influence the quality of treatment and also does not increase toxicity. It is a change in method, but the outcomes are equivalent. The consequence of this change in method is that because it is impossible to give four HDR fractions using the same applicator, those patients will undergo two interventions in the OR. Both interventions are then followed by two fractions. Those interventions will take place a week after each other. The workflow of PDR GYN will not change significantly. The only difference is that after the first fraction, the patient will stay in the hospital at night, in a nursing ward but not in the bunker, and receives the second fraction the next day. Then, the applicator is removed, and the patient can go home. The next week, the patient returns and will follow the same steps as the previous week for fractions three and four after the second intervention. Because the demand of HDR will increase and because no PDR is executed, both the available bunkers will be provided with an HDR afterloader.

Another consequence of the move from F5N is that the patient can no longer wait at F5N between treatment steps. This will also happen in the radiotherapy department, where special waiting areas are created. If a patient needs to stay the night, the patient goes to the nursing rooms of another department.

During the bridging phase, the intervention rooms at F5N are also not available anymore. That is why the HDR Ring interventions and the volume measurements of urological patients will occur inside the bunker.

A positive consequence is that during the bridging phase, all steps in the process are performed either in the day center or at the radiotherapy department; thus, less patient transport between departments is necessary. Both those departments are established on the ground floor and relatively close to each other compared to F5N.

2.5 Current appointment and shift-staff scheduling

2.5.1 Appointment scheduling

All the clinical treatment days are scheduled on Tuesdays because the brachytherapy department can only utilize an OR on Tuesdays. The brachytherapy department assumes that the maximum number of interventions is three. The OR can be used from 08.00, and interventions must be completed before 16.30. At this moment, the planning decisions are based not on data but on experience and expectations. The following rules are used for planning the OR interventions based on these experiences and expectations:

- There is a maximum of 3 OR interventions per day
  Assumption: when performing four interventions, the end time of the OR is exceeded

- The third intervention can only be an LDR prostate intervention
  Assumption: when HDR or PDR is performed as the third intervention, the subsequent process steps take too long and cause too much overtime

- If an HDR prostate (1 or 3 fractions) is planned, this must be the first intervention of the OR-day
  Assumption: the subsequent process steps of HDR prostate takes too long when performed second and will cause too much overtime of personnel

- PDR or HDR intervention(s) must always be performed earlier on the day than an LDR intervention.
  Reasoning: because PDR and HDR have follow-up process steps on the same day, they should be performed before LDR, which does not have follow-up steps to avoid overtime of personnel

This leads to five different potential OR days. Figure 2.5 shows the different OR days where one stack of blocks represents one day, and the upper block is the first intervention. These are the combination assuming that three interventions take place on one day. It can happen that not three interventions take place on one day, and then one block will be removed from the three blocks. It is important to note that for the PDR GYN blocks, it does not matter if it is a cervix, endometrium, or vagina PDR GYN.

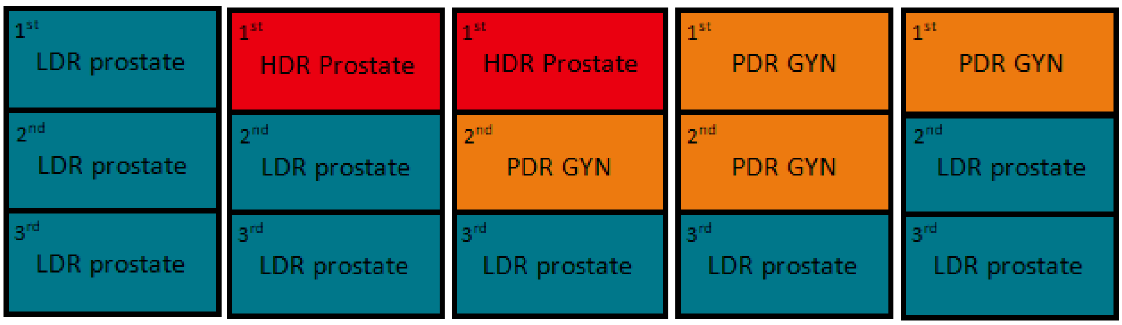


Figure 2.5: Current OR schedule options

Based on the process types scheduled on a day, MRI timeslots are reserved if necessary. When the first intervention of a day is not an LDR Prostate I-125, then the MRI timeslot of 12.00-12.45 is reserved. An MRI timeslot of 13.30-14.15 is reserved for the second intervention. When an LDR Prostate I-125 is performed, reservation of an MRI timeslot is unnecessary.

The HDR Ring process is the only process that is non-clinical and thus is performed on a non-OR day. To plan this, spread over different days, different blocks in the agenda of the radiotherapists are reserved for doing an HDR Ring or volume measurement. So, within this block, an HDR Ring can be scheduled.

Volume measurements are thus planned in the same block as the HDR Ring. Another block made in the radiotherapist's agenda is a block for patient consults. In addition, for GYN patients that need a pre-brachy MRI, those MRIs can be planned on non-OR days between 12.00-14.00.

2.5.2 Shift-staff scheduling

Currently, three RTTs and four radiotherapists work at the hospital. For all healthcare personnel, a full-time workweek consists of 36 hours. The only exceptions are the doctors, for which a full-time workweek consists of 46 hours. However, most personnel do not work full-time, and the hours are divided among the radiotherapy department. Table 2.3 shows an overview of the current working hours of the RTTs. The current schedule of radiotherapists is more complicated. This is because the radiotherapists divide their time between brachytherapy and EBRT. In addition, they have set times for multidisciplinary consultation (MDO) where consultations take place with other departments such as gynecology and urology. That is why radiotherapists have a block schedule to indicate when certain appointments can be scheduled. Table 2.4 shows the current block schedule of the radiotherapists with blocks that are reserved for brachytherapy appointments. As shown, all personnel work on Tuesday because it is the OR day.

Table 2.3: Current workhours RTTs

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
RTT1	08.00 – 17.30*	07.30 – 17.30		08.00 – 17.30	08.00 – 17.30*
RTT2		07.30 – 17.30	08.00 - 12.30		
RTT3	08.00 – 17.30**	07.30 – 17.30		08.00 – 17.30	08.00 – 17.30**

*Remote

**Every other Monday on even weeks and every other Friday on odd weeks.

Table 2.4: Current workhours radiotherapists

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
Radiotherapist1	09.30 – 14.00	07.30 – 17.30	11.30 - 13.00	09.00 – 12.00	8.00 – 17.30*
Radiotherapist2		07.30 – 17.30	11.30 - 13.00	09.00 – 12.00	8.00 – 17.30*
Radiotherapist3	09.00 - 12.00	07.30 – 17.30	08.00 - 12.00	13.00 – 16.00	
Radiotherapist4		07.30 – 17.30	08.00 - 10.00		8.00 – 17.30

*Radiotherapist 1 and 2 work alternately on Friday

2.6 Current performance

The current performance is measured using four key performance indicators (KPI). The first KPI is the number of patients treated with brachytherapy. This is considered the production of the department. The second KPI is the time it takes to treat a patient, referred to as the access time. The time it takes on a treatment day to perform the intervention and to make a treatment plan is considered the third KPI, the lead time. The last KPI is the utilization of resources. In this case, the utilization of three resources is determined: OR, MRI, and the radiation bunkers and afterloaders.

The data used to determine the current performance is gathered from the electronic medical record software application Epic. Only the utilization of the radiation bunkers and afterloaders is determined based on other data. This data is collected from the application connected to the afterloaders.

2.6.1 Number of treated patients

The first performance indicator analyzed is the number of patients treated with brachytherapy. Figure 2.6 shows these numbers from 2016 up to and including 2022.

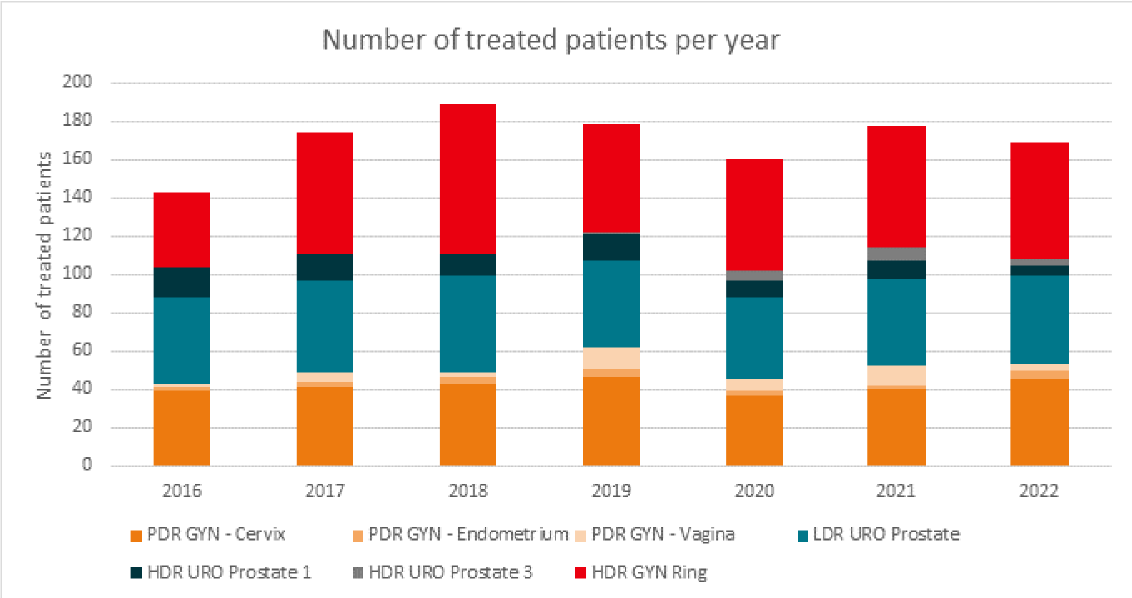


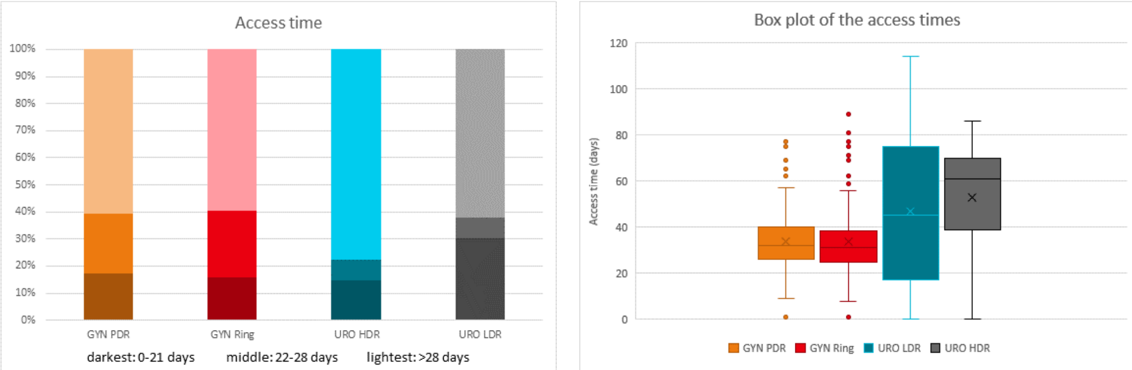
Figure 2.6: Number of treated patients per year

It shows that the throughput has fluctuated between 170 and 190 patients yearly since 2017. The only exception is in 2020; the COVID-19 pandemic presumably caused this decrease.

2.6.2 Access time

The access time is measured as the time between the first consult and the first treatment at the radiotherapy department. This decision is made because mainly PDR patients undergo EBRT before receiving brachytherapy. And the schedule of the EBRT is adjusted based on the availability of the brachytherapy. In other words, sometimes the EBRT is started later because there was no availability at the brachytherapy. This is done because the time between EBRT and brachytherapy is preferably less than two weeks.

Based on the regulations of the NVRO, 80 percent of the patients need to be treated within 21 days and 100 percent in 28 days (NVRO, 2018). These regulations apply to the radiotherapy department and not only to the patients receiving brachytherapy. However, this is considered to be the goal of the brachytherapy department. Figure 2.7a shows the percentage of patients who fulfill these requirements grouped by treatment type. The distribution of the access time is shown in Figure 2.7b.



(a) Regulations (b) Distribution

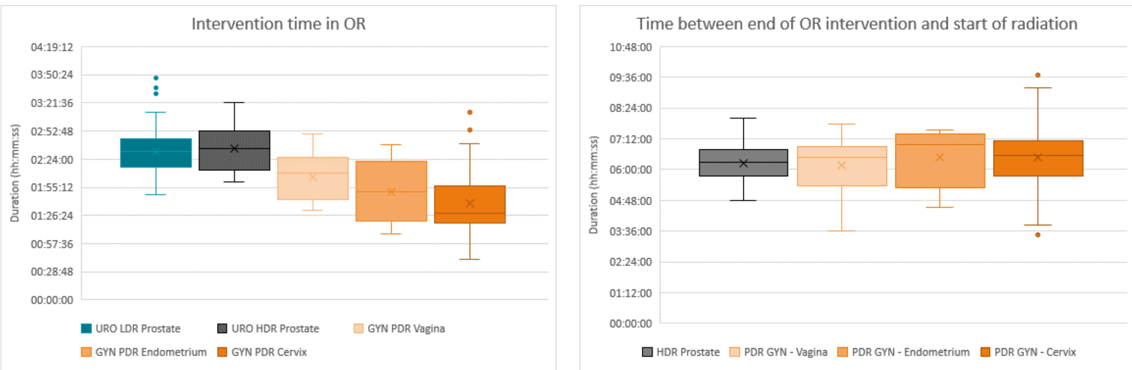
Figure 2.7: Access time (*n: 347; T: 2021-2022*)

The figures show that the access time is often higher than the regulation prescribed. It also indicates that the access time for gynecology patients is, on average shorter than that of urology patients. This is caused by the fact that the cancer is more aggressive and early treatment is of greater importance than for prostate patients.

2.6.3 Lead time

Lead time equals the intervention time for LDR treatment. In contrast, for the other treatment types, the lead time is calculated as the time between the start of the intervention and the beginning of the radiation. However, to gain insight into where the time comes from, a deviation is made between the OR intervention time and treatment planning time, thus the time between the end of the intervention and the start of the radiation (see Figure 2.8).

This figure shows that the average OR time of LDR and HDR Prostate treatments, 2.5 hours, is higher than the OR time of PDR GYN treatments which is around 2 hours. In addition, there is a higher variation in time between the end of the intervention and the beginning of the radiation for PDR cervix treatment compared to the other threatment types. Figure 2.9 shows the total lead time from the start of the OR intervention until the beginning of radiation. It shows that the total time of a LDR treatment is much lower than for the other treatment types. The LDR treatment takes on average about 2.5 hours while the other treatment types take around 8 hours in total.



(a) OR intervention time (*n: 201; T: 2021-2022*) (b) Time between end of intervention and start radiation (*n: 109; T: 2021-2022*)

Figure 2.8: Split lead time

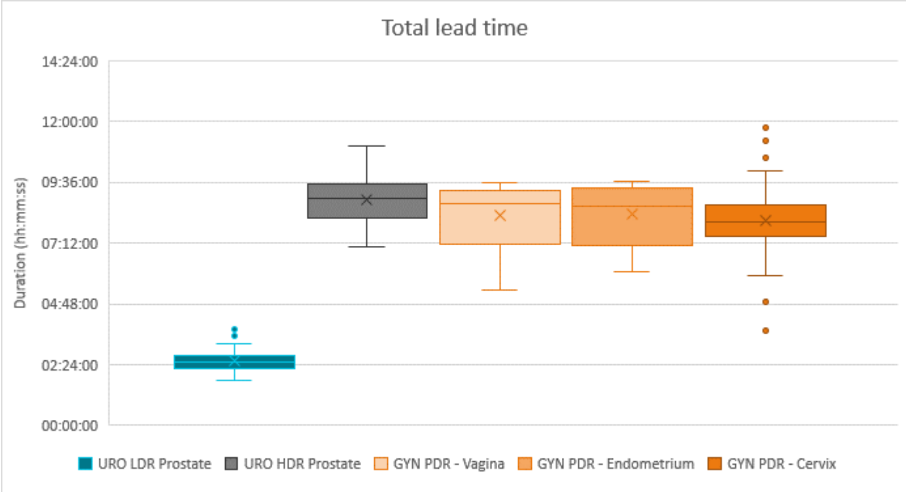


Figure 2.9: Total lead time (*n: 201; T: 2021-2022*)

2.6.4 Utilization

There are three resources of which the utilization is essential. This is the utilization of the bunkers/afterloaders, the utilization of the OR, and the utilization of an MRI.

Utilization Bunkers/Afterloaders

There are two PDR bunkers and afterloaders and one HDR bunker and afterloader. The calculation of the utilization for the different bunkers and afterloader is done in two ways. The PDR bunker and afterloader can be used day and night during weekdays. In contrast, the HDR bunker and afterloader can only be used during the day.

It is assumed that the PDR bunkers and afterloaders are fully utilized if they are always used from Monday 08.00 until Friday 17.30. This equals 105.5 hours per week. The HDR bunker/afterloader is fully utilized if it is used every day from 08.00 to 17.30, which is 9.5 hours per day. It is important to note that it is not the goal to utilize 100 percent. This because maximizing utilization also leads to maximizing patient waiting time and maximizing overtime.

Table 2.5: Available time

	PDR	HDR
Hours per year	$52 \cdot 105.5 = 5,486$	$52 \cdot 5 \cdot 9.5 = 2,470$
Holiday (hours)	$6 \cdot 24 = 144$	$6 \cdot 9.5 = 57$
Maintenance (hours)	$5 \cdot 24 = 120$	$8 \cdot 9.5 = 76$
Patient change (hours)	$52 \cdot 12 = 624$	$52 \cdot 6 = 312$
Remaining hours	4,598	2,025
#Machines	2	1
Total available hours/year	9,196	2,025

Table 2.5 shows the number of hours used to calculate the utilization. The utilization is calculated by dividing the occupied hours of the bunker/afterloader for a year by the total number of hours available per year.

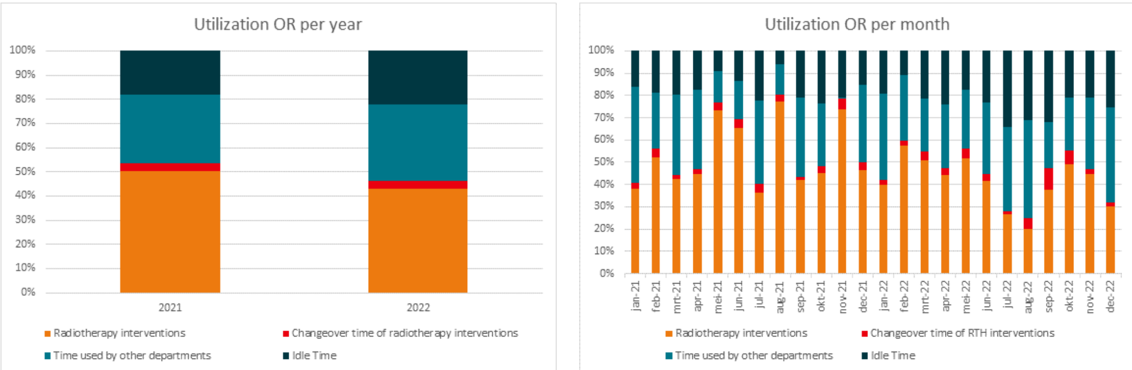
The bunkers are considered occupied from the moment a gynecology or HDR urology patient is admitted at F5N until they are discharged. This is because even if the patient is not present in the bunker, the bunker cannot be used by other patients. The afterloaders are considered in use for the whole moment that the afterloaders are connected to the applicator. Figure 2.6 shows the utilization of the PDR bunkers and afterloaders and of the HDR bunker and afterloader.

Table 2.6: Utilization of bunkers and afterloaders

	PDR bunkers	HDR bunker	PDR afterloaders	HDR afterloader
2021	42.96%	68.01%	26.95%	8.10%
2022	40.21%	65.87%	28.99%	7.64%

Utilization OR

If the OR is assigned to the brachytherapy team, it can be utilized from 08.00 until 16.30. However, when the OR is only filled with interventions in the morning, the afternoon can be given to another department such that the OR is not empty. Figure 2.10 shows how much time the radiotherapy department uses and how much time is given to other departments. It also indicates how much time is used between two interventions, the changeover time. Figure 2.10b shows that the utilization of the OR fluctuates significantly during the year. There are several reasons for this, but the primary cause is decreased staffing (see July and August 2022) or a change in the amount of available OR time. However, the yearly average stays relatively constant (see Figure 2.10a).



(a) per year (b) per month

Figure 2.10: OR utilization

Utilization MRI

The utilization of the MRI is hard to calculate because it is a shared resource between the radiotherapy and radiology departments. That is why it is investigated how much time is used in the time slots. If an MRI is required, a time slot of 45 minutes is reserved. Otherwise, the time slot is given away so others can use it. Figure 2.11 shows the time it takes to make an MRI. The average time it takes to make an MRI is somewhat lower than 45 minutes. However, there are some significant outliers. In addition, a difference can be noted between the time it takes to make an MRI for each treatment type. This is further discussed in Subsection 4.5.2.

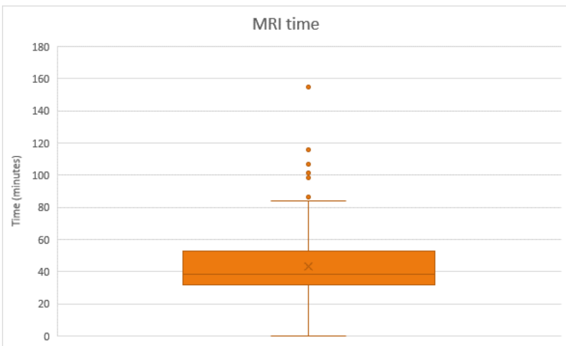


Figure 2.11: MRI time during OR day

2.7 Conclusion

This chapter answers research question 1: "What is the current situation regarding the brachytherapy treatment process, and what will change when moving into the bridging phase?"

Currently, the brachytherapy department treats seven main treatment types. Those seven treatment types can be linked to one of five treatment processes. Of those five treatment processes, four require an OR intervention. For brachytherapy, there are several personnel types and equipment required. There are three personnel types required that are from the brachytherapy team. These are the radiotherapist, RTTs, and MPEs. In addition, imaging devices, radiation bunkers, intervention rooms, and an OR are required to perform brachytherapy. The brachytherapy team treats between 170 and 190 patients annually with these personnel and resources.

During the bridging phase, the main difference is that due to changes in available resources, the gynecological patients currently treated with PDR will be treated with HDR. This is only possible when those patients have two OR interventions instead of one. Consequently, the demand for OR time and personnel time will increase.

Chapter 3

Literature review

This chapter aims to answer research question 2. Section 3.1 discusses the approach used to conduct this literature review. Then, the literature found regarding multi-disciplinary scheduling is discussed in section 3.2. Section 3.3 describes the literature regarding master surgery schedules.

3.1 Literature search approach

A systematic literature review is based on the structure of the grounded theory literature review method of Wolfswinkel et al. (2013). The grounded-theory method consists of five stages. The first stage consists of four steps: defining the inclusion/exclusion criteria, identifying the research fields, determining the appropriate sources, and determining specific search terms. In the second stage, the search occurs in the predetermined sources. Then, the sample of texts is selected. First, the doubles are filtered, then the sample is refined based on the title and abstracts of the articles. Then, the full articles are read, and again the sample is refined. The last step is to check the forward and backward citations to enrich to quality of the text sample. After the selection of the text sample, the articles are analyzed. After the articles are analyzed, the findings and insights are presented.

The appointment and staff-shift schedule that is the purpose of this thesis is a combination of multi-disciplinary appointment scheduling and master surgery scheduling. That is why two separate searches are conducted. First, a search is done regarding multi-disciplinary appointment scheduling in healthcare. The second search was regarding master surgery schedules for surgery types. Appendix B shows the used search terms and the selected sample of articles.

3.2 Multi-disciplinary scheduling

Leeftink et al. (2020) defined a multi-disciplinary care system as "a care system in which multiple interrelated appointments per patient are scheduled, where health care professionals from various facilities or with different skills are involved" (p. 95).

A multi-disciplinary planning problem consists of six different components (Leeftink et al., 2020). The first component is appointment characteristics. This encompasses the type of appointments and the necessary resources for each appointment. The second component is the resource characteristics, which include each resource's quantity, skillset, capacity restrictions, and whether they can be renewed. Another component is the care pathway characteristics, which account for the patient types, the number and type of appointments required for each patient, urgency levels, time constraints, and precedence constraints. The fourth component is the objective, referring to the model's objective or set of objectives. The planning characteristics involve decision-making for capacity dimensioning, planning, or allocating patients. The last component is the environmental characteristics (e.g. if there are no-shows, the punctuality of patients).

As stated, one element of the care pathway characteristics is precedence constraints. Based on these precedence constraints, a distinction is made between three multi-disciplinary systems: a flow shop, an open shop, and a mixed shop (Leeftink et al., 2020). Patients follow a predetermined sequence of activities across multiple facilities in a flow-shop system. In an open-shop system, patients undergo activities that can be scheduled in any order. A mixed-shop system is a combination of a flow-shop and an open-shop system. Figure 3.1 shows a graphical representation of the different multi-appointment systems.

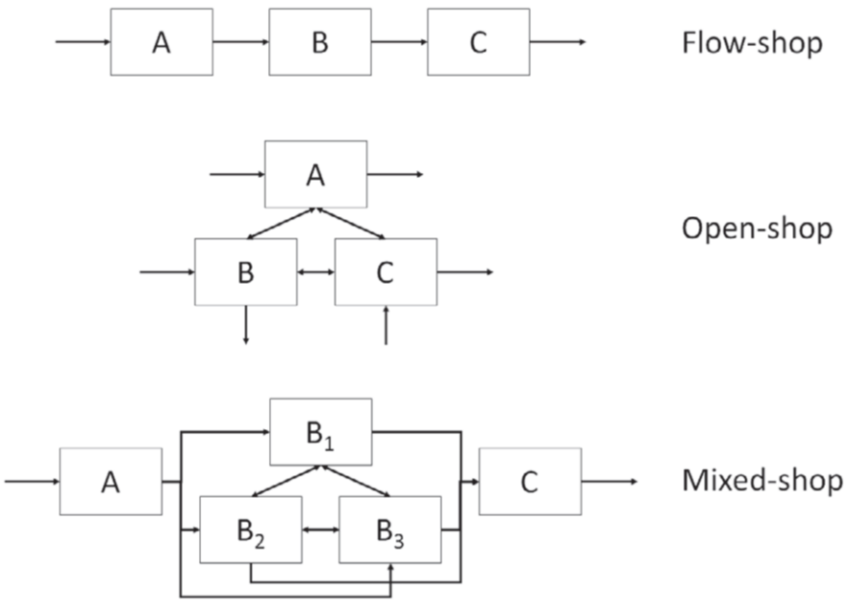


Figure 3.1: Graphical representation of multi-appointment systems (source: Leeftink et al., 2020)

Capacity planning involves allocating resource capacity to specialties, patient groups, or time slots. According to Leeftink et al. (2020), capacity planning for multi-disciplinary systems can be done in three ways: blueprint schedule, patient admission planning, and temporary capacity changes. In this literature review, the only focus is on the blueprint schedule because the other decisions are outside the scope of this research. A blueprint schedule outlines the capacity to be utilized by specific patient types on a given day or at particular time slots. Typical objectives of blueprint schedules are to combine consultations on one day (Dharmadhikari and Zhang, 2013), to minimize waiting time (Liang et al., 2015), or to reduce access time or throughput time (Bikker et al., 2015; Leeftink et al., 2018).

3.2.1 Blueprint schedule

According to Hulshof et al. (2012), seven key decisions design an appointment schedule.

- **The number of patients per consultation session**. This decision influences the patient access time and patient waiting times. Increasing the number of patients per consultation session will probably decrease access time but increase patient waiting time and staff overtime.
- **Overbooking of patients**. Patient overbooking, booking more patients than the number of planned slots, is done to anticipate possible no-shows and can thus increase utilization and decrease access time. However, it can also increase waiting time and staff overtime.
- **The length of the appointment interval**. If an interval's length is decreased, a resource's idle time is also decreased but the waiting time increases and vice versa.
- **The number of patients per appointment slot**. The two extremes of this decision. The first is to schedule all patients in the first appointment slot of a consultation session, and this decision decreases resource idle time but also increases waiting time. The other extreme is distributing all patients evenly over the consultation session, which is done to balance the utilization and waiting time.
- **The sequence of appointments**. This is especially important when different patient types are involved. This is because the variance between the different patient types likely differs more. And this can influence waiting time and utilization. A sequencing rule can be to sequence by increasing variance (i.e., scheduling the appointment with the lowest variance first).
- **Queuing discipline in the waiting room**. A commonly used queue discipline is first-come-first-served (FCFS). Another discipline can be to serve the patient with the highest priority. This is a discipline typically used when emergency patients are involved.
- **Anticipation for unscheduled patients**. To anticipate walk-ins or emergency patients, it can be helpful to leave some time slots empty (Dobson et al., 2011) or to increase appointment intervals (Cayirli and Veral, 2003).

3.2.2 Methods to design blueprints

There are multiple methods to design blueprints. According to Leeftink et al. (2020), mathematical programming or heuristics in combination with computer simulation or robust optimization to ensure robustness are suitable methods to design blueprints. The following paragraphs will show some examples of the use of these methods and some other methods that are used.

Mathematical programming

Apergi et al. (2020) wanted to minimize the number of hospital visits and the waiting time. Both are important for the convenience of the patients. To achieve this, an integer program was formulated.

The objective of Mutlu et al. (2015) was to design schedules that maximize the co-availability time of personnel from different specialties. This was done by developing an integer programming model. The constraints were that each clinic's coverage, preference, and extraneous responsibilities still needed to be satisfied.

Heuristics

Dharmadhikari and Zhang (2013) developed a block scheduling with priority (BSP) policy. This policy is for a multi-clinic appointment scheduling problem in the centralized scheduling system. A centralized scheduling system means that only one dedicated scheduler (or scheduling system) is responsible for scheduling all appointments. The BSP policy is a heuristic approach involving simulation optimization to combine consultations on one day. The performance of the block schedule is measured in total rewards, which is the revenue of a patient's visit minus the cost of mismatching appointments, patient waiting costs, and idle provider costs.

Mathematical programming in combination with simulation

Otten et al. (2021) suggest an iterative simulation optimization approach. This approach was developed during the COVID-19 pandemic and aimed to maximize the in-person consultation restricted by the maximum number of patients allowed in the waiting room. The iterative simulation optimization approach consists of a integer linear programming (ILP) model and a Monte Carlo simulation (MCS) model. The ILP model maximizes the in-person consultations based on the average early arrival and bridging times (time between appointments that is minimally needed). Then, the MCS model tests the output of the ILP model by including the effect of waiting time due to randomness. Based on the output of the MCS model, the parameters of the ILP are adjusted until the MCS returns a 95% confidence interval (CI) that the number of patients in the waiting room does not exceed its capacity.

Bikker et al. (2015) created an ILP model that designs a weekly doctors' scheme for a radiotherapy department. The objective of the ILP model was to minimize the expected access times of all patient types. In addition, the number of consultation time slots in the doctors' schedule needed to match the demand. Accordingly, the results of the ILP model were tested via a DES model by evaluating the consequences of the schemes in a stochastic environment. Liang et al. (2015) used a similar approach, namely a mixed-integer programming (MIP) model was developed to design a balanced appointment schedule within the chemotherapy department. And then, a DES model was used to evaluate the operational performance. The difference between the two approaches is the objective of the mathematical program because the objective of Liang et al. (2015) was to minimize waiting time.

Bovim et al. (2022) introduce an optimization model for solving an integrated master surgery and outpatient clinic scheduling problem. This is because physicians perform both surgeries and consultations. In addition, the physicians differ in experience. The model allocates specialties, number of surgeons, and activity types to time slots. A mathematical model produces two cyclic master schedules, one for the outpatient clinic and one for the ORs. Then, these two schedules are evaluated with a DES model.

Others

Vrugt et al. (2017) developed a discrete-time queueing model to evaluate the access time distribution of new patients. This model derived the minimum capacity required to meet the guideline stating that states that 90% of the patients must be helped within a week. In addition, to reduce patients' waiting time, a DES was used to identify the best appointment schedule and to tweak this schedule iteratively.

Dehghanimohammadabadi et al. (2022) developed a Multi-Objective Patient Appointment Scheduling framework. This framework consists of three modules. The first module consists of a multi-objective particle swarm optimization (MOPSO) algorithm. The second module is a simulation and the third module exchanges data of the MOPSO to the simulation module. The framework was tested by solving two appointment scheduling problems. One problem's objective is to minimize the total service time. Another is to maximize the number of (admitted) patients with no overtime.

3.3 Master surgery schedule

A master surgery schedule (MSS) assigns operating room capacity to surgical specialties or surgery types. Most MSS research appoints surgical specialties to ORs. However, there is some research regarding surgery-type-specific MSS.

Van Oostrum et al. (2006) developed an MSS where procedure types are planned cyclically. A slack factor was added to deal with the uncertainty of the duration of procedures. This slack factor was included to reduce the probability of overtime by planning a certain amount of slack into the schedule. The construction of an MSS is represented as a mathematical program that includes probabilistic constraints. A column generation approach was used to maximize utilization and evenly spread the demand for downstream resources. Both Mohsenigol et al. (2018) and Samanlioglu et al. (2010) developed an ILP model to construct an MSS. Both had the objective of minimizing the spare time of the OR. Yang et al. (2022) used a variable neighborhood search algorithm to develop an MSS with multiple objectives and considered upstream and downstream resource capacity.

Vanberkel et al. (2011) developed a model based on queuing theory to project the workload for downstream departments based on the MSS. For example, the ward occupancy distributions, patient admission/discharge distributions, and the distributions for ongoing interventions/treatments. The model can be used as a tool to support decisions to relate downstream departments to ORs. This model was used by Vanberkel et al. (2021), which focuses on the relationship between the OR and the ward. The objective is to level the ward occupancy and avoid peaks. Van Oostrum et al. (2008) developed a model to cluster surgery types to minimize the variability in resource demand of surgery types. Accordingly, those surgery-type clusters can be used in a MSS.

3.4 Conclusion

In this chapter, research question 2 is answered by performing literature reviews about multi-disciplinary scheduling and about master surgery scheduling. Capacity planning for multi-disciplinary systems can be done in three ways. One of which is the blueprint schedule, which is the focus of this study. There are seven key decisions to design a blueprint schedule and several methods to do that. One method is to use mathematical programming. In addition, often heuristics are used to design a blueprint schedule. Another method is to combine mathematical programming with computer simulation. According to Leeftink et al. (2020), this ensures robustness. Most research about MSS is regarding appointing specialties to ORs, but in this study, we are interested in surgery-type specific MSS. A suitable method therefore is mathematical programming. In addition, a model based on queuing theory is also used as a method to design a MSS.

Chapter 4

Model

In this chapter, the model is described that is used to answer the research question. An introduction of the approach used is given in Section 4.1. Section 4.2 discusses the method to determine the feasible OR days. After that, the model that constructs the weekly schedule around the OR days is explained. Section 4.4 explains the decision tree that is used to select the weekly schedules. Then, the DES model is explained and validated. Lastly, in Section 4.6, the experimental design is discussed.

4.1 3-phase approach

To the best of our knowledge, no literature combines a surgery schedule with required appointments before and after the intervention. We have decided to integrate a master surgery schedule with multi-discipline appointment scheduling, where a DES model is used as an evaluation tool, which is in line with Leeftink et al. (2020). A 3-phase approach is proposed to solve the research problem.

Phase 1 consists of constructing all feasible brachytherapy master surgery schedules for one OR day using a DES model. A schedule is feasible when the interventions in the OR finish on time, and there is enough time and capacity for the required following appointment on a treatment day. The DES model simulates an OR day.

Phase 2 creates a complete schedule of all appointment types for each feasible OR schedule with a ILP model. In other words, for each combination of surgery types in one OR day, a schedule is made, including preparation appointments and non-OR interventions. These schedules are evaluated using a DES model. This second DES model simulates a week where the week schedule that the ILP model produces is followed. The purpose of this simulation is to evaluate if the outcome of the ILP model is feasible or if certain constraints are missing or incorrect.

The construction of the master surgery schedules and the complete weekly schedules are split into two phases instead of combined into one phase for two reasons. First, the expectation is that the OR time demand during the bridging phase will increase drastically and is considered the biggest bottleneck. That is why, first, the focus is on scheduling the OR, after which the rest of the appointments are determined. The other reason is that using two separate phases makes the ILP model in phase 2 less complex and easier to solve.

Phase 3 develops planning rules to identify which schedule to use in which situation using decision trees. The resulting proposed way of working in the bridging phase will again be tested in a DES model. This third DES model incorporates the entire brachytherapy system.

In total three different DES models will be used in this 3-phase approach. In 2022, an DES model was already developed by de Bruijn (2022). This DES model is a simulation of the whole brachytherapy system of Amsterdam UMC and was made for the current situation and the bridging phase. The purpose of this study was to identify bottlenecks within the brachytherapy process to be able to improve the brachytherapy process. The DES model of de Bruijn is used as a starting point for the three DES models. Because the purposes of the DES models in the phases are different than that of the study of de Bruijn and because the time horizons differ, quite some adjustments were needed to use it in the three phases. The general structure of the model was kept the same. However, how and when a patient moves in the simulation completely changed. In addition, the previous DES model was mainly based on estimated data, and now the simulation is primarily based on actual data. This ensures that the model is a more accurate representation of the real world. The following sections, which zoom in on the different phases, will provide more information on the various DES models.

4.2 Phase 1 - OR-day scheduling

First, this section explains the conditions that hold for an OR day. Then, it is explained how the feasible OR days are determined.

4.2.1 Conditions for an OR-day

Multiple conditions are set for an OR-day to be considered a feasible solution. These conditions are determined in consultation with the brachytherapy team. The following conditions are selected:

1. The last OR intervention must be finished before 16:30 in more than 90% of the cases.
   The threshold has been set at a relatively low level. In practice, if the OR interventions take too long to finish on time, the intervention time can be shortened by having the radiotherapist perform the entire intervention rather than the resident. However, the simulation does not take that into account. This is further discussed in Section 6.3.3.
2. The overtime of the personnel needs to be limited to 30 minutes in 90% of the cases.

4.2.2 Selection feasible OR days

As stated in the previous section, two conditions must be met. Therefore, the selection of the feasible OR days is split into two steps. First, all possible combinations that fulfill the finishing time in the OR constraint are selected. Afterward, these remaining combinations are assessed against the second condition. This is executed stepwise to limit the number of possible combinations and, therefore, the time it takes to solve this problem.

Because it is now considered that a maximum of three OR interventions can take place on one OR day, the OR finish time condition is first assessed for a combination of a maximum of three OR interventions. In addition, it is decided to join the HDR cervix, HDR endometrium, and HDR vagina to one caller named HDR GYN. It is also important to note that a combination can also consist of one or two interventions, and an intervention can have three types: HDR prostate, HDR GYN, and LDR. This eventually leads to ten combination possibilities containing three interventions, six combinations containing two interventions, and three combinations containing one intervention. Based on the results of these combinations concerning the finish time of the OR, combinations with four interventions are formed and assessed. The order in which the OR interventions take place does not matter when testing for the first requirement because the time to switch between two interventions is considered to be equal.

To assess the different OR days, an DES model is used. This decision is made because an OR day is a complex care process with many dynamic factors that influence each other. A computer simulation effectively evaluates complex and comprehensive systems as it can handle those dynamic factors (Bikker et al., 2015).

This DES consists only of the process steps performed during an OR day. The process is divided into four parts: OR, imaging devices, treatment planning, and radiation. In the OR part, the patient arrives and the application is inserted. Depending on the treatment type, the patient then leaves the system or will move, when recovered, to the imaging devices. After that, a patient file is created in the treatment planning part, where the critical organs and tumor are contoured, the application is reconstructed, and the treatment plan is constructed when that is finished. When the treatment plan is approved, the patient will move to the radiation bunker to be irradiated.

In addition, to test the different OR days, the number of arriving patients equals the number of patients treated on the OR day. This is done to ensure that the arrival of patients does not influence the reliability of the simulation results. In addition, the process time for each step is based on obtained data. The process of fitting a distribution to the data and the results are explained in Section 4.5.2. Moreover, for assessing the first criterion, a large number of personnel is used to prevent any impact on the duration of the OR process steps.

The simulation is characterized as terminating. This is because a natural event marks the end of an OR day, which results in the termination of the simulation. Consequently, each OR day is considered one independent replication. Because the simulation is terminating, it is not necessary to determine a warm-up period. Thus, only the number of replications needs to be determined. Performing more replications results in a reduction of the confidence interval. However, more replications increase the runtime of the simulation. The idea is to select several replications for which the width of the confidence interval of a selected KPI is, relative to the average, sufficiently small (Law, 2015). The confidence level is set to 99 percent, and the finish time of the last OR intervention is considered the KPI. This KPI is selected because this timestamp indicates the finish time in the OR. This results in a minimum required number of replications of 73. That is why the simulation is run for two years for each combination, in which 104 independent OR days occur.

Once the OR days that meet the criteria of finishing before 16:30 in over 90 percent of cases are identified, the OR intervention combinations are tested for the second criterion, the overtime of personnel. For each replication, it is determined if there is overtime and, if so, how much overtime. It is considered overtime if the end time of the last process step of that day is later than the end of the shift. Unlike the first criterion, the sequence of the OR interventions influences the overtime. This is because each type of intervention has different steps after the intervention. For example, an LDR patient does not require any next steps, but an HDR prostate patient has several follow-up steps on an OR day. Simply put, each treatment type requires a varying amount of additional time after the intervention. The start time of an intervention influences the end time of all consecutive steps and, therefore, the end time for the personnel. Because the sequence is essential, all possible sequences are evaluated for each combination of OR interventions. For each sequence of interventions, 104 independent replications are performed, the same as for the selection of the first condition.

4.3 Phase 2 - Creating complete week schedules with ILP model

In the second phase, an ILP model is created to schedule all other appointments that do not occur on an OR day. This ILP model develops weekly schedules for those other appointments for a given OR day combination. Figure 4.1 shows a graphical representation of the input parameters and the output variables used in the ILP model. The main input of the ILP model is the OR intervention combination generated in phase 1, here denoted as scenarios. Other input parameters of the model are the availability of resources and the flow of appointments per treatment type. The output values of the model are the objective variables, which are the number of possible starting ring patients and the number of patients that still need their second or third intervention in the next weeks. The other output variable is the weekly schedule per OR intervention combination.

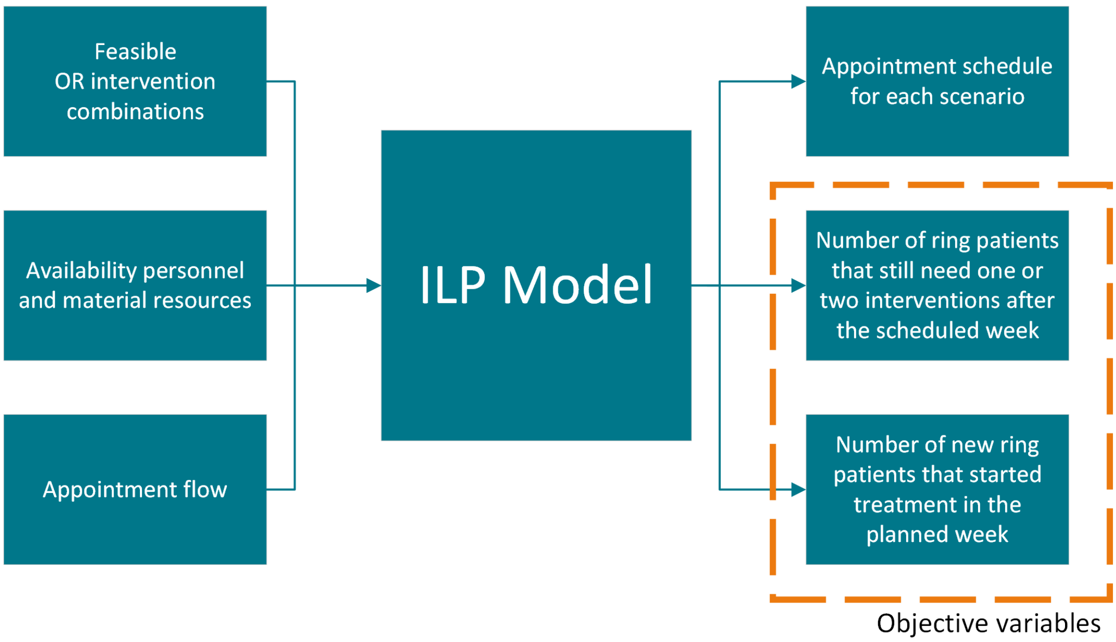


Figure 4.1: Schematic overview ILP model

The ILP model produces a blueprint of a week for each scenario. A scenario consists of the patients treated on the OR day and the number of HDR ring patients treated in the previous week(s) who still need one or two interventions at the start of the planned week. It is important to note that the same hours of the week are used for each blueprint. Only the appointment type that takes place can be different.

In this section, the mathematical formulation of the model is explained. First, all the sets and indices are defined. After which, the parameters and variables are discussed. Third, the constraints of the ILP are explained. Finally, the objective of the ILP model is discussed.

4.3.1 Sets and indices

Table 4.1 shows the sets and indices used in the ILP model. Two sets represent the personnel: $\mathcal{O}$ and $\mathcal{T}$. There is no set for the MPEs because there is always one available at every time, and it is considered a resource type. They are depicted in set $\mathcal{R}$ with all the other resources and room required for brachytherapy. All the different patient types are in set $\mathcal{P}$. Here the patient-type HDR ring is split into three kinds: ring patients that do not have had an intervention, ring patients that already had their first intervention, and ring patients that already had two interventions at the start of the week. These are included in the subset $\mathcal{P}_{int}$. The other patient types that do need an OR intervention are included in $\mathcal{P}_{or}$. In addition, there is another subset of $\mathcal{P}$, $\mathcal{P}_{known}$, which contains all patient types where, in advance, the number of patients is known. So, all patient types except the new HDR ring patients. Because there are, in some scenarios, multiple patients with the same patient type, the set $\mathcal{I}$ is introduced. The combination of i and p indicates one specific patient.

Table 4.1: Sets and indices in the ILP model

Set	Index	Description	Subset
$\mathcal{O}$	o	Radiotherapists	
$\mathcal{T}$	t	RTTs	
$\mathcal{R}$	r	Resource type	
$\mathcal{P}$	p	Patient type	
$\mathcal{P}_{or}$	p	OR Patient type	$\mathcal{P}_{or} \subset \mathcal{P}$
$\mathcal{P}_{int}$	p	Ring Patient type	$\mathcal{P}_{int} \subset \mathcal{P}$
$\mathcal{P}_{known}$	p	Known Patient type	$\mathcal{P}_{known} \subset \mathcal{P}$
$\mathcal{I}$	i	Patient id number	
$\mathcal{A}$	a, a'	Appointment type	
$\mathcal{A}_{or}$	a, a'	OR Appointment type	$\mathcal{A}_{or} \subset \mathcal{A}$
$\mathcal{A}_{int}$	a, a'	Ring Appointment type	$\mathcal{A}_{int} \subset \mathcal{A}$
$\mathcal{B}$	b	Time slots per day	
$\mathcal{D}$	d	Time slots in the planning horizon	
$\mathcal{D}_{week}$	d	Time slots of focus week	$\mathcal{D}_{week} \subset \mathcal{D}$
$\mathcal{J}$	j	Day of the week	
$\mathcal{S}$	s	Scenario	

Set $\mathcal{A}$ represents all different appointment types. $\mathcal{A}_{or}$ denotes the appointments for OR patients and $\mathcal{A}_{int}$ the appointments for ring patients. Four sets represent time. $\mathcal{B}$ represents the number of timeslots in one day. The total number of timeslots in the whole planning horizon is represented by $\mathcal{D}$. This entire planning horizon is longer than a week, the planning horizon for which the blueprint is designed. This extra time is required to plan the HDR ring interventions that cannot take place within the planning horizon of the blueprint.

However, these appointments are incorporated to allow the model to plan those appointments within the planning horizon of the blueprint if possible. However, if they are scheduled outside the planning horizon of the blueprint, they are not taken into account in the blueprint schedule. The timeslots that are part of the blueprint are a subset of $\mathcal{D}$, $\mathcal{D}_{week}$. Set $\mathcal{J}$ denotes the days in the blueprint schedule. Finally, set $\mathcal{S}$ represents the different scenarios.

4.3.2 Decision variables and parameters

The decision variables used in the ILP model are represented in Table 4.2.

Table 4.2: Parameters and variables in the ILP model

Notation	Description
Binary parameters	
A_{od}	1 if radiotherapist o is available during time slot d, 0 otherwise
A_{td}	1 if RTT t is available during time slot d, 0 otherwise
P_{pa}	1 if patient type p requires appointment type a
$E_{paa'}$	1 if patient type p requires appointment a' after appointment a, 0 otherwise
L_s	1 if scenario s is based on a half OR day, 0 if the scenario is based on a full OR day
Integer parameters	
N_{ps}	Number of patient with patient type p in scenario s
G_a	Number of radiotherapists required for appointment a
H_a	Number of RTTs is required for appointment a, 0 otherwise
I_{ra}	Number of resources of type r required for appointment a
R_{rd}	Number of resources of type r available at time slot d
K_o	Maximum number of time slots for radiotherapist o
K_t	Maximum number of time slots for RTT t
M_t	Maximum number of workdays per week for RTT t
$Q_{paa'}$	Minimum number of prescribed slots for patient type p between appointment types a and a' (0 if consecutive)
$F_{paa'}$	Maximum number of prescribed slots for patient type p between appointment types a and a' (0 if consecutive)
V_s	Number of volume measurements to plan in the first week in scenario s
Binary variables	
c_{ips}	1 if patient i with patient type p exist in scenario s, 0 otherwise
l_{tj}	1 if RTT t works on workday j, 0 otherwise
g_{ipoads}	1 if patient i,p has appointment type a at time slot d if assigned to radiotherapist o, 0 otherwise
h_{iptads}	1 if patient i,p has appointment type a at time slot d if assigned to RTT t, 0 otherwise
u_{ipos}	1 if patient type p with patient id i is assigned to radiotherapist o in scenario s, 0 otherwise
v_{ipads}	1 if patient type p with patient id i is assigned to appointment type a on time slot d in scenario s , 0 otherwise
y_{do}	1 if time slot d is active for radiotherapist o, 0 otherwise
z_{dt}	1 if time slot d is active for RTT t, 0 otherwise
Integer variables	
n_{ads}	Number of appointments of type a at time slot d in scenario s
τ_s	Number of ring patients that still need two interventions after one week
ϕ_s	Number of ring patients that still need one intervention after one week

4.3.3 Constraints

The first constraint concerns the different scenarios

- Initialize the amount of patients with patient type p for each scenario s

$$\sum_{i} c_{ips} = N_{ps} \quad \forall s, p \in \mathcal{P}_{known} \tag{4.1}$$

The following constraints are regarding the appointment restrictions

- Each appointment type a has to take place P_{pa} times for each patient that exists in scenario s

$$\sum_{d \in \mathcal{D}} v_{ipads} = P_{pa} c_{ips} \quad \forall i, p \in \mathcal{P}, a \in \mathcal{A}, s \tag{4.2}$$

- Appointment types have to be fulfilled in the right order and with the right time constraints between the appointment types

$$c_{ips}\left(\sum_{d\in\mathcal{D}}(d(v_{ipa'ds}-v_{ipads}))-(1+Q_{paa'})+(1-E_{paa'})|\mathcal{D}|\right)\geq 0 \quad \forall i,p\in\mathcal{P},a\in\mathcal{A},a'\in\mathcal{A},s \tag{4.3}$$

- A maximum number of timeslots limits the number of timeslots between two consecutive appointments in between

$$c_{ips}E_{paa'}\sum_{d\in\mathcal{D}}d(v_{ipa'ds}-v_{ipads})\leq 1+F_{paa'} \quad \forall i,p\in\mathcal{P},a\in\mathcal{A},a'\in\mathcal{A},s \tag{4.4}$$

Another constraint is regarding personnel-patient allocation

- A patient of type p with patient id i is assigned to one radiotherapist o

$$\sum_{o}u_{ipos}=c_{ips} \quad \forall i,p\in\mathcal{P},s \tag{4.5}$$

The following constraints are regarding patient-appointment allocation

- Only assign a patient to an appointment if the patient is assigned to the radiotherapist

$$g_{ipoads}\leq u_{ipos} \quad \forall i,p\in\mathcal{P},o,a\in\mathcal{A},d\in\mathcal{D},s \tag{4.6}$$

- A patient i,p can have appointment type a at time slot d, only if he/she is assigned to radiotherapist o that has a appointment type a scheduled during that timeslot

$$\sum_{o}g_{ipoads}=G_a v_{ipads} \quad \forall i,p\in\mathcal{P},a\in\mathcal{A},d\in\mathcal{D},s \tag{4.7}$$

- A patient i,p can have appointment type a at time slot d, only if an RTT t is assigned to appointment type a scheduled during that timeslot

$$\sum_{t}h_{iptads}=H_a v_{ipads} \quad \forall i,p\in\mathcal{P},a\in\mathcal{A},d\in\mathcal{D},s \tag{4.8}$$

In addition, there are also time restrictions for the personnel

- A radiotherapist o (RTT t) can do at most one activity on time slot d, and only if the radiotherapist (RTT) is available and if that time slot d is active to ensure that during all scenarios the same time slots are used:

$$\sum_{i}\sum_{p\in\mathcal{P}}\sum_{a\in\mathcal{A}}g_{ipoads}\leq A_{od}y_{od} \quad \forall o,d\in\mathcal{D},s \tag{4.9}$$

$$\sum_{i}\sum_{p\in\mathcal{P}}\sum_{a\in\mathcal{A}}h_{iptads}\leq A_{td}z_{td} \quad \forall t,d\in\mathcal{D},s \tag{4.10}$$

- The total number of time slots dedicated to brachytherapy appointments of a radiotherapist o (RTT t) per week is a given parameter

$$\sum_{d\in\mathcal{D}_{week}}y_{do}\leq K_o \quad \forall o \tag{4.11}$$

$$\sum_{d\in\mathcal{D}_{week}}z_{dt}\leq K_t \quad \forall t \tag{4.12}$$

- An RTT t can only be assigned to a timeslot on a restricted number of days per week

$$\sum_{d=1+(j-1)|\mathcal{B}|}^{j|\mathcal{B}|} z_{td} \geq l_{tj} \quad \forall t, j \tag{4.13}$$

$$\sum_{d=1+(j-1)|\mathcal{B}|}^{j|\mathcal{B}|} z_{td} \leq l_{tj}|\mathcal{B}| \quad \forall t, j \tag{4.14}$$

$$\sum_{j} l_{tj} \leq M_t \quad \forall t \tag{4.15}$$

There are also resource capacity constraints

- The number of appointments using recourse r at any timeslot d is restricted to the facility's capacity

$$n_{ads} = \sum_{i} \sum_{p \in \mathcal{P}} v_{ipads} \quad \forall a \in \mathcal{A}, d \in \mathcal{A}, s \tag{4.16}$$

$$\sum_{a \in \mathcal{A}} n_{ads} I_{ra} \leq R_{rd} \quad \forall r, d \in \mathcal{D}, s \tag{4.17}$$

Other constraints are:

- When the OR can be used a full day, it is on Tuesday. On the weeks that the OR can be used only in the morning, this happens on Monday. So all patients who need an OR intervention are scheduled on Monday or Tuesday.

$$v_{ipads} = c_{ips} \quad \forall i, s, p \in \mathcal{P}_{or}, a = \{OR1\}, d = L_s|\mathcal{B}| + 1 \tag{4.18}$$

- The HDR ring patients need at least one intervention in the first week if they exist

$$\sum_{d \in \mathcal{D}_{week}} \sum_{a \in \mathcal{A}_{int}} v_{ipads} \geq c_{ips} \quad \forall i, s, p \in \mathcal{P}_{int}, \tag{4.19}$$

The following constraints define the objective variables

- The number of ring patients that still need two interventions next week(s)

$$\tau_s = \sum_{i} \sum_{p \in \mathcal{P}_{int}} \sum_{d > 5|\mathcal{B}|} v_{ipads} \quad \forall s, a = \{Intervention2\} \tag{4.20}$$

- The number of ring patients that still need one intervention next week(s)

$$\phi_s = \sum_{i} \sum_{p \in \mathcal{P}_{int}} \sum_{d > 5|\mathcal{B}|} v_{ipads} - \tau_s \quad \forall s, a = \{Intervention3\} \tag{4.21}$$

4.3.4 Objective

The objective of the ILP is to create as many timeslots for ring patients as possible. That is why the number of new ring patients is maximized. In addition, a penalty is subtracted for the patients who still need one or two intervention(s) next week(s). This ensures that also more second and third interventions are scheduled. The value of the three objective variables are weighted by α, β, and γ, where $\alpha > \beta + \gamma$ and $\beta > \gamma$.

$$\max \alpha \sum_{i} \sum_{s} c_{ips} - \beta \sum_{s} \tau_s - \gamma \sum_{s} \phi_s \quad \text{where } p = \{NewRing\} \tag{4.22}$$

This objective is solved by implementing the ILP model in AIMMS 4.95 and is solved using CPLEX 22.1.

4.4 Phase 3 - Decision tree for blueprint selection

In the last phase, a decision tree is developed that decides which week schedule to use in which week. This decision tree aims to maximize the OR capacity and minimize the access time. If this aim is reached is evaluated with the use of the DES discussed in Section 4.5, where the results of the implementation of this tree are evaluated with the current scheduling method of FCFS.

In this section, we will discuss how the decision tree will be determined. Because the OR is considered to be the biggest bottleneck, the weekly schedules are first selected on that basis. That is why the first step is to determine the constraints to select an OR combination. This refers to whether some OR combinations can take place one after the other. The next step is to state the constraints of the week to schedule. This refers to character traits of a week, for example, that there will be no OR in the following week. Based on these constraints, the first branches of the decision tree are constructed.

Then, it is checked if there is one solution at the end of the branch or if multiple solution possibilities exist. For each branch for which multiple solutions are still possible, a decision is made based on the patients that can have treatment this week. If there are no patients of a certain type to schedule, the solution follows automatically. If there are still multiple OR combinations possible, in consultation with the brachytherapy team, considerations were made as to which combination would be more advantageous. The final decisions of the decision tree are based on these opinions.

Last, if the OR combination is selected, the total weekly schedule is selected based on the OR combination, and the number of ring patients is the previous week.

4.5 DES model

After the execution of phases 1 to 3, a DES model is used to evaluate the whole system. As explained earlier, a DES model is a suitable method to evaluate complex and detailed systems like the brachytherapy department system. To be used as an evaluation tool, it is crucial that the simulation accurately represents the real world.

In this section, first, a description of the simulation system will be provided. Second, data is collected to use as input parameters. Then, the performance measurements are defined, and the experimental settings are determined. After which, the DES is validated and verified.

4.5.1 System description

Two different simulation models are developed, one of the current situation and one of the bridging situation. The simulation software that is used is Tecnomatix Plant Simulation by Siemens. For both models, the brachytherapy process is split into seven parts. These parts are Home, Preparation, Application Insertion, Imaging, Treatment Planning, Radiation, and Exit. These divisions are placed on a Control Panel in Tecnomatix Plant Simulation. More detailed information can be found in Appendix C.

At Home patients arrive according to a Poisson distribution. After arrival, the appointment for treatment is made immediately. If an appointment cannot be made within the time constraints, the patient is referred to another hospital and will leave the system via

Exit. If a patient can be scheduled on time, the patient waits at home until the appointment day is reached. At Preparation, the preparation appointments are executed. After these appointments, the patients go back to home.

Figure 4.2 shows the flow of patients through the DES model. The treatment day of a patient starts at Application Insertion. Depending on the treatment type a patient receives, the patient will go to the OR or the intervention room in Application Insertion. If the patient is recovered and the MRI or CT appointment time has arrived, the patient will go to imaging when necessary. When the imaging is finished, the patient will wait in the waiting area while a patient file is created in Treatment Planning. After the treatment planning steps are conducted, the patient will receive radiation. Depending if multiple treatments are necessary, the patient will go to Exit and leave the system or go back home to wait for the new appointment.

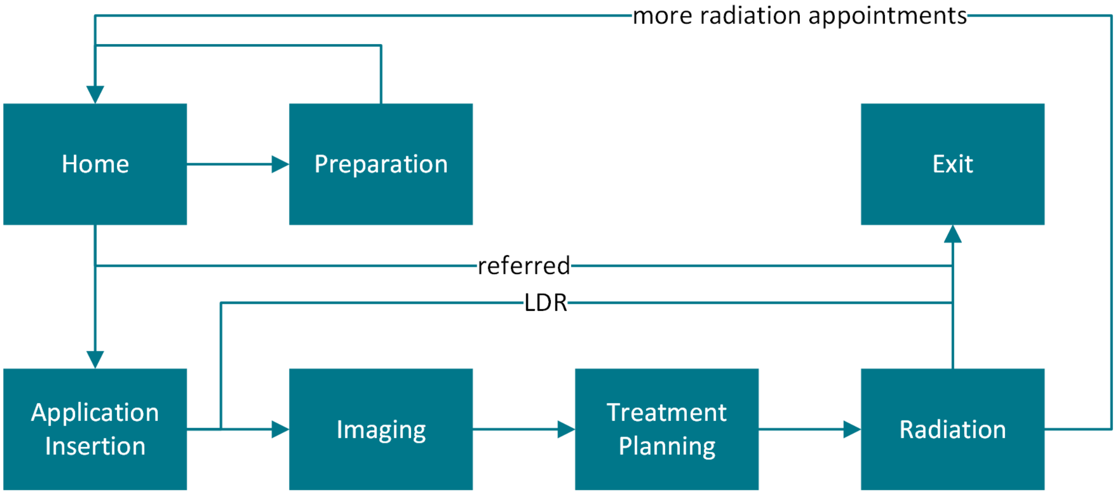


Figure 4.2: Flow chart of movements in DES model

4.5.2 Uncontrollable input parameters

As mentioned, the first step is to collect data that can be used within the DES. The data for the uncontrollable input parameters, which management decisions cannot influence (Law, 2015), can be subtracted from two different systems. The first is Epic, an electronic medical record software application. The other system is the system connected to the afterloaders. This data must be fitted with a distribution to use in the DES. The collected data is divided into three categories. The first category is the process times per treatment type, and the second category consists of the arrival rate of patients with varying types of treatment. The other category consists of the deviation of actual and planned start times of the OR and MRI.

Process times

The Epic and afterloader databases store eight timestamps for each patient during a treatment day. These are the scheduled OR time, the actual OR start and end time, the scheduled MRI start time, the actual MRI start and end times, and the actual start and end time of the radiation. Based on this information, four distributions regarding process time can be determined.

The first process time is the OR time. The start time is defined by the moment a patient arrives in the OR, and the end time is when the patient leaves the OR. Thus, the OR time includes, among other things, putting the patient under general anesthesia. The second process time is the imaging time. Depending on the imaging technique, this can be an CT or an MRI. The third process time is the radiation time. For PDR, this includes the time between the different fractions and thus is represented by the time the afterloader is connected with the applicator.

The fourth process time is the time between the end of the imaging and the start of the radiation. During this time, the critical organs and tumor are contoured, the application is reconstructed, and the treatment plan is made and checked. In addition, the applicator is connected within this time. The separate start and end times of these process steps are not registered. However, to gain insight into the duration of these steps, manually, these times are registered for ten patients. Based on these times, for each process step, an estimate is made of which part of the total treatment planning it takes. For this fraction, a uniform distribution is determined.

After the time values are collected, a distribution needs to be fitted for these times. This is done in a stepwise manner. The first step is to hypothesize the distribution. This is done based on descriptive statistics and a graphical representation of the data. The next step is to estimate the parameters. Then it is determined how representative the fitted distribution is. The final step is to perform a chi-square test. Appendix D presents an example of these steps. Table 4.4 shows the outcome of the distribution fitting.

There is no representative data available for the process steps not shown in the table. There are two reasons that this data is not available. The first reason is that it is not registered in the system. Another reason is the incorrect registered timestamps, such as the end time being recorded before the start time. Those process times are based on estimates. This includes the HDR ring application insertion, imaging and total treatment planning, and the duration of a CT for HDR prostate patients. Also, note that the data for radiation of gynecology patients is the duration of PDR treatment. The time for HDR GYN radiation is unknown and thus also based on estimation.

Arrival rate

For each treatment type, the interarrival time distribution is determined. This is done with the same approach as explained in the previous section. All the interarrival times are exponentially distributed, all with a different lambda (see Table 4.3). This means that in the simulation, the arrival rate of patients follows a Poisson distribution.

Table 4.3: Arrival rate per treatment type

Treatment type	λ	Test statistic
HDR cervix	0.163	$16.06 < \chi^2_{0.95,9}$
HDR endometrium	0.013	$1.00 < \chi^2_{0.95,2}$
HDR vagina	0.025	$0.23 < \chi^2_{0.95,3}$
HDR prostate	0.048	$3.60 < \chi^2_{0.95,4}$
LDR	0.177	$7.79 < \chi^2_{0.95,9}$
HDR ring	0.240	$15.11 < \chi^2_{0.95,10}$

Table 4.4: Process times distributions in minutes

Process Step	Treatment type	Distributions	Test statistic
Application insertion	LDR prostate	Lognormal(4.99, 0.13)	$3.12 < \chi^2_{0.95,9}$
	HDR prostate (1 and 3 fractions)	Uniform(121.99, 201.90)	$3.00 < \chi^2_{0.95,4}$
	PDR GYN - Cervix	Lognormal(4.55, 0.30)	$11.95 < \chi^2_{0.95,8}$
	PDR GYN - Endometrium	Uniform(67.17, 181.52)	$0.89 < \chi^2_{0.95,4}$
	PDR GYN - Vagina	Uniform(92.00, 169.88)	$4.67 < \chi^2_{0.95,3}$
MRI	HDR prostate (1 and 3 fractions)	Gamma(5.00, 10.62)	$2.25 < \chi^2_{0.95,4}$
	PDR GYN - Cervix	Lognormal(3.74, 0.37)	$16.00 < \chi^2_{0.95,9}$
	PDR GYN - Endometrium	Lognormal(3.46, 0.30)	$1.80 < \chi^2_{0.95,3}$
	PDR GYN - Vagina	Lognormal(3.76, 0.37)	$1.00 < \chi^2_{0.95,3}$
Contouring, Reconstruction & Treatment Planning	HDR prostate (1 and 3 fractions)	Lognormal(5.42, 0.17)	$2.10 < \chi^2_{0.95,4}$
	PDR GYN - Cervix	Lognormal(5.42, 0.23)	$6.27 < \chi^2_{0.95,8}$
	PDR GYN - Endometrium	Lognormal(5.41, 0.22)	$1.60 < \chi^2_{0.95,2}$
	PDR GYN - Vagina	Lognormal(5.41, 0.22)	$1.73 < \chi^2_{0.95,3}$
Radiation	HDR prostate (1 and 3 fractions)	Uniform(15, 30)	$6.40 < \chi^2_{0.95,4}$
	PDR GYN - Cervix	Uniform(2640,2880)	$12.22 < \chi^2_{0.95,8}$
	PDR GYN - Endometrium	Uniform(2400, 2880)	$0.67 < \chi^2_{0.95,2}$
	PDR GYN - Vagina	Uniform(2400, 2880)	$1.50 < \chi^2_{0.95,3}$
	HDR Ring	Uniform(8, 12)	$3.63 < \chi^2_{0.95,8}$

Time deviation from appointment time

There are two appointments where the starting time sometimes deviates from the planned one. This holds for the start of the first intervention in the OR and the MRI's start time. The planned start time of the first OR intervention is 08.00. And the intentional start times of the MRI are 12.00 for the patient with the first OR intervention and 13.30 for the patient with the second OR intervention.

The intentional start time of the first OR intervention is 08.00; however, sometimes, it starts somewhat earlier but more often later. This can have multiple reasons, but most often, it is caused by the fact that the anesthetist is unavailable. Only the deviation of the first OR intervention is included because the other interventions' starting time depends on the end time of the previous intervention. The deviation of start time is defined as the time difference between the actual start time and 07.45. This is because it is assumed, also based on data, that an early start before 07.45 is unrealistic. And by taking the deviation from 07.45, all the deviation values are positive, which is more convenient for distribution fitting. The consequence is that a deviation of 15 means the intervention starts on time. After the distribution is fitted, it is concluded that the deviation follows a lognormal distribution with a μ of 3.21 and a σ of 0.56.

The next time deviation is the start time of the MRI. During an OR day, the brachytherapy department has two timeslots available for the MRI, at 12.00 and 13.30. There are multiple reasons why the starting time of the MRI differs from the planned. In this case, the time difference caused by patients not recovering on time is not considered. Based on the remaining data, it is concluded that the deviation from the start of the first timeslot follows a lognormal distribution with μ of 3.58 and σ of 0.59. The distribution of the second MRI follows a lognormal distribution with μ of 3.88 and σ of 0.41. If the deviation is zero, the start time of the first MRI equals 11.30 and 13.00 for the second MRI.

4.5.3 Controllable input parameters

In contrast to uncontrollable input parameters, there are also controllable input parameters. Controllable parameters are represented by action options for managers (Law, 2015). Most controllable input parameters are related to personnel. The two most important personnel parameters are the number of employees per personnel type and the working hours of those employees. The current work hours of the personnel are already discussed in Section 2.5.2.

The availability of equipment and rooms is also a controllable input parameter. Seven pieces of equipment and rooms are used in the brachytherapy process. Table 4.5 shows the availability of those rooms and equipment.

Table 4.5: Current availability of equipment and rooms

	Monday	Tuesday	Wednesday	Thursday	Friday
CT	08:00 - 17:30	08:00 - 17:30	08:00 - 17:30	08:00 - 17:30	08:00 - 17:30
MRI	12:00 - 14:00	12:00 - 12:45 13:30 - 14:15	12:00 - 14:00	12:00 - 14:00	12:00 - 14:00
OR		08:00 - 16:30**			
PDR Afterloaders F5N*	08:00 - 23:59	00:00 - 23:59	00:00 - 23:59	00:00 - 23:59	00:00 - 17:30
HDR Afterloader F5N*	08:00 - 17:30	08:00 - 17:30	08:00 - 17:30	08:00 - 17:30	08:00 - 17:30
F5N Bunkers*	08:00 - 23:59	00:00 - 23:59	00:00 - 23:59	00:00 - 23:59	00:00 - 17:30
Intervention room*	08:00 - 17:30	08:00 - 17:30	08:00 - 17:30	08:00 - 17:30	08:00 - 17:30
HDR Afterloader B	08:00 - 17:30	08:00 - 17:30	08:00 - 17:30	08:00 - 17:30	08:00 - 17:30
HDR Afterloader C	08:00 - 17:30	08:00 - 17:30	08:00 - 17:30	08:00 - 17:30	08:00 - 17:30
Bunker B(onaire)	08:00 - 17:30	08:00 - 17:30	08:00 - 17:30	08:00 - 17:30	08:00 - 17:30
Bunker C(uracao)	08:00 - 17:30	08:00 - 17:30	08:00 - 17:30	08:00 - 17:30	08:00 - 17:30

*Not available during bridging phase

**Every month, there is a week when the OR is not available.

4.5.4 Performance measurements

Five different performance measurements are determined to assess the different configurations in the simulation. These performance measures are determined in consultation with the brachytherapy team. The performance measurements are as follows:

- Number of treated patients per year
- Access time
  Number of days between the arrival of a patient and the first treatment day.
- Lead time
  Time between inserting the application and the beginning of the radiation treatment.
- Utilization
  Determined for the OR, Bunkers, and Afterloaders
- Overtime
  How much time an employee spends after their shift has ended.

4.5.5 Experimental settings

The simulation model of the total system is characterized as a non-terminating, steady-state simulation. A simulation run is considered non-terminating when no natural event indicates its end (Law, 2015). The experimental settings that need to be set are the warm-up period, run length, and number of replications. The adequately chosen settings will affect the accuracy of the model.

Warm-up period and run length

No patients are in the system at the start of a simulation. The consequence is that the access time but also the utilization of the resources do not match the current situation because all appointment slots are still open. That is why a warm-up period is introduced. After this warm-up period, a steady state arises, for which the performance measures stay fairly constant. Welch's graphical method determines the length of the warm-up period (Law, 2015). The observation used to determine the warm-up period is, for each day, the average access time of patients waiting for their treatment day. Based on this, the steady-state starts at day 288. For convenience, the warm-up period will be set for one year.

Based on the duration of the warm-up period and the need to measure performance over a year, it has been determined that the run will last for two years. This means there will be one remaining year after subtracting the warm-up period.

Replications

The same technique is used to determine the number of replications as described in Section 4.2.2. In this case, a significance level of 97.5% is used with a relative error of 2.5%. The relative error goes below the threshold of 2.5% after 29 replications. Therefore the number of replications will be set to 29.

4.5.6 Validation and verification

As stated in Section 4.5.1, two simulations are developed, one of the current situation and one of the bridging phase. The simulation of the current situation is developed for validation and verification purposes. This is because the outcome of the bridging phase simulation cannot be compared. After all, the situation does not exist yet, and for the current situation, this is possible. After validation, the simulation of the bridging phase is used for the rest of the study.

After the model is discussed with the brachytherapy team and is considered correct, the simulation outputs are compared with the actual current performance. Table 4.6 compares those two and presents the percentual differences.

Table 4.6: Performance simulation compared to the actual situation

	Actual performance	Simulation	Difference
Number of Treated Patients	173	172.90	-0.06%
Average Access Time HDR Prostate	61 days	65.6 days	7.54%
Average Access Time LDR	46 days	40.77 days	-11.37%
Average Access Time PDR GYN	32 days	32.46 days	1.44%
Average Access Time HDR ring	31 days	33.77 days	8.94%
OR Utilization	49.82%	66.70%	33.88%
HDR Bunker Utilization	55.41%	53.67%	-3.14%
HDR Afterloader Utilization	7.87%	5.88%	-25.28%
PDR Bunker Utilization	41.58%	35.95%	-13.54%
PDR Afterloader Utilization	27.97%	24.44%	-12.62%
Average Lead Time HDR Prostate / PDR GYN patients (hh:mm:ss)	08:17:07	08:05:02	-2.43%

There are significant differences regarding OR utilization, bunker utilization, and access time for LDR patients between the simulation and the real world. There are several logical explanations for this. The difference between OR utilization can be caused by the fact that, in reality, sometimes the brachytherapy department gives some time in the afternoon to the gynecology department in return for OR time from their department in the morning. However, in our calculations, this time is considered unoccupied. And the time of other departments is not considered. While in the simulation, no OR time is given away. The significant percentage difference of the HDR afterloader can be explained by the small utilization; thus, a slight deviation leads directly to a significant percentage difference. The utilization difference in the PDR bunker can be explained by the fact that patients are admitted earlier. Lastly, the access time of LDR patients is probably higher in real life because sometimes patients request to be scheduled later. This is due to personal preference, for example, due to a holiday or other hindrances.

Despite these differences, the simulation is, in consultation with the brachytherapy team, considered to be an adequate representation of the real world.

4.6 Experimental design

In this section, the different experiments that are performed are discussed. The primary assumption of the brachytherapy team is that the OR capacity and the number of personnel, particularly the number of RTTs, are the main reasons a limited number of patients can be treated during a year. Another factor that the brachytherapy team is working on is reducing the process times. This is considered an uncontrollable input parameter because it is not a decision that can be made, but innovation is needed to reduce the process times. The expectation is that innovation can improve the process times of the OR and the total treatment planning time. Examples of innovation are automatic contouring and automatic planning. Because these three factors are considered the most important, they are selected for the experimental design.

Only two factors influence the first phase, the OR-day schedule, namely the number of personnel and the process times. That is why the experiments depicted in Table 4.7 are executed for this phase.

Table 4.7: Experiments phase 1

Experiment Name	Number of Radiotherapists	Number of RTT	Process Time
Base case	4	3	Current Speed
'4Therapist+4RTT+0%PT'	4	4	Current Speed
'4Therapist+5RTT+0%PT'	4	5	Current Speed
'5Therapist+5RTT+0%PT'	5	5	Current Speed
'4Therapist+3RTT+10%PT'	4	3	Reduction of 10 percent
'4Therapist+4RTT+10%PT'	4	4	Reduction of 10 percent
'4Therapist+5RTT+10%PT'	4	5	Reduction of 10 percent
'5Therapist+5RTT+10%PT'	5	5	Reduction of 10 percent
'4Therapist+3RTT+25%PT'	4	3	Reduction of 25 percent
'4Therapist+4RTT+25%PT'	4	4	Reduction of 25 percent
'4Therapist+5RTT+25%PT'	4	5	Reduction of 25 percent
'5Therapist+5RTT+25%PT'	5	5	Reduction of 25 percent

The OR capacity influences only phases 2 and 3. For those phases, a combination of the experiments shown in Table 4.7 and the experiments from Table 4.8 are used. The base case represents the current personnel and process time settings. For the factor OR capacity, a difference is made between dividing the OR time differently or increasing OR time, which is indicated in the last column of Table 4.8.

Table 4.8: Experiments OR capacity

Experiment name	**OR capacity**	**Same number of OR hours**
'3full in 4w'	3 full OR days in 4 weeks	True
'2full+2morning in 4w'	2 full OR days and 2 morning OR days in 4 weeks	True
'5full+2morning in 8w'	5 full OR days and 2 morning OR days in 8 weeks	True
'4full in 4w'	4 full OR days in 4 weeks	False
'4full+2morning in 4w'	4 full OR days and 2 morning OR days in 4 weeks	False
'4full+4morning in 4w'	4 full OR days and 4 morning OR days in 4 weeks	False

Furthermore, a sensitivity analysis is conducted regarding the arrival of patients. We tested scenarios where there was a 20% decrease or a 20% increase in patient arrival. This sensitivity analysis is performed to identify the influence of an uncontrollable input parameter on the outcome of the model.

4.7 Conclusion

In this chapter, the three-phase approach is described. First, a description of the DES is provided, after which the simulation of the current situation is validated and verified. An adjusted version of the simulation of the bridging phase is then used to select all feasible OR-day schedules. Then, the ILP model used in phase 2 is explained. The objective of the ILP model is to maximize the number of starting HDR Ring patients while limiting the number of HDR ring patients that need intervention(s) in the next week(s). For phase 3, the decision tree indicates which week schedule to use based on the arriving patients. Lastly, the experimental design is presented. To perform experiments, three factors need to be considered: number of personnel available, process durations, and OR availability. In addition, a sensitivity analysis is conducted regarding the arrival of patients.

Chapter 5

Results

This chapter discusses the results of the 3-phase approach described in Chapter 4. In Section 5.1, the first phase results are presented. After which, an example of a generated weekly schedule is provided in Section 5.2. Section 5.3 presents the decision tree. Then, in Section 5.4, the DES model results are discussed. In the DES, the weekly schedules and decision trees are incorporated.

5.1 OR days

In this section, the results of the first phase are provided. First, the results of the current configuration are discussed, after which the results of the experiments are evaluated. As mentioned in Section 4.2.1, the OR days need to fulfill two conditions. That is why first, the OR finish time results are shown of all possible combinations considering the maximum of three interventions. Then, based on these outcomes, combinations are formed to check if four interventions on an OR day are feasible. Accordingly, the results of those combinations are shown for the second condition.

5.1.1 Condition 1: Finish time in OR

Table 5.1 shows the average finish time of all possible combinations in the OR. The percentage indicates the proportion of OR days that finish on time, in this case, before 16:30. It is important to note that if a combination of three interventions meets the condition, this also implies that the combination minus one of the interventions also meets the criterion. E.g., combination 2 consists of two LDR interventions and one HDR GYN intervention, so a combination of one LDR and one HDR GYN intervention also meets the requirements. Based on this, it can be stated that all combinations of two interventions meet the OR finish time condition. And, of course, an OR day of one intervention also meets the criterion.

Table 5.1: Results feasibility OR days based on finish time in OR

Combination	HDR Prostate	HDR GYN	LDR	Percentage finished on time	Average finishing time *(hh:mm:ss)*
1	0	0	3	41.35%	16:40:03
2	0	1	2	92.93%	15:27:19
3	0	2	1	98.00%	14:47:52
4	0	3	0	100.00%	13:38:03
5	1	0	2	48.08%	16:34:13
6	1	1	1	93.26%	15:31:12
7	1	2	0	98.88%	14:33:29
8	2	0	1	43.26%	16:40:15
9	2	1	0	94.05%	15:37:18
10	3	0	0	31.73%	16:45:09

In addition, based on the results in Table 5.1, OR day combinations containing four interventions are evaluated. These results are shown in Table 5.2. This shows that only one combination fulfills the OR finish time condition, which is the combination of four HDR GYN interventions.

Table 5.2: Feasibility OR days with four interventions based on finish time in OR with three interventions

Combination	HDR Prostate	HDR GYN	LDR	Percentage finished on time	Average finishing time *(hh:mm:ss)*
α	0	4	0	90.20%	15:32:38
β	0	3	1	41.41%	16:42:22
γ	1	3	0	29.41%	16:50:29
δ	1	2	1	0.00%	17:48:03
ϵ	2	2	0	0.00%	17:40:22
ζ	0	2	2	0.00%	17:57:53

This eventually leads to sixteen OR day combinations that meet the OR finish time criteria. These are three OR days with one intervention, six combinations with two interventions, six interventions with three interventions, and one with four interventions. These combinations are subsequently assessed against the second criterion.

5.1.2 Condition 2: Limited overtime personnel

As mentioned in Section 4.2.2, the sequence of interventions in the OR is essential for this condition because each process type has different follow-up steps after the OR intervention. For each sequence, it is determined if there is overtime and how much it is. This is determined for two different cases. In the first case, there are no different shifts for the personnel. The personnel does work in shifts in the second case.

For the first case, the DES model shows that only three OR day sequence meets the overtime criterion. These OR days consist of two (or one) LDR interventions — this OR day ended 100 percent of the days within 30 minutes of overtime - and the OR days consisted of only one HDR GYN intervention. The two OR day sequences closest to the threshold were the OR days with one HDR GYN intervention and one or two LDR interventions, where the HDR GYN intervention was performed first. This sequence is finished in 85.7 percent of the cases within 30 minutes of overtime.

In the second scenario, working with different shifts is an option. Because the first OR starts around 08.00, at least two RTTs and one radiotherapist must be present at the start of the OR day. In addition, it is decided to have a maximum of two shifts to keep it evident. Based on the available number of personnel, all different shift times and configurations are evaluated, and the shift time for which most OR days meet the overtime condition is selected. Table 5.3 shows the results based on the first shift starting from 07.30 until 17.30 and the second shift starting from 10.00 until 20.00. And where two radiotherapists start in shift 1 and two in shift 2. Two RTTs start in shift 1, and one RTT starts in shift 2.

Table 5.3: Feasibility OR days based on the overtime of personnel using shifts

Combination	**OR 1**	**OR 2**	**OR 3**	**OR 4**	**Percentage overtime less than 30 minutes**
2-1	HDR GYN	LDR	LDR		100.00%
2-2	LDR	HDR GYN	LDR		94.29%
2-3	LDR	LDR	HDR GYN		41.90%
3-1	HDR GYN	HDR GYN	LDR		89.52%
3-2	HDR GYN	LDR	HDR GYN		65.71%
3-3	LDR	HDR GYN	HDR GYN		64.76%
4	HDR GYN	HDR GYN	HDR GYN		80.95%
6-1	HDR prostate	HDR GYN	LDR		75.24%
6-2	HDR prostate	LDR	HDR GYN		32.38%
6-3	HDR GYN	HDR prostate	LDR		75.24%
6-4	HDR GYN	LDR	HDR prostate		27.62%
6-5	LDR	HDR GYN	HDR prostate		22.86%
6-6	LDR	HDR prostate	HDR GYN		36.19%
7-1	HDR GYN	HDR GYN	HDR prostate		26.67%
7-2	HDR GYN	HDR prostate	HDR GYN		51.43%
7-3	HDR prostate	HDR GYN	HDR GYN		48.57%
9-1	HDR prostate	HDR prostate	HDR GYN		33.33%
9-2	HDR prostate	HDR GYN	HDR prostate		29.52%
9-3	HDR GYN	HDR prostate	HDR prostate		24.76%
A	LDR	LDR			100.00%
B-1	HDR prostate	LDR			99.05%
B-2	LDR	HDR prostate			77.38%
C	HDR prostate	HDR prostate			72.38%
D-1	HDR GYN	LDR			100.00%
D-2	LDR	HDR GYN			96.19%
E-1	HDR GYN	HDR prostate			93.33%
E-2	HDR prostate	HDR GYN			95.24%
F	HDR GYN	HDR GYN			99.05%
α	HDR GYN	HDR GYN	HDR GYN	HDR GYN	32.38%

The table does not show the OR days with only one intervention, but these are also feasible. This results in nine feasible OR day combinations, where only the sequence with the highest percentage without overtime is used.

5.1.3 Experiments results

The steps executed in the previous two subsections are also performed for the experiments defined in Section 4.6. First, the OR days are feasible OR days are presented when the whole day the OR is available for the brachytherapy team. In the second subsection, the feasible OR days where the OR can only be utilized in the morning.

Full OR days

Table 5.4 shows the results of the feasible combinations for the experiments. All combinations not shown in the table are not feasible in any of the experiments. Appendix E shows the finish time results in the OR for the different levels of process time. The table shows that reducing the process times has more influence on the number of possible OR intervention combinations than adding personnel. For example, if the process times are reduced, adding any personnel would not influence the number of possible OR intervention combinations. And when more OR day combinations are feasible, you are more flexible in planning your ORs. In addition, reducing the process time also leads to the possibility of performing four interventions on an OR day instead of three, which can increase the number of treated patients.

Table 5.4: Feasible full OR days for all experimental settings

Exp. Name	Combination 1 *LDR, LDR, LDR*	Combination 2 *HDR GYN, LDR, LDR*	Combination 3 *HDR GYN, HDR GYN, LDR*	Combination 4 *HDR GYN, HDR GYN, HDR GYN*	Combination 5 *HDR prostate, LDR, LDR*	Combination 6 *HDR prostate, HDR GYN, LDR*	Combination 7 *HDR prostate, HDR GYN, HDR GYN*	Combination 8 *HDR prostate, HDR prostate, LDR*	Combination 9 *HDR prostate, HDR prostate, HDR GYN*	Combination A *LDR, LDR*	Combination B *HDR prostate, LDR*	Combination C *HDR prostate, HDR prostate*	Combination D *HDR GYN, LDR*	Combination E *HDR prostate, HDR GYN*	Combination F *HDR GYN, HDR GYN*	Combination β *HDR GYN, HDR GYN, HDR GYN, LDR*
Base case		✓								✓	✓		✓	✓	✓	
'4Therapist+4RTT+0%PT'		✓	✓			✓				✓	✓		✓	✓	✓	
'4Therapist+5RTT+0%PT'		✓	✓			✓				✓	✓		✓	✓	✓	
'5Therapist+5RTT+0%PT'		✓	✓			✓				✓	✓		✓	✓	✓	
'4Therapist+3RTT+10%PT'		✓	✓		✓	✓				✓	✓	✓	✓	✓	✓	
'4Therapist+4RTT+10%PT'		✓	✓	✓	✓	✓				✓	✓	✓	✓	✓	✓	
'4Therapist+5RTT+10%PT'		✓	✓	✓	✓	✓				✓	✓	✓	✓	✓	✓	
'5Therapist+5RTT+10%PT'		✓	✓	✓	✓	✓				✓	✓	✓	✓	✓	✓	
'4Therapist+3RTT+25%PT'	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
'4Therapist+4RTT+25%PT'	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
'4Therapist+5RTT+25%PT'	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
'5Therapist+5RTT+25%PT'	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Half OR days

An alternative within the OR capacity is to use a half OR day. Then, the brachytherapy team can utilize the OR in the morning from 08.00 until 12.15. For that reason, the feasible combinations are also determined for half OR days (see Table 5.5). Only the results for the different process time levels are shown in this case. This is because the number of personnel and shifts does not influence the selection of feasible half OR days. In addition, all half OR days that fulfill the OR end time condition also meet the overtime criterium. That is also why these results are not depicted.

Table 5.5: Feasibility half OR days based on finish time OR for three levels of process times

Combination	OR 1	OR 2	Percentage finished on time (current process time)	Percentage finished on time (10% reduction)	Percentage finished on time (25% reduction)
H1	HDR GYN	HDR GYN	78.43%	90.24%	97.92%
H2	HDR GYN	LDR	17.31%	39.42%	88.46%
H3	HDR prostate	HDR GYN	19.23%	42.31%	93.27%
H4	LDR	LDR	0.96%	4.81%	39.42%
H5	HDR prostate	LDR	0.00%	2.88%	32.69%
H6	HDR prostate	HDR prostate	0.00%	0.96%	36.54%
H7	HDR prostate		100.00%	100.00%	100.00%
H8	HDR GYN		100.00%	100.00%	100.00%
H9	LDR		100.00%	100.00%	100.00%

5.2 Complete week schedules

A weekly schedule is constructed for the radiotherapist and RTT for all feasible OR days and the corresponding OR capacity. Table 5.6 shows an example of a generated weekly schedule for a radiotherapist where each block represents a timeslot of two hours. It does not mean all slots are filled with appointments, but scheduling them in these time slots is possible. Each row represents a different possible week schedule.

Table 5.6: Example schedule of radiotherapist for base case

OR combination	Monday					Tuesday					Wednesday					Thursday					Friday				
2	FR	FR	V			OR	OR	OR	OR	OR	SP	SP			SR	NP	NP				FR	FR			
A	FR	FR	V			OR	OR	OR	OR	OR	FR	FR			SR	NP	NP				FR	FR			
B	FR	FR	V			OR	OR	OR	OR	OR	SP	SP			TP	NP	NP				FR	FR			
D	FR	FR	V			OR	OR	OR	OR	OR	SP	SP			SR	NP	NP				FR	FR			
E	FR	FR	V			OR	OR	OR	OR	OR	SP	SP	SP		TP	NP	NP				FR	FR			
F	FR	FR	V			OR	OR	OR	OR	OR	SP	SP	SP		SR	NP	NP				FR	FR			
–	FR	FR	V			FR	FR	FR	FR	FR	FR	FR	FR		SR	NP	NP				FR	FR			

OR	OR day appointments
SP	Second pulse HDR GYN/HDR prostate patient
TP	Third pulse HDR prostate patient
FR	First ring intervention (two consecutive slots) or second/third ring (one slot)
SR	Second/Third ring intervention
V	Volume measurement
NP	New patient consult
	Block not reserved for brachytherapy

In addition to the appointment schedule, the outcome of the ILP model is also the number of new ring patients that can start in the week and the number of second/third HDR ring interventions that take place. For the base case, a minimum of two new ring patients can start during a week. This occurs when the OR combination consists of an HDR patient. Four new ring patients can start during the week when only LDR patients are treated during the OR day. And if there is no OR during a week, in theory, 14 new ring patients can start. However, because HDR ring patients need at least one intervention per week, this is not feasible because this also means that at least 14 ring interventions need to occur the following week. And it is impossible that there is no OR for two consecutive weeks. However, this is not considered an option in the ILP model. Nevertheless, the DES model checks if it is possible to schedule three interventions within the constraint, so it will never occur that 14 HDR ring patients start during one week.

Overall, when comparing all outcomes for the different experiments, it shows that when the OR capacity increases, the number of possible new ring appointments decreases. This is because then more of the total time is occupied by appointments related to the OR interventions. However, in every scenario, at least one new ring patient can start each week.

An essential factor in making these schedules possible is the working days of the RTTs. The ILP model does consider the number of working days but not what those days are. This means that the working days of RTTs can change based on the generated schedules. In Table 5.7, the required number of RTTs for each OR capacity experiment, along with the breakdown of staff composition, are shown.

Table 5.7: Number of RTT per workday per experiment

Experiment	#RTT	Monday	Tuesday	Wednesday	Thursday	Friday
	3	1	3	2		1
'3full in 4w'	**4**	1	4	2		1
	5	2	4	3		1
	3	2	3	1		1
'2full+2morning in 4w'	**4**	2	3	2		1
	5	3	4	2		1
	3	2	3	1		1
'5full+2morning in 8w'	**4**	2	3	2		1
	5	3	4	2		1
	3	1	3	2		1
'4full in 4w'	**4**	1	4	2		1
	5	1	4	3		1
	3		3	1	2	1
'4full+2morning in 4w'	**4**		3	2	2	1
	5		3	2	3	2
	3		3	1	2	1
'4full+4morning in 4w'	**4**		3	2	2	1
	5		3	2	3	2

5.3 Evaluation decision tree for blueprint selection

For the base case, two decision trees are constructed, one that states the number of intervention slots meant for gynecology patients and one for urology patients. This is because the decision when to schedule an HDR GYN should be made earlier than for HDR prostate or LDR patient types. The reason for this is that, before the brachytherapy, HDR GYN patients will receive EBRT, and there needs to be a fixed amount of time between the end of EBRT and the start of brachytherapy. The date that an HDR GYN patient has an intervention needs to be known eight weeks in advance. That is why a decision tree is developed that needs to be followed for the 8th week from now. This tree determines the number of spots used in the OR for HDR GYN patients. Then, if the number of GYN patients is determined, the total OR day combination can be determined using the URO decision tree. If the OR day is determined, the corresponding scheme for the other appointments can be selected based on the previous week and the OR interventions.

Figure 5.1 shows the decision tree for selecting the number of HDR GYN patients on an OR day. The first thing that is considered is the type of OR day. Each day has three possibilities: a full OR day, a half OR day, or no OR day. The half OR day is further explained in Section 4.6. Based on this characteristic, different OR day combinations are possible. Then, a distinction is made between days with an OR day the following week and those without. If there is no OR day the following week, starting an HDR GYN patient this week is impossible because an HDR GYN needs two intervention slots a week after each other. The next decision made is to check if there were starting HDR GYN patients in the previous week. If this statement is accurate, the patient or patients in question require an intervention this week. If there is no OR day next week, the number of HDR GYN intervention slots equals the number of starting HDR GYN in the previous week. Suppose there is an OR day next week, and there are HDR GYN patients(s) that can be scheduled this week. In that case, the number of HDR GYN intervention slots equals the maximum number of HDR GYN patients possible on the OR day under the condition that there are enough HDR GYN patients to schedule on that day.

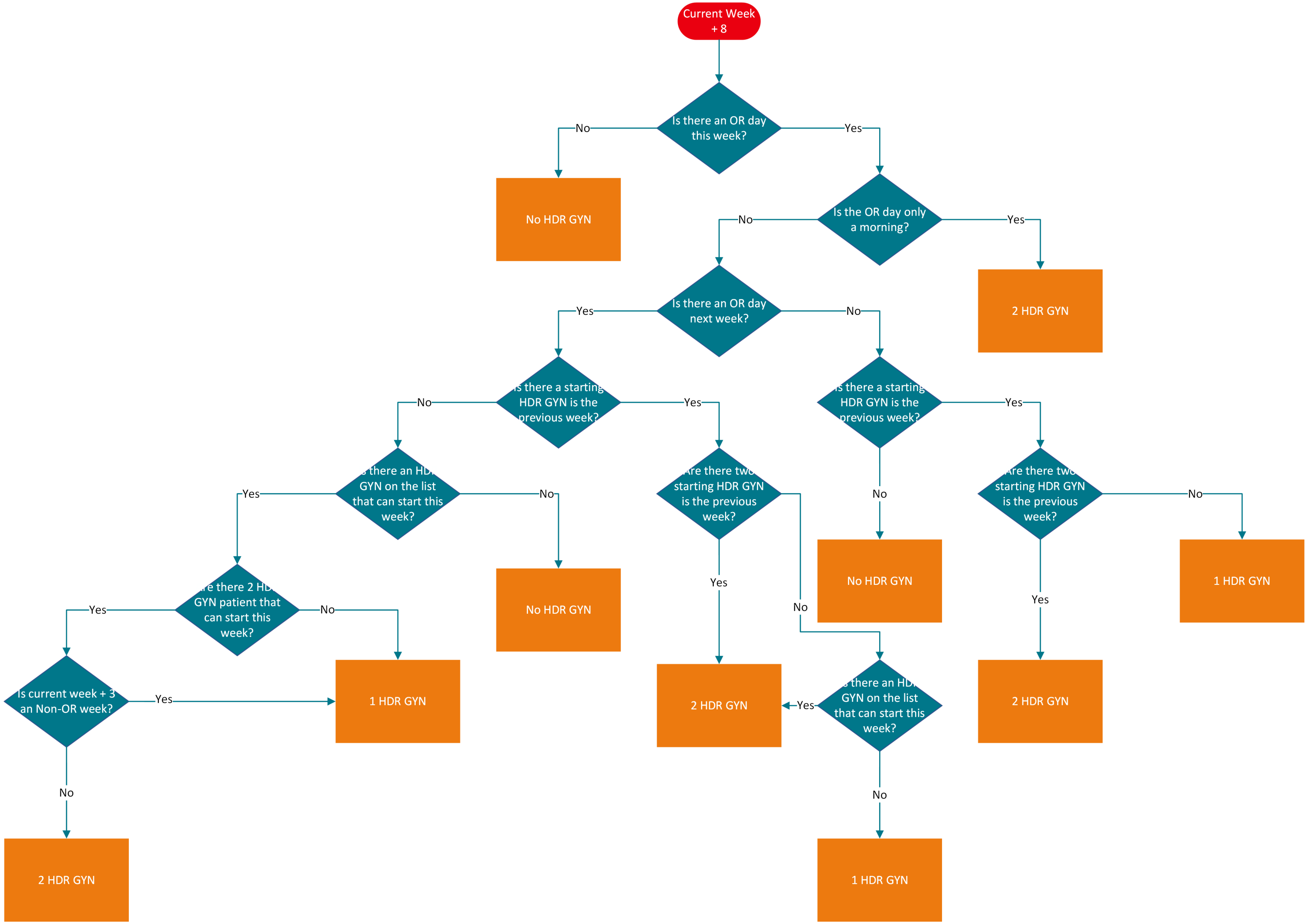


Figure 5.1: Decision tree to determine HDR GYN patient

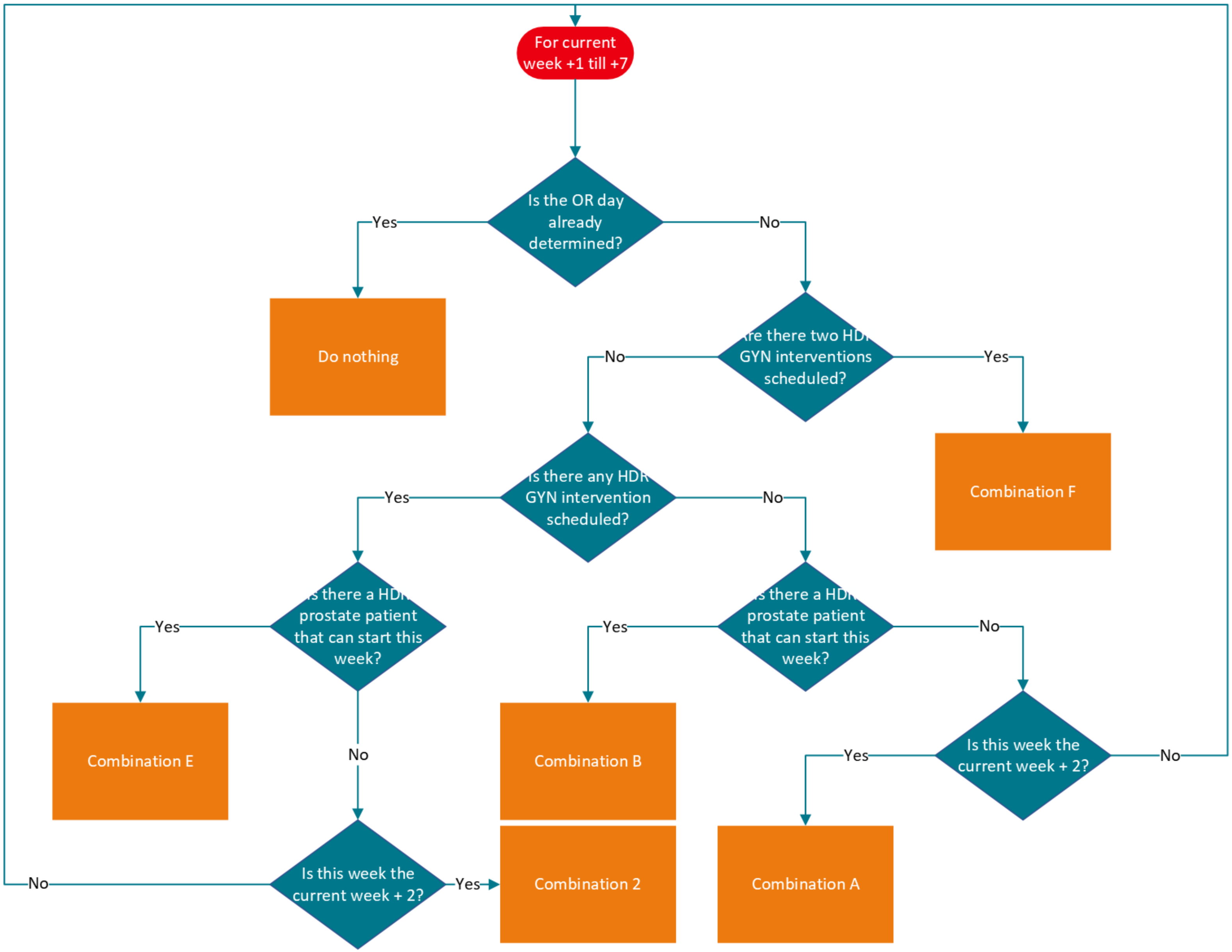


Figure 5.2: Decision tree to determine URO patient

There is one specific scenario that should be considered. If three weeks from the week that is being scheduled, there is no OR day, and there was also no starting HDR GYN patient in the previous week, and more than one HDR GYN patient could be scheduled, then an exception will apply. This is because, according to the previously explained rules, the maximum number of HDR GYN should be scheduled. However, in this case, only once HDR GYN is scheduled. The reason is that when two beginning HDR GYN patients are scheduled this week, there are also two spots for HDR GYN used the following week. But the week after that, scheduling any HDR GYN patient is impossible due to no OR the week after that, so that OR day can only be used for urological intervention. Letting one HDR GYN patient start a week later will result in two days with one HDR GYN patient and one day with two HDR GYN patients instead of two with two patients and one with zero. The advantage of this is that you have more possibilities when scheduling urological patients.

If only one option for an OR day combination is possible after the number of HDR GYN patients is determined, the OR day combination is set immediately. If multiple OR combinations are possible, the final decision of which OR-day schedule to use is postponed until at most two weeks before the treatment day. The other decision tree is used for this decision, which is shown in Figure 5.2. At the end of each week, this decision tree is run through for the coming seven weeks, starting with the first week from now. The decision on which OR day combination to use depends on the arrival of urological patients. For the urological patients that arrived and are not scheduled, the next week, when a spot for that patient type is available, is selected. If that week's schedule was already determined, nothing would change, and the intervention spot would be filled with a specific patient. If the OR schedule was not fixed, it is checked if that spot could be used for both LDR and HDR prostate patients or just for LDR patients or just for HDR prostate patients. If the spot can be used for both types and, for example, the possibilities to schedule HDR prostate are more limited than for LDR patients, depending on the results of phase 1, the LDR patient is scheduled on a later spot. The LDR patient is rescheduled if that spot is empty two weeks before the treatment day.

After the OR-day schedule is determined, the entire week schedule is selected. This is based on the number of ring patients treated in the previous week(s) who still need an intervention this week. The corresponding schedule is selected based on these numbers and the OR day combination.

For the experiments discussed in Section 4.6, the decision tree is altered based on the experimental settings. However, the same principles apply to all decision trees.

After the construction of the decision trees, the performance is evaluated. Here, the results of the implementation of this tree are evaluated with the current scheduling method of FCFS. Table 5.8 shows the results of the base case where there are three OR days per four weeks. This table shows that the access times using the decision tree are slightly better and that the utilization of the OR is a bit lower than with the FCFS method.

Table 5.8: Comparison between FCFS and the use of the decision tree

	OR utilization (%)	Access time HDR prostate (days)	Access time LDR (days)	Access time HDR GYN (days)	Access time HDR ring (days)
FCFS	43.23	85.98	72.04	35.14	16.30
Decision tree	42.34	82.93	70.33	32.56	16.48

It was expected that the difference between access times would be bigger than it is. This could be caused by the fact that if the access time of an HDR GYN patient exceeds the upper boundary, the patient is referred. Therefore the maximal access time is limited. In addition, by referring those patients, In addition, there are some spots in the OR day that can only be used by URO patients, which ensures that regardless of the method of planning, the access time does not increase drastically.

5.4 Implementing weekly schedules and decision tree in DES

In this section, the implementation of the 3-phase approach is prospectively assessed using a DES model. In the DES, the weekly schedules constructed in phase 2 and the decision tree for selecting the weekly schedule are implemented. The results are explained per performance indicator. Because the feasible MSS per experiment number of phase 1 were the same for multiple experiments, it was decided only to use the settings of the base case, experiment ’4Therapist+4RTT+0%PT’, ’4Therapist+3RTT+10%PT’, and ’4Therapist+3RTT+25%PT’. These settings are combined with the experiment settings of the OR capacity.

5.4.1 Number of treated patients per year

Figure 5.3 shows the results of the number of treated patients per year for the different experimental settings.

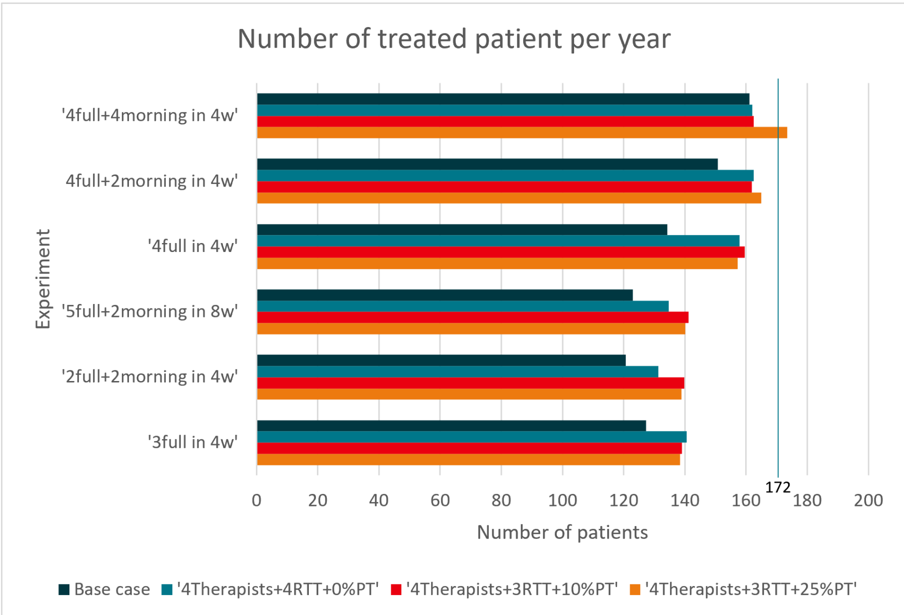


Figure 5.3: Number of treated patients per year

From the data presented, it appears that the quantity of treated patients is relatively consistent across experiments ’4Therapist+4RTT+0%PT’, ’4Therapist+3RTT+10%PT’, and ’4Therapist+3RTT+25%PT’. However, Figure 5.4 shows the specific patient types that are treated. This shows that the division between the patient types differs, especially, for example, for experiment ’2full+2morning in 4w’. Here it shows that more HDR GYN patients are treated in experiments ’4Therapist+3RTT+10%PT’ and ’4Therapist+3RTT+25 %PT’ compared to experiment ’4Therapist+4RTT+0%PT’. About the same number of patients were treated in those experiments, but there were more interventions in experiments ’4Therapist+3RTT+10%PT’ and ’4Therapist+3RTT+25%PT’.

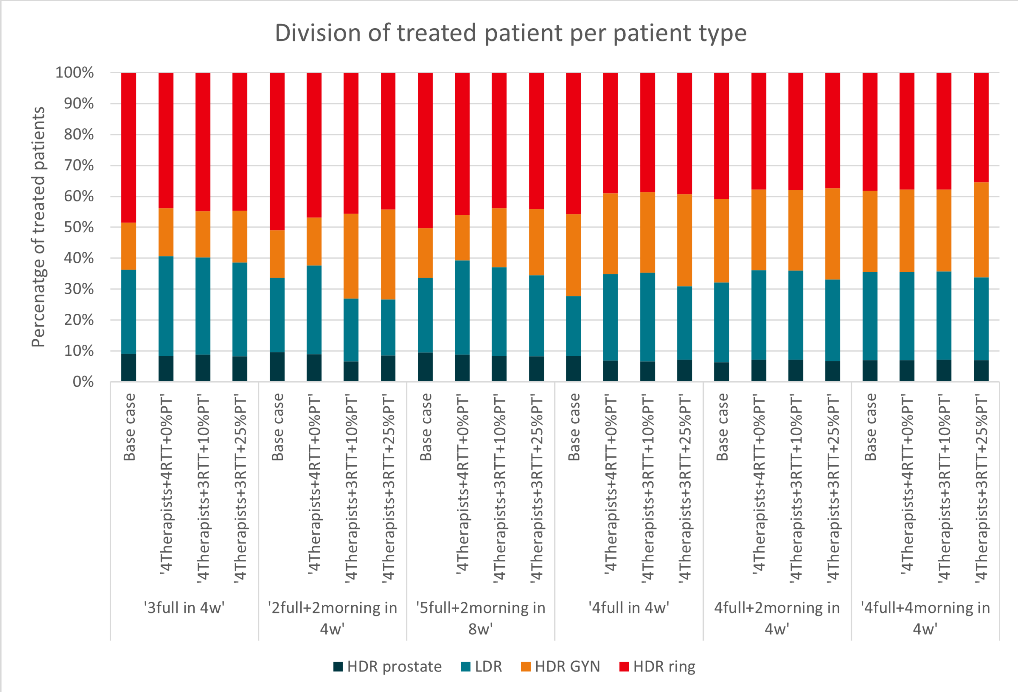


Figure 5.4: Division of treated patients

5.4.2 Access time

Figures 5.5 and 5.6 show the average access time per patient type for the different experimental settings. The most striking data are the outliers for HDR prostate and LDR patients. These outliers are probably caused by the fact that the HDR GYN patients are scheduled in advance, and in these experimental settings, this causes a shortage of OR spots available for HDR prostate and LDR patients. This could be explained by the fact that with this OR capacity, there are more available spots for HDR GYN patients to fill, which causes fewer available spots for URO patients.

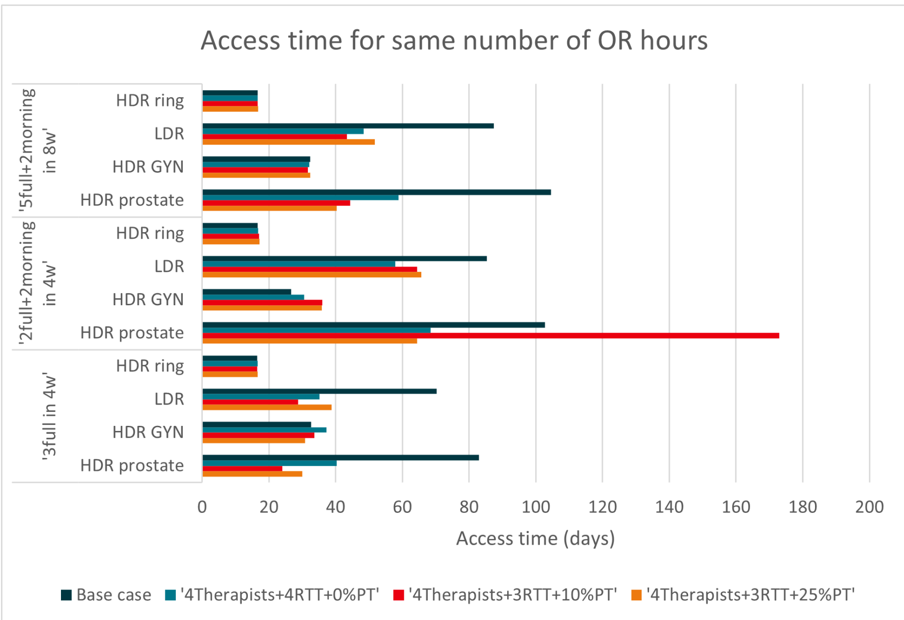


Figure 5.5: Access time for experiments with equal OR time

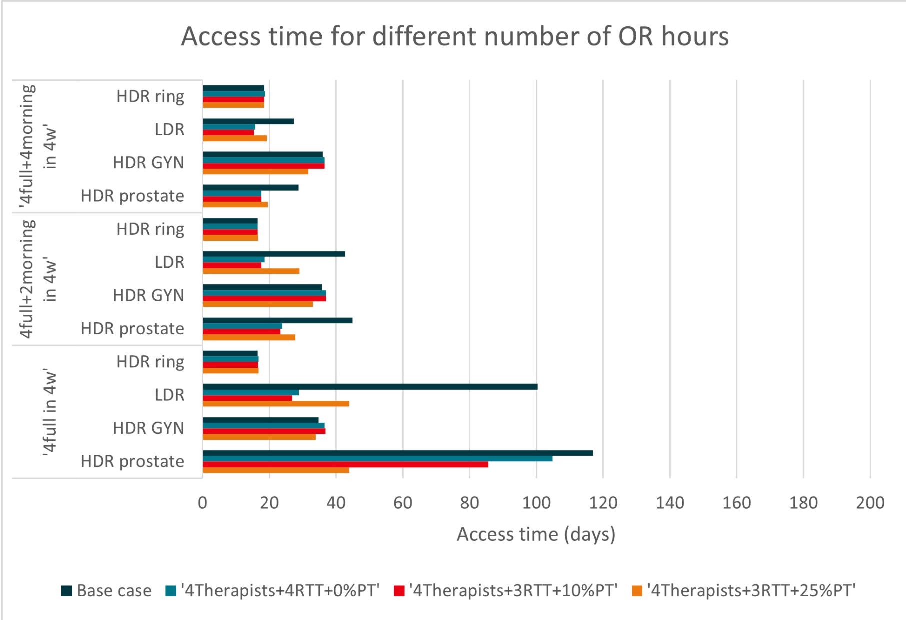


Figure 5.6: Access time for experiments with more OR time

5.4.3 Utilization

The last performance indicator is the utilization of the OR, the HDR bunkers, and the HDR afterloaders. Figures 5.7 and 5.8 show the utilization for each experiment. It shows that regardless of the experimental setting, the utilization of the Bunker and Afterloader stays relatively constant. In addition, it shows that in the experiments where half an OR day is used, the utilization is higher than when only full OR days are used. This contradicts the pooling principle. This is further explained in Section 6.3.1.

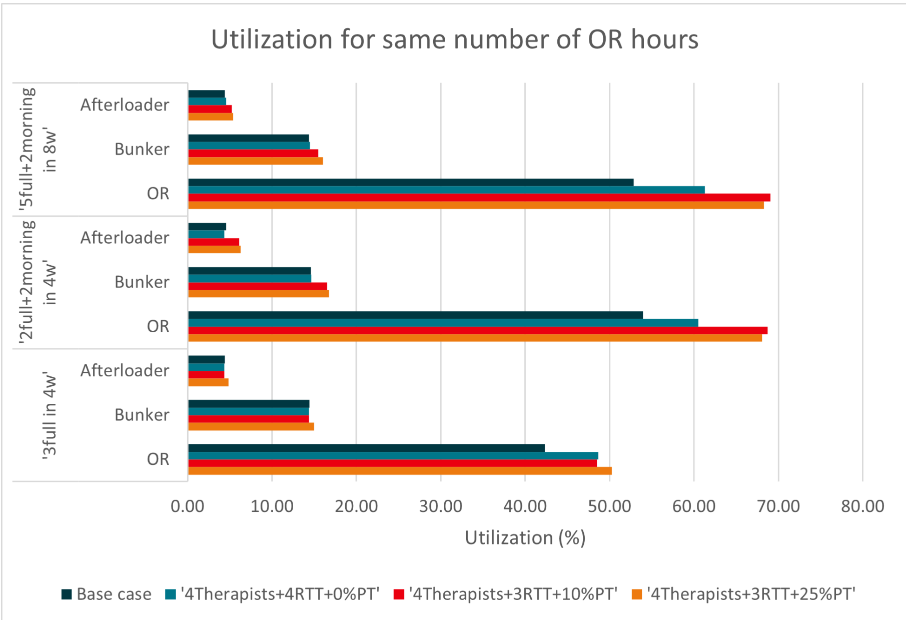


Figure 5.7: Utilization for experiments with equal OR time

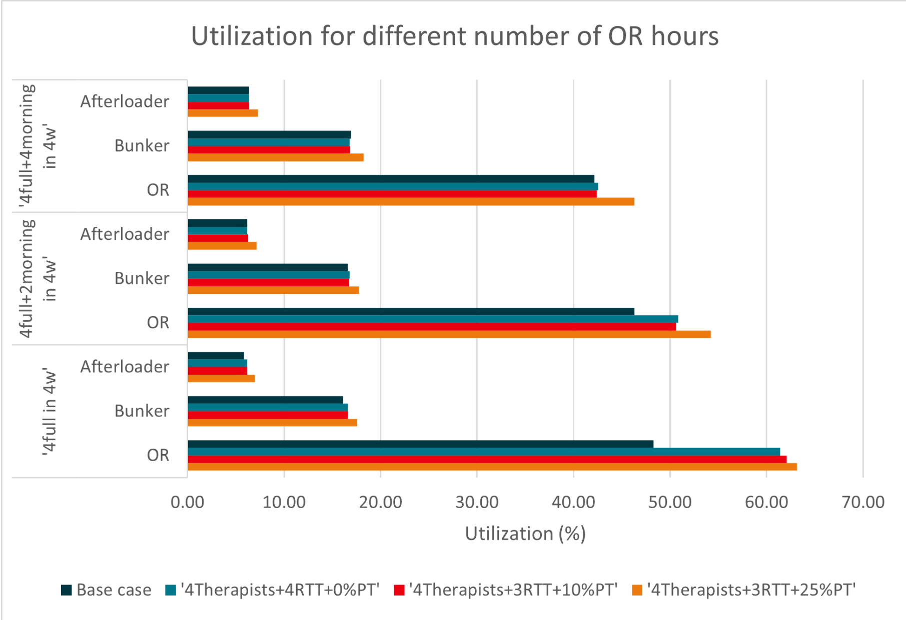
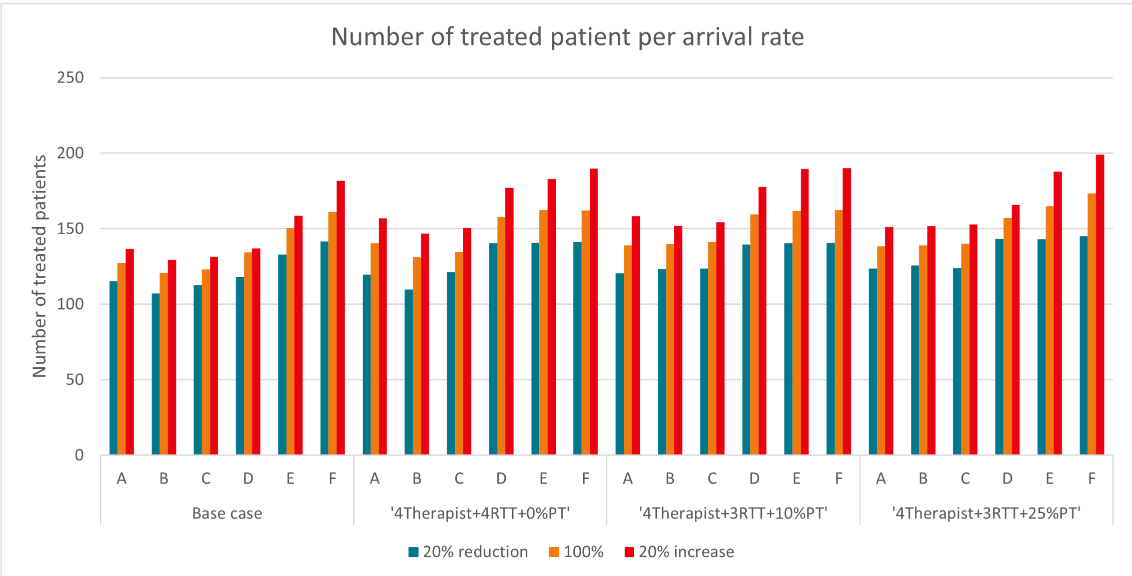


Figure 5.8: Utilization for experiments with more OR time

5.4.4 Sensitivity analysis of the arrival rate

Figure 5.9 shows the number of treated patients per different arrival rate. It shows that the more patients arrive, the more patients are treated, and vice versa. However, the number of increases depends on the experiment. For example, the increase for experiment '4Therapist+3RTT+10%PT' differs for OR settings '3full in 4w', '2full+2morning in 4w', and '5full+2morning in 8w' while the number of patients at 100% are given or take the same.



Note: A = '3full in 4w', B = '2full+2morning in 4w', C = '5full+2morning in 8w', D = '4full in 4w', E = '4full+2morning in 4w', F = '4full+4morning in 4w'

Figure 5.9: Number of treated patients per different arrival rate

5.5 Conclusion

In this chapter, the results of the three different phases are provided. First, for all experimental settings, the feasible OR days are selected. From these experiments, three different settings led to significant changes in feasible OR days compared to the current settings (i.e., the base case). These were experiments '4Therapist+4RTT+0%PT', '4Therapist+3RTT+10%PT', and '4Therapist+3RTT+25%PT'. The other outcomes were the same as in any of these experiments. That is why for these four experiments, the experimental settings of the OR capacity in phases 2 and 3 were evaluated.

The generated weekly schedules and decision trees were tested in the DES model. This showed that the number of treated patients per year increases as the OR time available increases. In addition, experiments '4Therapist+4RTT+0%PT', '4Therapist+3RTT+10%PT', and '4Therapist+3RTT+25%PT' led to more treated patients, but the difference between these experiments is relatively low in some OR capacity settings. However, there is a difference in the treated patient division between these experiments. The DES model also shows that the different OR capacity settings influence the access time drastically, especially for the HDR prostate and LDR patients. In addition, the OR utilization is higher when half OR days are used than the utilization if only full OR days are used.

If the current settings do not change and the brachytherapy team maintains the OR capacity setting of three full OR days per 4 weeks, the average number of treated patients will be 127.3. This number is a reduction of 26.4 percent compared with the current number of treated patients. Rearranging the same amount of OR capacity using half OR days will not increase the number of treated patients. The number of treated patients even decreases. This can be explained by the fact that only one intervention can occur in the morning under these circumstances. Thus the number of interventions performed in two OR mornings is not more than there can be performed in one full OR day. In addition, the access time will increase when using another configuration of OR time. More OR time will ensure that more patients can be treated per year. The outcomes of the experiment with the most OR time led to an average of 161.2 treated patients a year. This is, however, still lower than the current 173 patients, but the loss is limited to 6.8 percent. More OR time also reduces the access time.

Based on the evaluation, it can be concluded that in experiments '4Therapist+4RTT+0%PT', '4Therapist+3RTT+10%PT', and '4Therapist+3RTT+25%PT', where there are more feasible OR combinations, more patients can be treated per year compared to the outcomes of the base case, regardless of the OR capacity settings. However, if more OR capacity is available, the difference between the base case and the other experiments becomes smaller. In addition, reducing the process time by 25 percent instead of 10 percent does not significantly influence the number of treated patients. However, when more OR capacity becomes available, a difference arises between the two.

When comparing the results of the experiment '3f in 4w' to experiments '2full+2morning in 4w' and '5full+2morning in 8w', a difference is noticeable when using OR mornings compared to only full OR days. The number of treated patients decreases in the base case and '4Therapist+4RTT+0%PT' experiments but slightly increases for experiments '4Therapist+3RTT+10%PT' and '4Therapist+3RTT+25%PT'. This is because a time reduction of a minimum of 10 percent ensures that two interventions can be performed on an OR morning. Because of this, four interventions can occur on two OR mornings in contrast to a maximum of three of a full OR day for experiment '4Therapist+3RTT+10%PT'.

Using morning ORs also ensures an increase in OR utilization. However, the access time for urology patients in experiment '2full+2morning in 4w' is much higher than in experiments '3full in 4w' and '5full+2morning in 8w'.

It can be stated that with the current OR time, experiment '3full in 4w' till '5full+2morning in 8w', it is impossible to annually treat the same number of patients during the bridging phase as during the current situation. Even a process time reduction of 25 percent is not enough to reach that goal. The number of patients treated yearly increases significantly when more OR time is available. However, the only setting for which the current number of patients is met is if there is a process time reduction of 25 percent and one full OR day and one half OR day per week is available. However, when a production loss of 10 percent is considered acceptable, one full OR day per week and one OR morning per two weeks, combined with a process time reduction or an extra RTT, ensures that more than 160 patients are treated annually.

Based on the sensitivity analysis of the arrival rate, it is shown that if more patients arrive in the system, more patients are treated in a year and vice versa. However, it is not true that if 20 percent more patients arrive, 20 percent more patients are treated. For the experiments with more OR combinations, a more significant increase in treated patients is realized than when fewer OR combinations are possible.

Chapter 6

Implementation, Conclusion, and Discussion

This chapter consists of three sections. In the first section, implementation suggestions for the solution are provided. Then, the research question is answered in Section 6.2, the conclusion. Section 6.3 discusses this research's limitations, theoretical and practical contributions, and suggestions for further research.

6.1 Implementation

One of the desires of Amsterdam UMC is to have a plan on how to implement the solution in practice. This section describes the steps that need to be taken to implement this solution. To implement the solution effectively, two necessary actions must be taken. The first action is to develop a program that schedules patients automatically. In addition, it is essential to monitor the brachytherapy process during the bridging phase.

6.1.1 Scheduling program

As stated, a way to implement the solution is to develop a program that automatically states the dates to plan appointments. Because there are quite some different week schedules and multiple rules that must be met for each appointment, an automated system makes it easier to use and less error-prone. In addition, it will save time for the personnel.

The idea of the program is to add new patients when they arrive. Then, the developed decision trees are followed to see if a patient can already be scheduled. The outcome of the program is the patient and the corresponding appointment date. If the patient cannot be treated in time, it will show that the patient needs to be referred to another hospital. This program can accordingly also give inside into the current access time.

6.1.2 Monitoring

Monitoring the process is also going to be an essential action. Because the situation of the bridging phase is unfamiliar, it is crucial to compare the results of the bridging phase with the results generated by the DES. If the results differ, it is essential to compare the input parameters used in DES with the actual data and to adjust when necessary.

6.2 Conclusion

In this section, the main research question is answered:

How to optimally deploy personnel and material resources for the brachytherapy treatment process during the bridging period at the AMC location so that the quality of the treatment is guaranteed and at least the same number of patients are treated?

Three phases have been completed to answer this question, after which a complete evaluation is performed through a DES model. Based on the initial phase, it can be inferred that enhancing the process times significantly influences increasing the range of options available during an OR day and enhancing the number of interventions performed on an OR day. However, if, in the short term, it is not possible to reduce the process times, the addition of one RTT also increases the OR day possibilities. In addition, the first phase shows that working in shifts during an OR day is essential for reducing the overtime of the personnel. Without working in shifts, the overtime condition is almost always exceeded.

Based on these OR days, weekly schedules are developed to maximize the number of ring treatments based on the OR day combination and the availability of the personnel and equipment. Compared to the current situation, the significant advantage of the bridging situation is that it becomes possible to conduct two HDR ring interventions simultaneously. This increases the number of possible moments to plan a ring intervention. Each weekly schedule, including the results of the experiments, includes at least one initial ring intervention, while the majority of schedules have space for at least three new ring patients. Changing the workdays for the RTTs is essential for these weekly schedules.

When to use which OR day combination and thus which weekly schedule is determined via decision trees. The goal of the decision tree is to minimize the access time and maximize the OR utilization. The combined outcomes of phases 1 to 3 are then evaluated using a DES model. First, a conclusion is given about the base case, where the current settings are used. After that, the comparison is made with experiments '4Therapist+4RTT+0%PT', '4Therapist+3RTT+10%PT', and '4Therapist+3RTT+25%PT'.

When the number of radiotherapists, RTTs, and the process times stay the same during the bridging phase, and the OR time also stays constant, most patients can be treated if three full OR days in 4 weeks are used and not another configuration. In that case, the average number of treated patients will be 127.3, which is a decrease of 26.4 percent compared to the current situation. Having four full OR days and four morning OR days in four weeks will lead to 161.2 patients, which is a decrease of 6.8 percent.

From the different experiments performed, it can be concluded that more feasible OR combinations lead to more patients that can be treated per year in every setting, regardless of the available OR capacity. However, if more capacity becomes available, the difference becomes smaller.

When comparing the different configurations of the same OR time, a difference is noticed when using OR mornings compared to only using full OR days. When in a morning OR day only one intervention can occur, which is the case if there is no process time improvement, using morning ORs will decrease the number of treated patients. If the process time is reduced, a small increase in treated patients occurs when using morning ORs.

When the OR capacity stays constant, regardless of the configuration, the number of employees, or the improvement of process time, it is impossible to annually treat the same number of patients during the bridging phase as during the current situation. The only setting for which the current number of patients is met is if there is a process time reduction of 25 percent and one full OR day and one half OR day per week is available.

Through a sensitivity analysis of the arrival rate, it has been observed that an increase in patient arrivals leads to more patients being treated in a year. In comparison, a decrease leads to fewer patients being treated. However, it's important to note that a 20 percent increase in patient arrivals doesn't necessarily mean a 20 percent increase in treated patients. Additionally, when more operating room combinations are available, there is a more substantial increase in treated patients than when fewer combinations are possible.

6.3 Discussion

This section provides the interpretation of the results, after which a reflection is made on the research approach. Then, the limitations of the research are discussed. Furthermore, the theoretical and practical contribution is explained. Finally, further research opportunities are discussed.

6.3.1 Interpretation of results

This subsection evaluates and explains any unexpected results. Two results contradicted the literature or the real world. The first unexpected result is that the OR combinations that fulfill the two conditions do not match the OR intervention combinations that are currently used (see Subsection 2.5.1, Figure 2.5). One of the OR scheduling options currently consists of three LDR interventions. However, according to the data and the output of the DES model, this combination will exceed the OR finishing time in around 60 percent of the days when the process times and the number of personnel stay the same. In practice, however, it is never experienced that this occurs. This could be explained by the fact that, in reality, an LDR procedure is usually performed in combination with two HDR or PDR interventions and then occurs at the end of the day. Then, there is often still a lot of time left, so there is no time pressure. In addition, work could slow down at the end of the day. These could be reasons why the data state that an LDR procedure takes longer, leading to the later finish time in the OR. The same reasoning holds for the combination of one HDR prostate and two LDR procedures. Not taking into account other factors that influence the OR intervention time is further discussed in the limitation section.

In addition, five combinations of OR interventions can currently be performed on one OR day, while the results of Phase 1 state that only one combination of three OR interventions fulfills the requirement. Two combinations are already discussed in the previous alinea. However, the other two are not. This deviation can be explained by the fact that GYN patients are now treated with HDR instead of PDR. Consequently, the personnel must wait until the fraction is finished before the workday is over instead of only starting the radiation.

The other unexpected result is that a morning OR day leads to higher utilization which contradicts the literature that states that combining resources, in this case OR time, will lead to higher utilization (Wischik et al. (2008)). This is called the pooling principle and occurs from the idea that a bigger timespan can be filled more efficiently than a longer timespan. However, this principle thus does not hold for the brachytherapy OR interventions. The reason for this is that there are consecutive appointments after the OR intervention, which ensures that it is not possible to schedule four interventions on one full OR day, but it is possible to schedule two OR interventions on a half (morning) OR day. Which therefore increases the utilization.

6.3.2 Reflection on research approach

Throughout the research, several methods were used, and multiple assumptions were made that influenced the outcome of this study. One of the first decisions made in the research approach was to state the two conditions that needed to be fulfilled in order to be considered as feasible OR days. As shown, these MSS have a great influence on the number of treated patients. Adjusting these conditions could lead to different results. In the future, it would be interesting to investigate what happens when these conditions are adjusted.

In addition, multiple DES models are used. However, because this study is about a situation in the future, it is not certain that these models represent this future situation accurately. The only validation and verification that could be done is to make a similar model that represents the current situation, however, that does not guarantee that the results of the bridging phase are also accurate. That is why it is important to monitor the results during the bridging phase and adjust the DES model if necessary.

Moreover, the decision for appointment scheduling and staff-shift scheduling is performed in 3 phases. The outcome of each phase was the input of the next phase. This means that a small decision in the first phase could lead to a big difference in the last phase without realizing it. Combining the phases could prevent that.

6.3.3 Limitations

A limitation of this study is that it only focuses on seven treatment types, although patients may pursue numerous other care paths. When a different care path is followed, it can disrupt other appointments, causing the weekly schedule to no longer be compatible.

Another limitation is that the only distinction made for the duration of the process steps is based on the treatment type. However, more factors influence the process step duration, such as the executive physician of the intervention, if there was a resident present, and the time of the day. As mentioned previously, there may be situations where interventions take longer than anticipated. In such cases, it could be advisable to have the radiotherapist carry out the intervention instead of the resident, for example, which increases the intervention time and can ensure that the end time of the OR does not exceed the closing time of the OR.

In addition, where the LP model takes into account patient radiotherapist allocation, the DES model does not take that into account. The DES model makes a certain amount of personnel available based on the outcomes of the LP model, but not specific personnel. It also does not register the utilization of specific personnel.

The DES model has some other limitations. Namely, although most input data is based on actual data, some are also estimated. This can lead to inaccurate results. Moreover, the DES model does not consider particular circumstances like sickness and vacation.

6.3.4 Theoretical contribution

During the literature review, no paper was found in which a schedule was made OR interventions where appointments were required before and after the intervention. This research shows a method in which an OR schedule was combined with multi-disciplinary appointment scheduling. It shows that dividing the problem into multiple phases and using a mathematical program as optimization and a computer simulation as an evaluation tool is an excellent way to solve similar problems.

In addition, no research is found regarding planning and control for brachytherapy. Research is done regarding EBRT, but not about brachytherapy. This study has demonstrated that employing a DES model is a practical approach to analyzing the complex care pathway of brachytherapy, which involves using multiple facilities.

6.3.5 Practical contribution

This research has three significant contributions to Amsterdam UMC. First, it constructs personnel rosters and a block schedule for appointment types. Which simplifies the planning process and also optimally deploys the personnel and resources. In addition, the developed DES model can also be used to answer other questions regarding brachytherapy. For example, what the consequence is if one afterloader breaks down. The third practical contribution of this research is that it can help convince the entire radiation therapy team that simulations and mathematical models can help the department solve its problems.

6.3.6 Further research

As discussed in the limitations of the research, a limited number of care paths of brachytherapy are included in this research. A suggestion for further research is to include the other treatment types. Another point was that the process time is only based on treatment type. One suggestion for future research would be to examine the factors that impact the duration of a process and use this information to establish a distribution. By analyzing these distributions, it may be possible to determine if more interventions can be performed in a day than what was found in this study.

Another research suggestion is to explore how to deal with holiday periods. A research question could be whether it is better to work longer with fewer staff or close the clinic for a short time. This is a question that is raised every year around summer.

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Appendix A

Work- and Patient Flows

This appendix depicts the work- and patient flows of the treatment processes. The work-flow is divided into the preparation phase and the treatment day phase.

A.1 Workflow of LDR Prostate I-125

A.1.1 Preparation

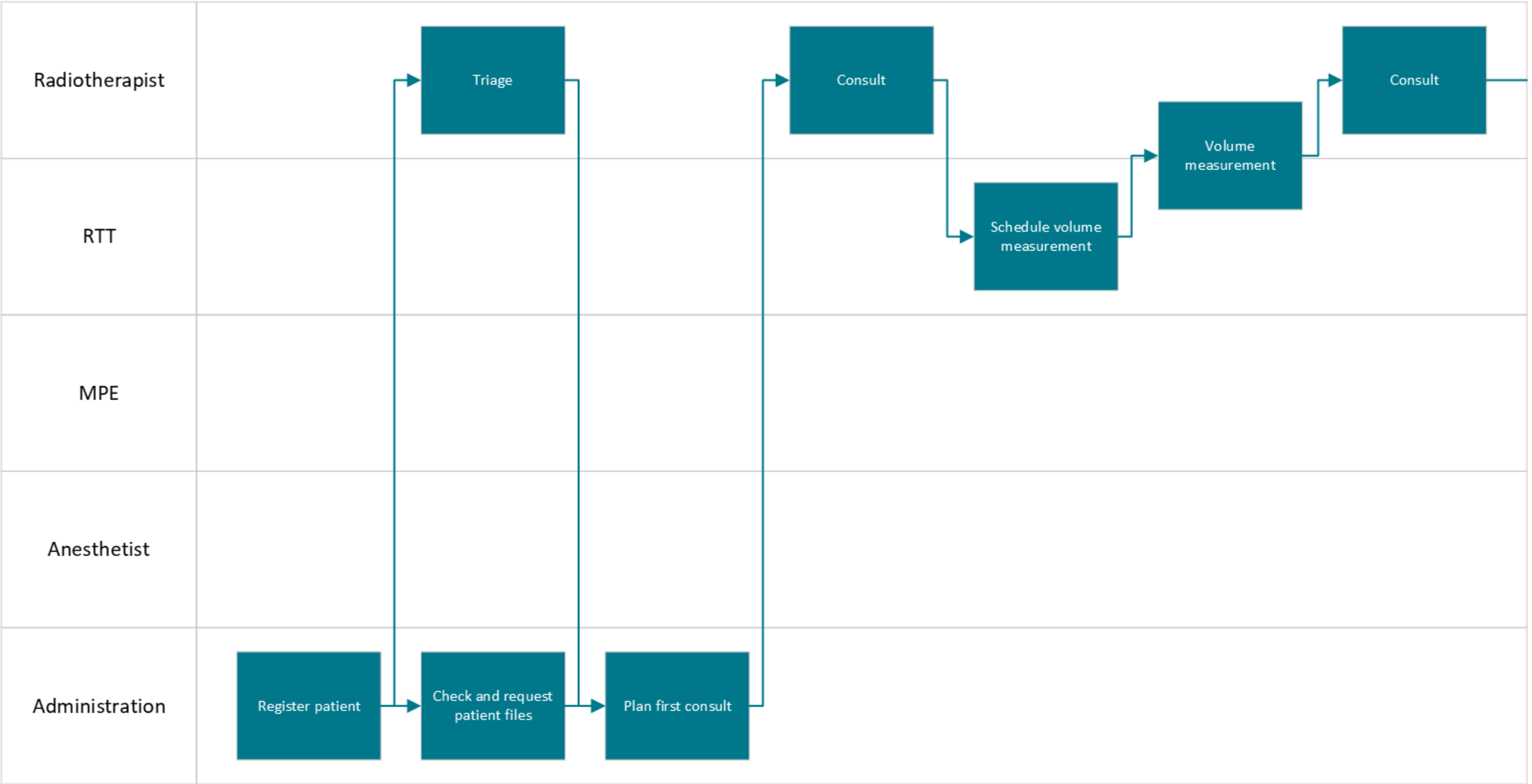

Figure A.1: Workflow of the preparation of I-125 Prostate treatment

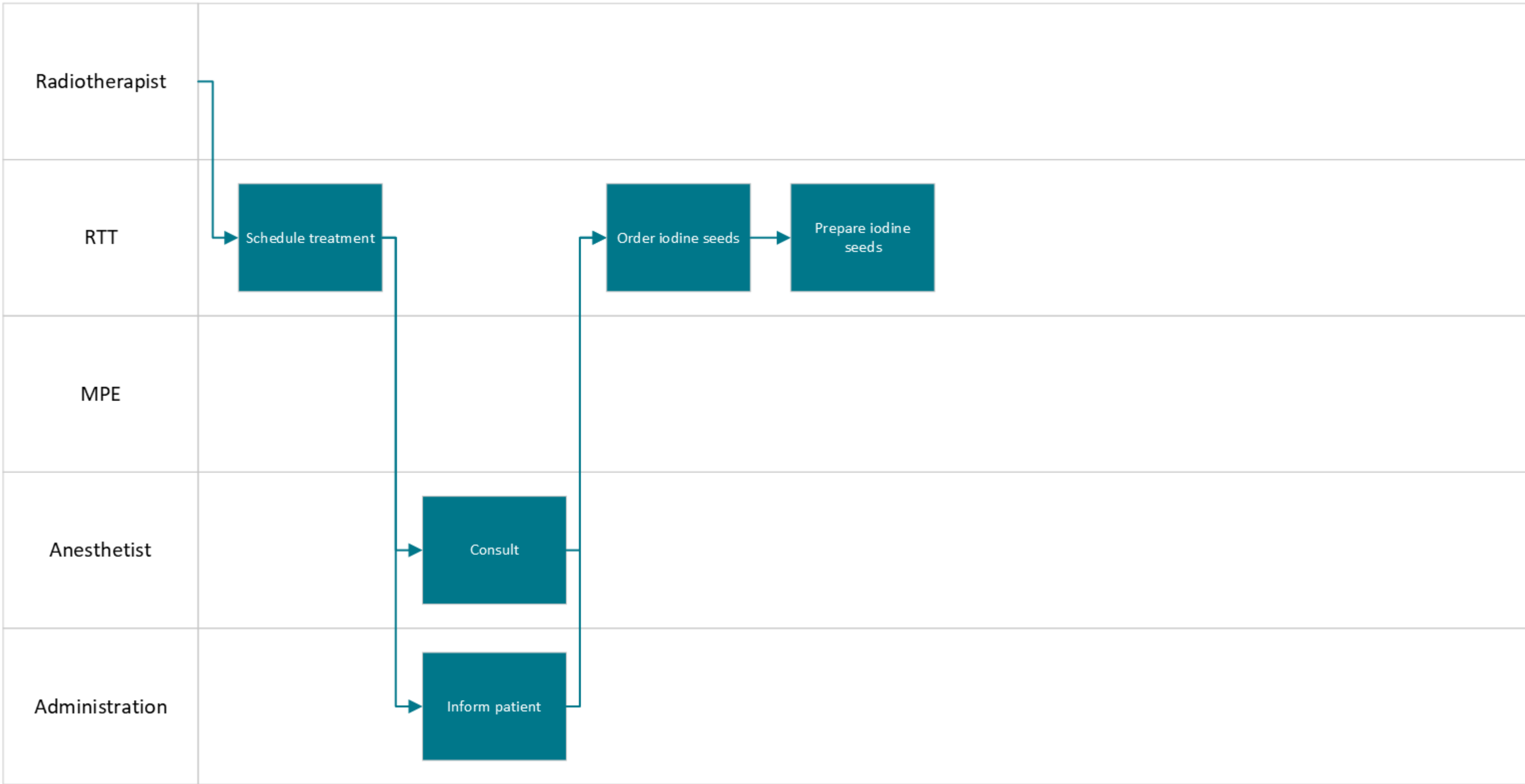

Figure A.1: Workflow of the preparation of I-125 Prostate treatment (*cont.*)

A.1.2 Treatment day

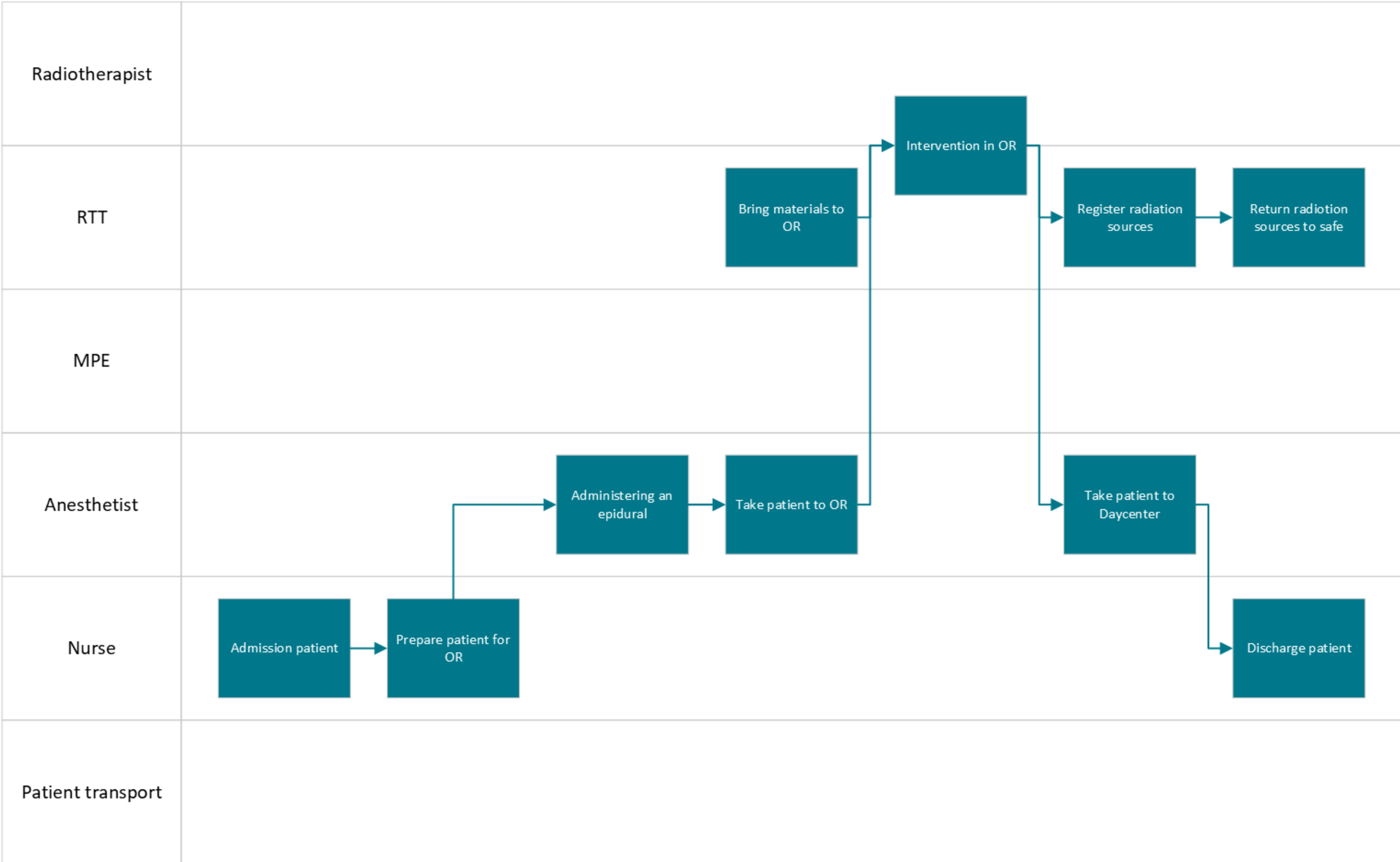

Figure A.2: Workflow of the treatment day of I-125 Prostate

A.2 Patient flow of LDR Prostate I-125

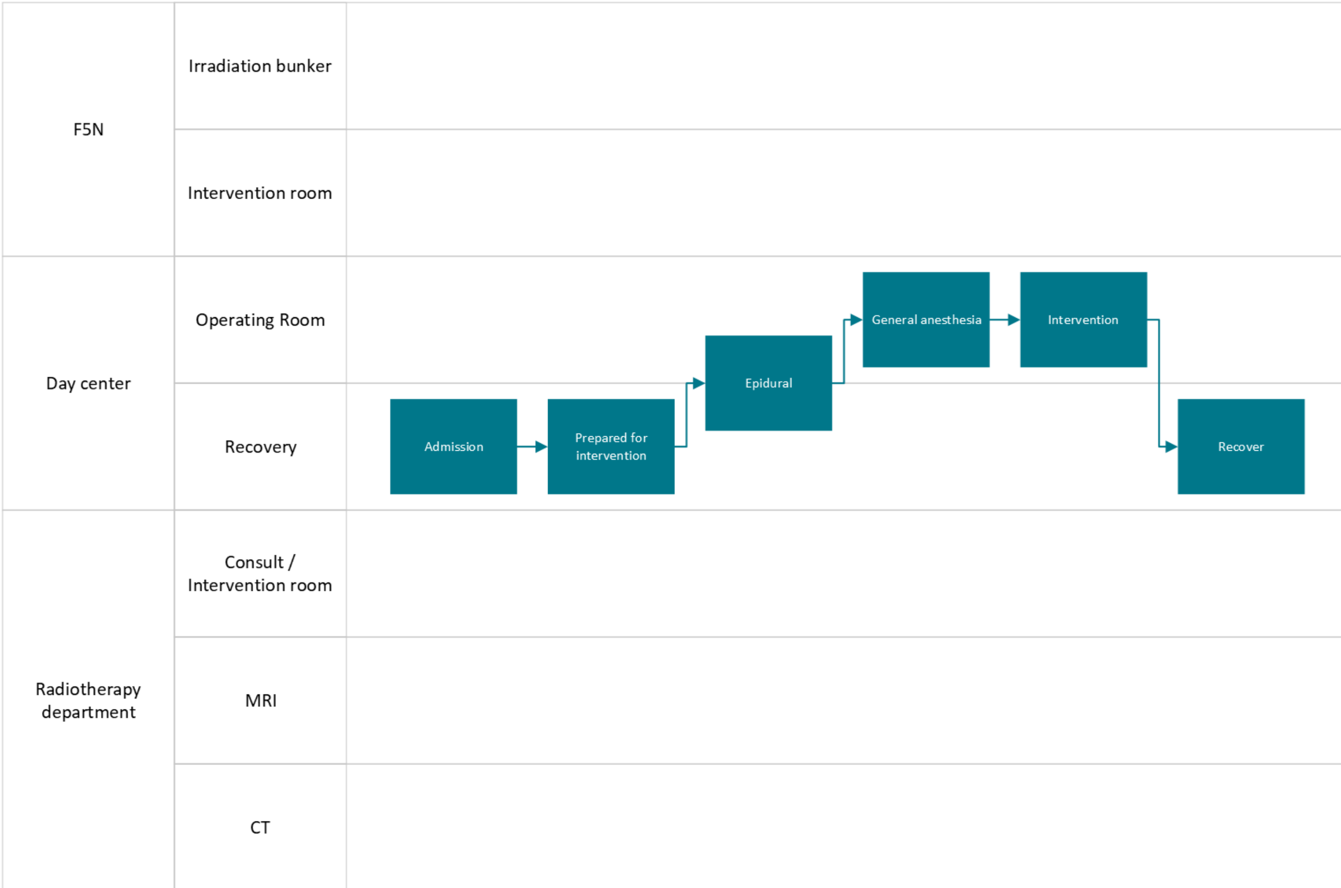

Figure A.3: Patient flow of the treatment day of I-125 Prostate

A.3 Workflow of HDR prostate

A.3.1 Preparation

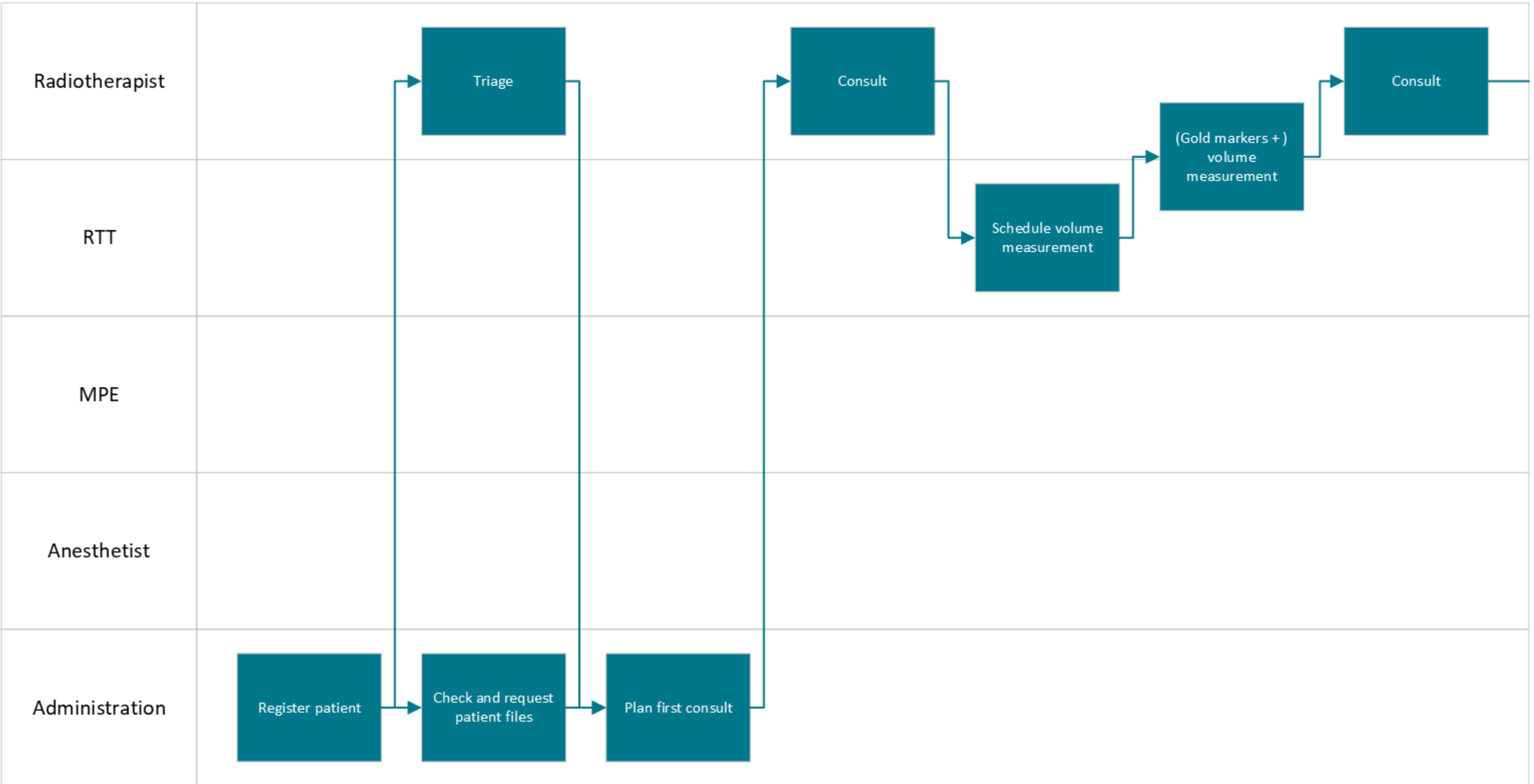

Figure A.4: Workflow of the preparation of HDR Prostate treatment

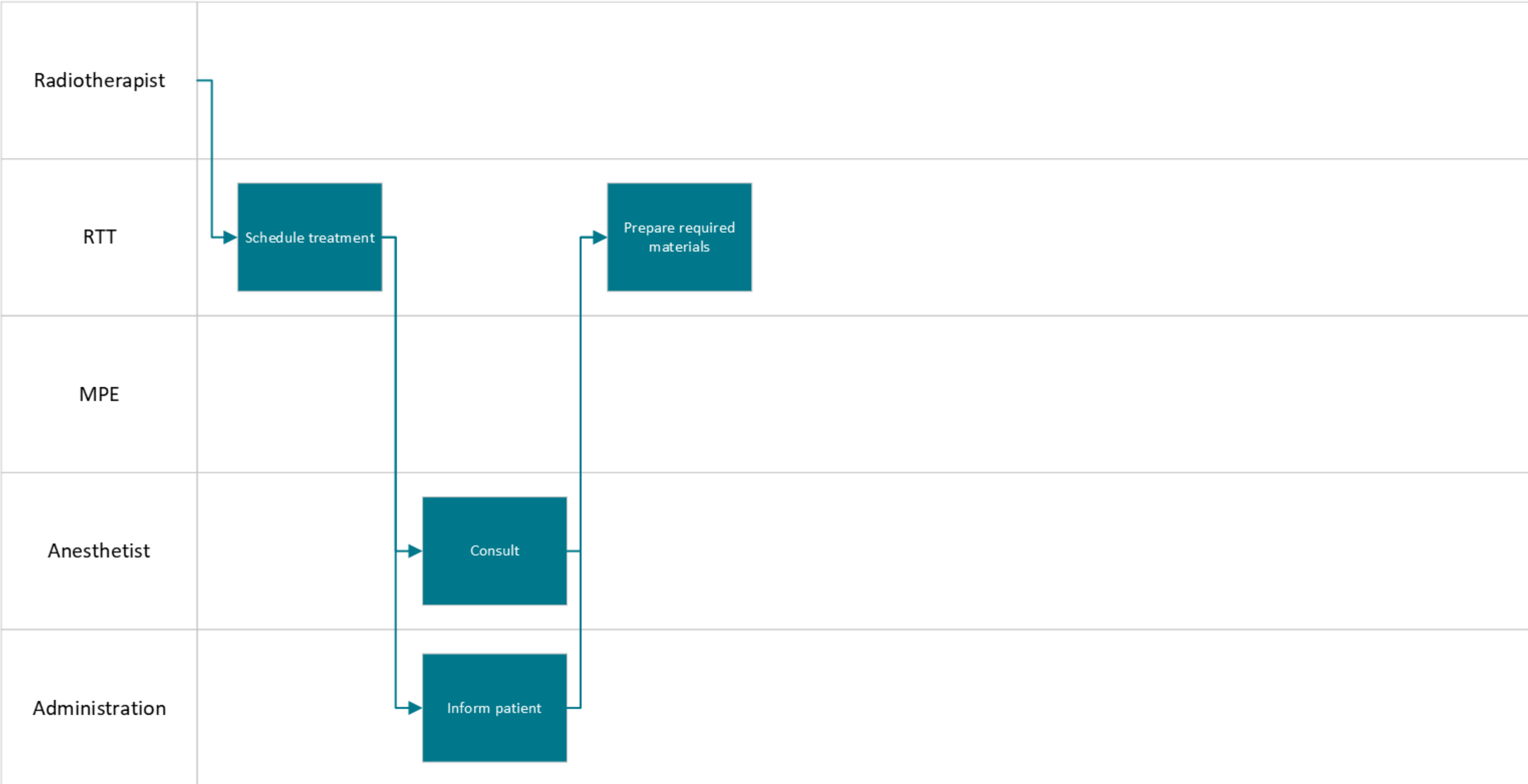

Figure A.4: Workflow of the preparation of HDR Prostate treatment (*cont.*)

A.3.2 Treatment day

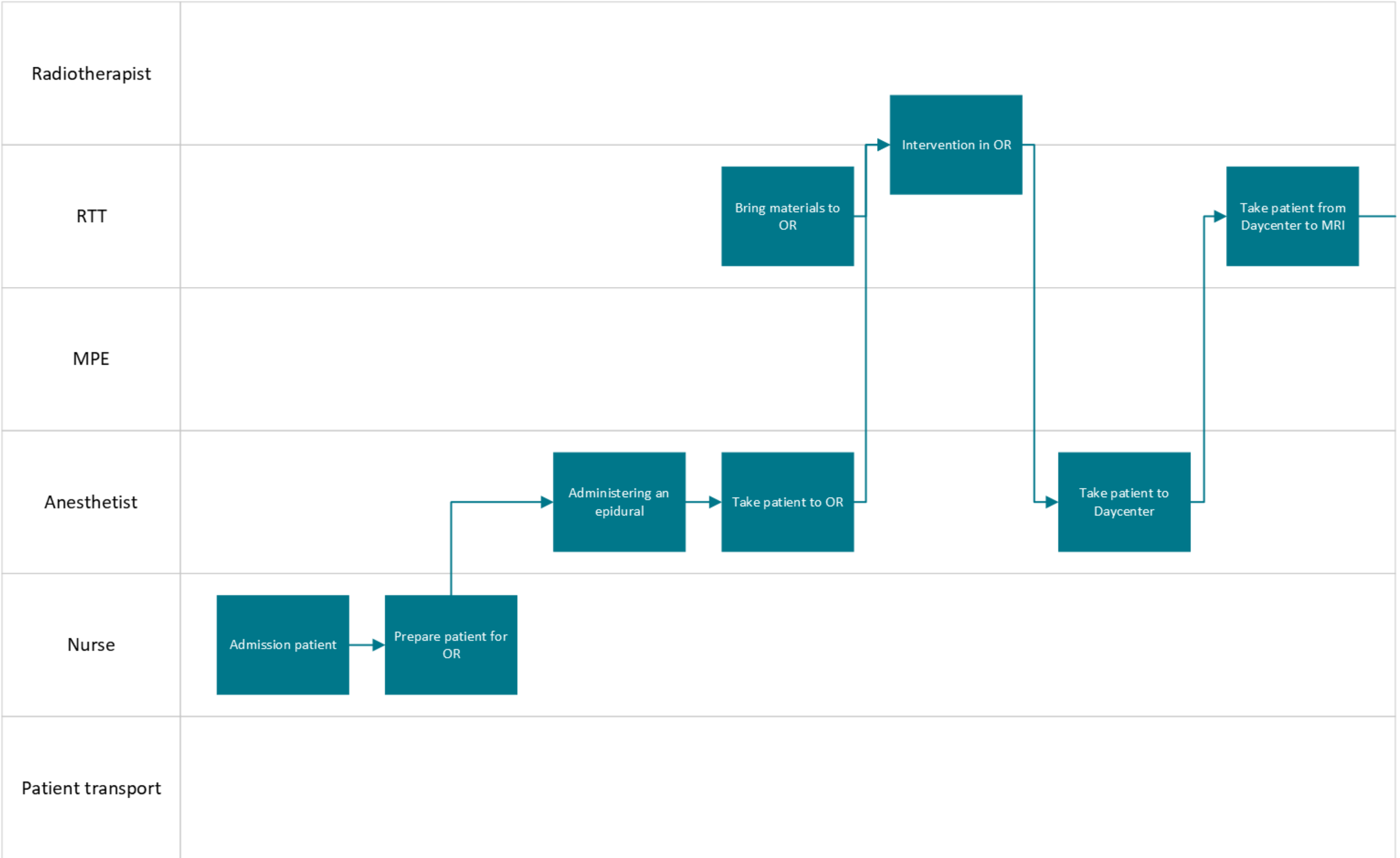

Figure A.5: Workflow of the treatment day of HDR prostate

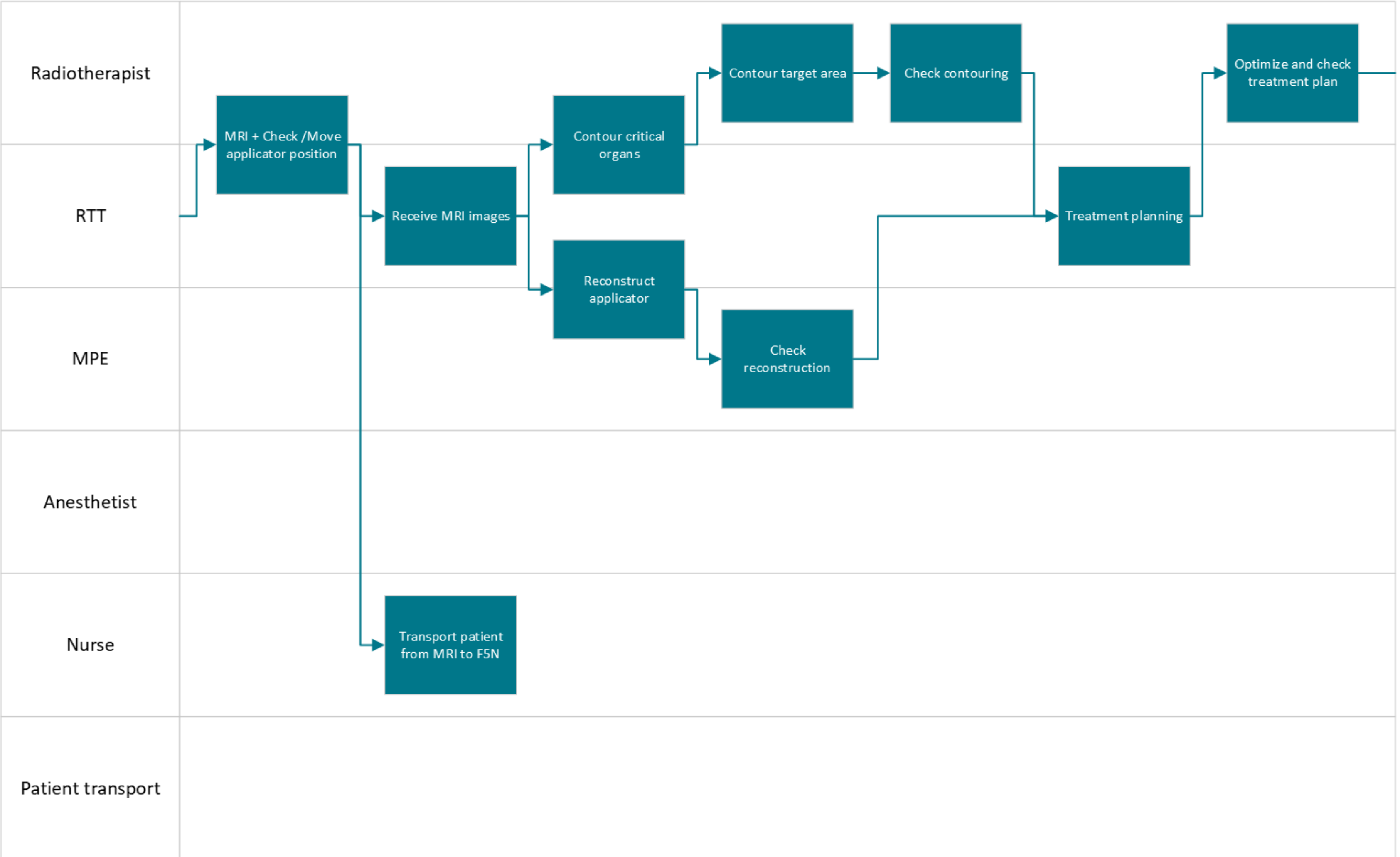

Figure A.5: Workflow of the treatment day of HDR prostate (*cont.*)

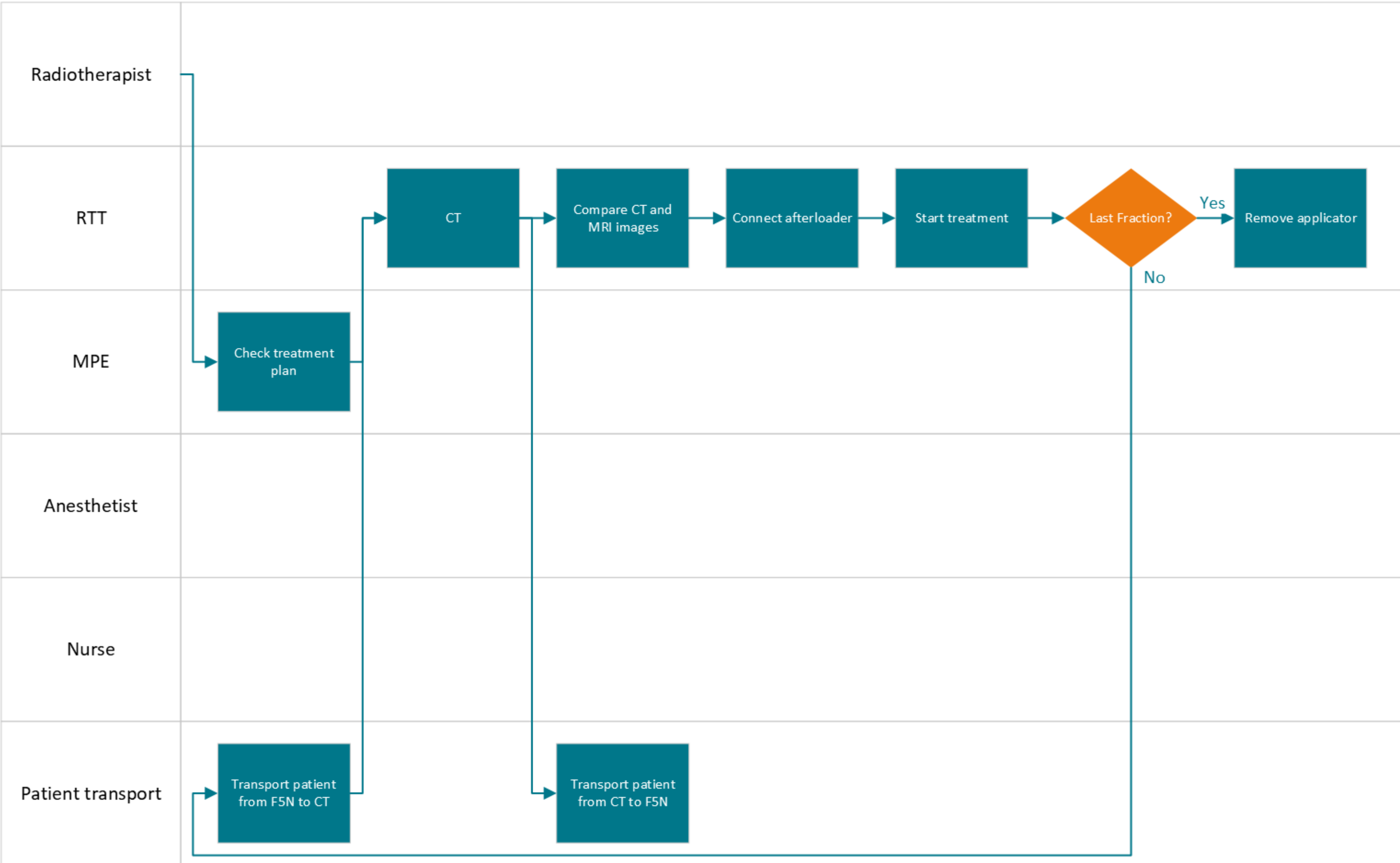

Figure A.5: Workflow of the treatment day of HDR prostate (*cont.*)

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A.4 Patient flow of HDR prostate

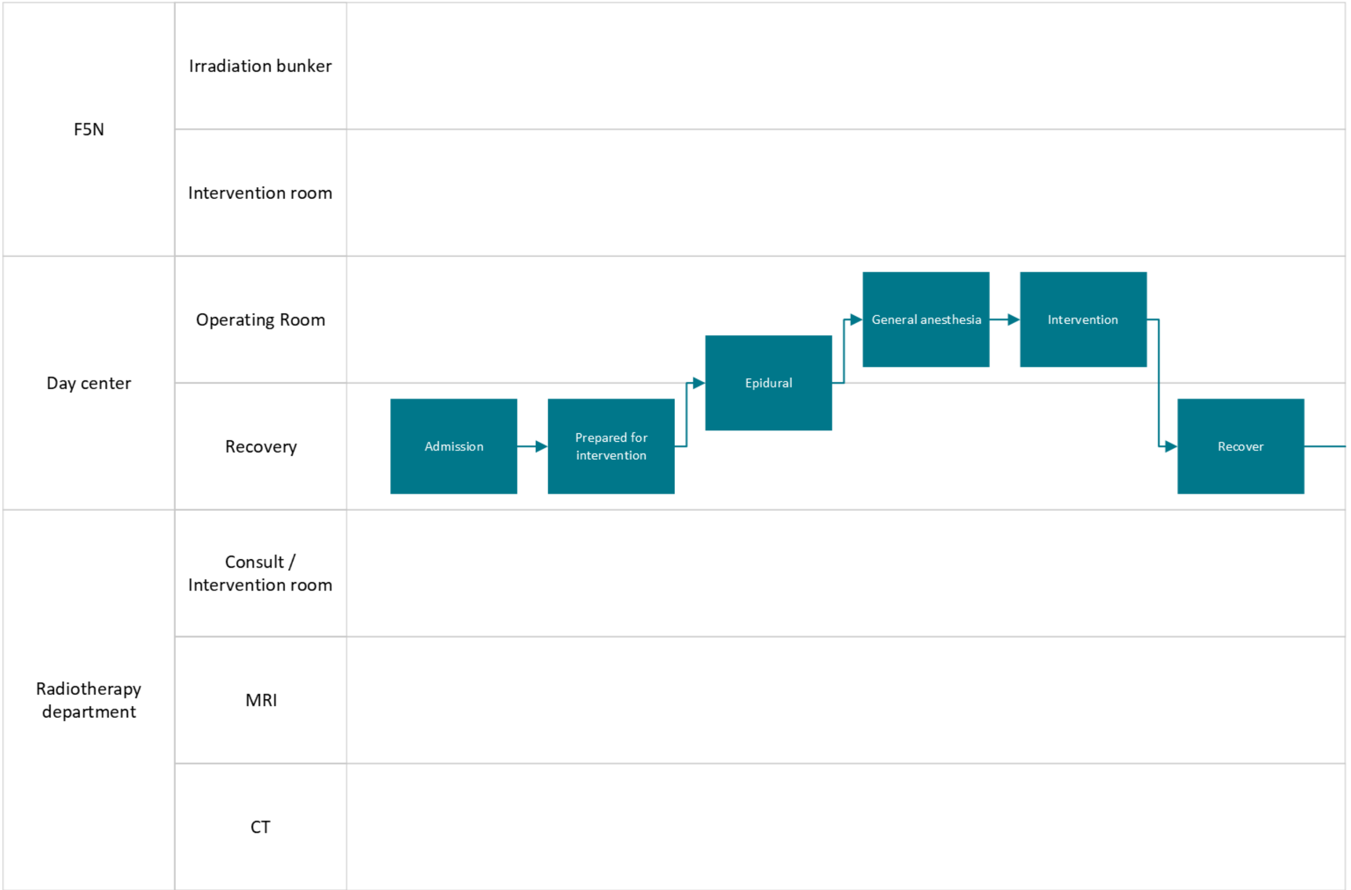

Figure A.6: Patient flow of the treatment day of HDR prostate

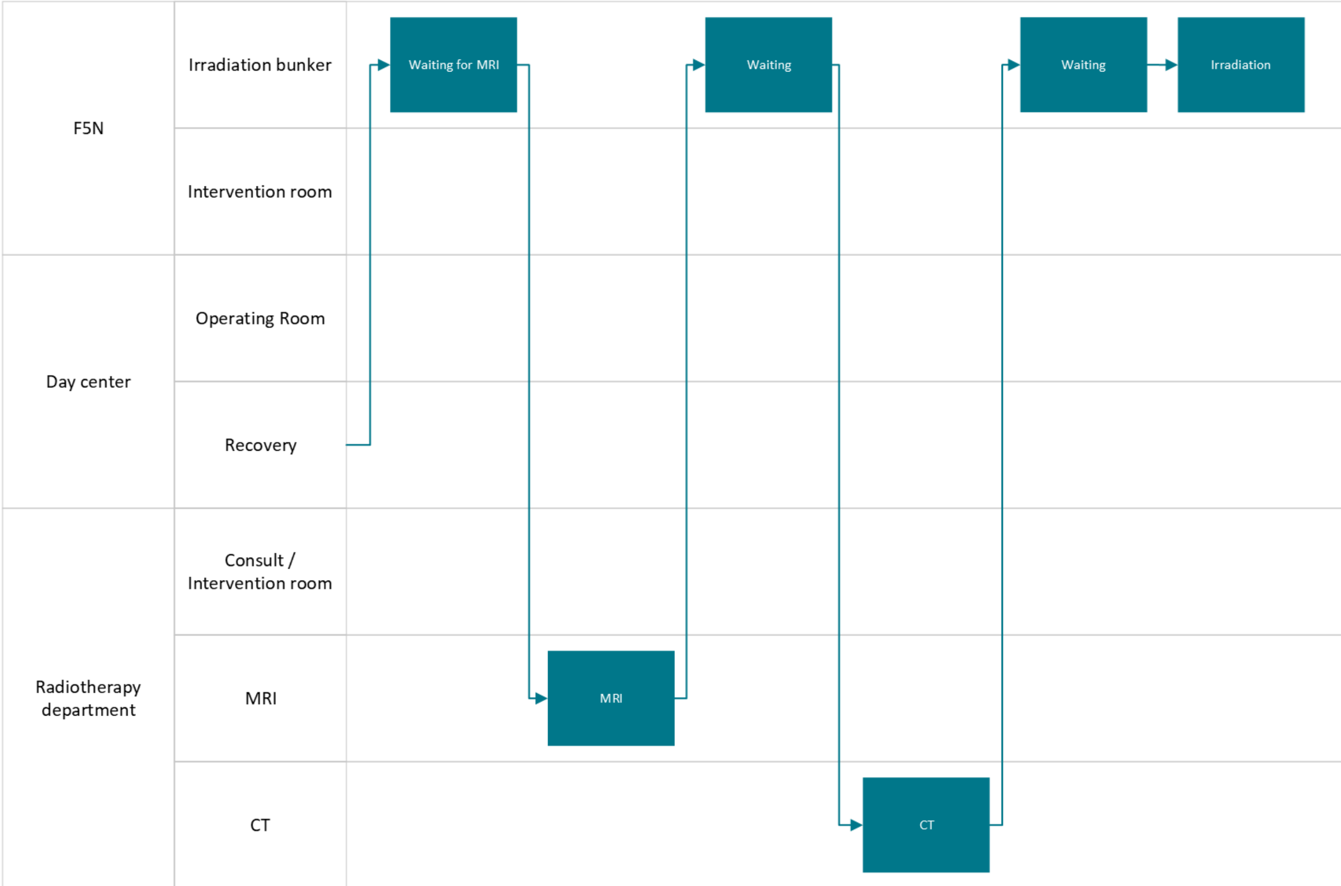

Figure A.6: Patient flow of the treatment day of HDR prostate (*cont.*)

A.5 Workflow of PDR gynecology

A.5.1 Preparation

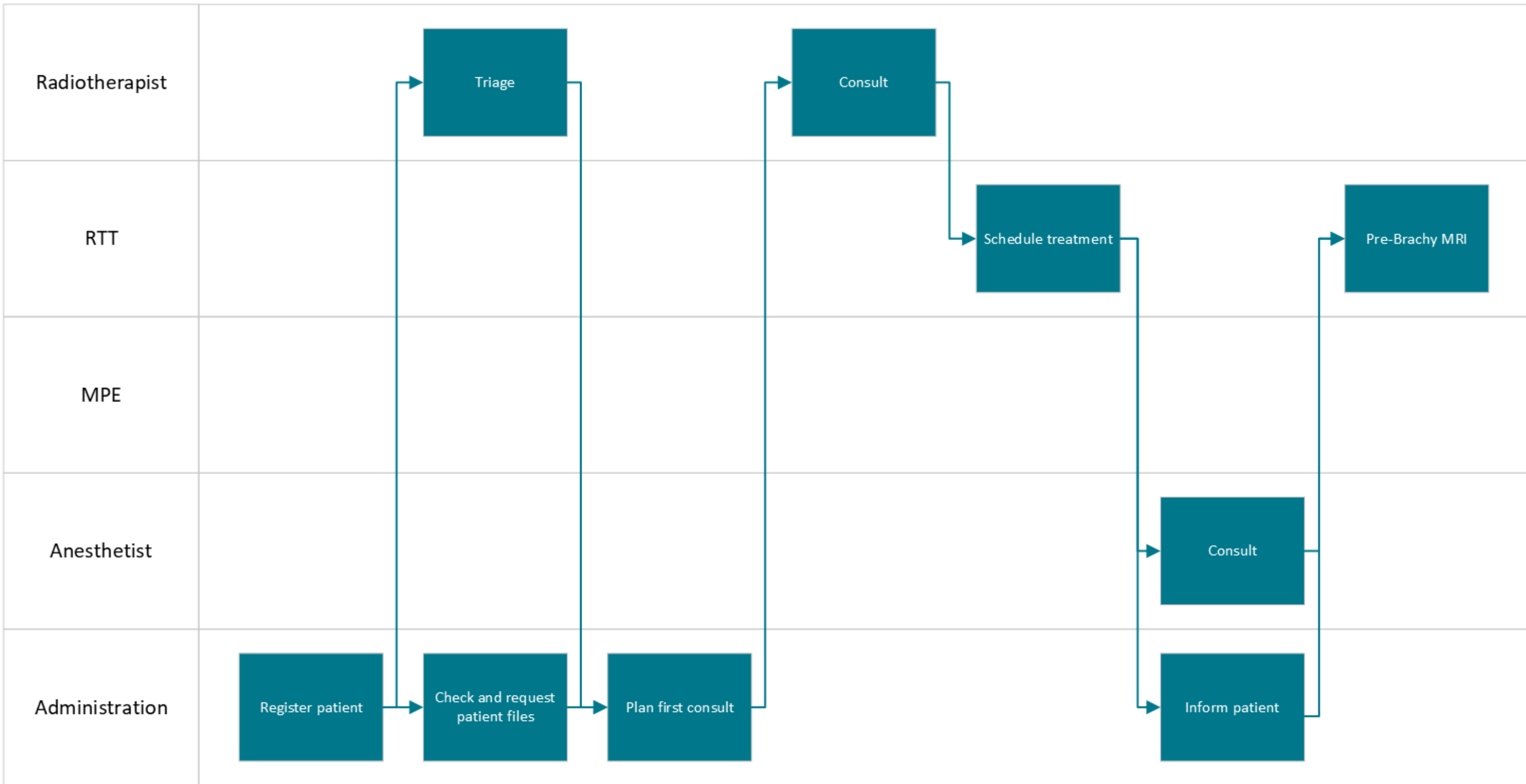

Figure A.7: Workflow of the preparation of PDR GYN treatment

A.5.2 Treatment day

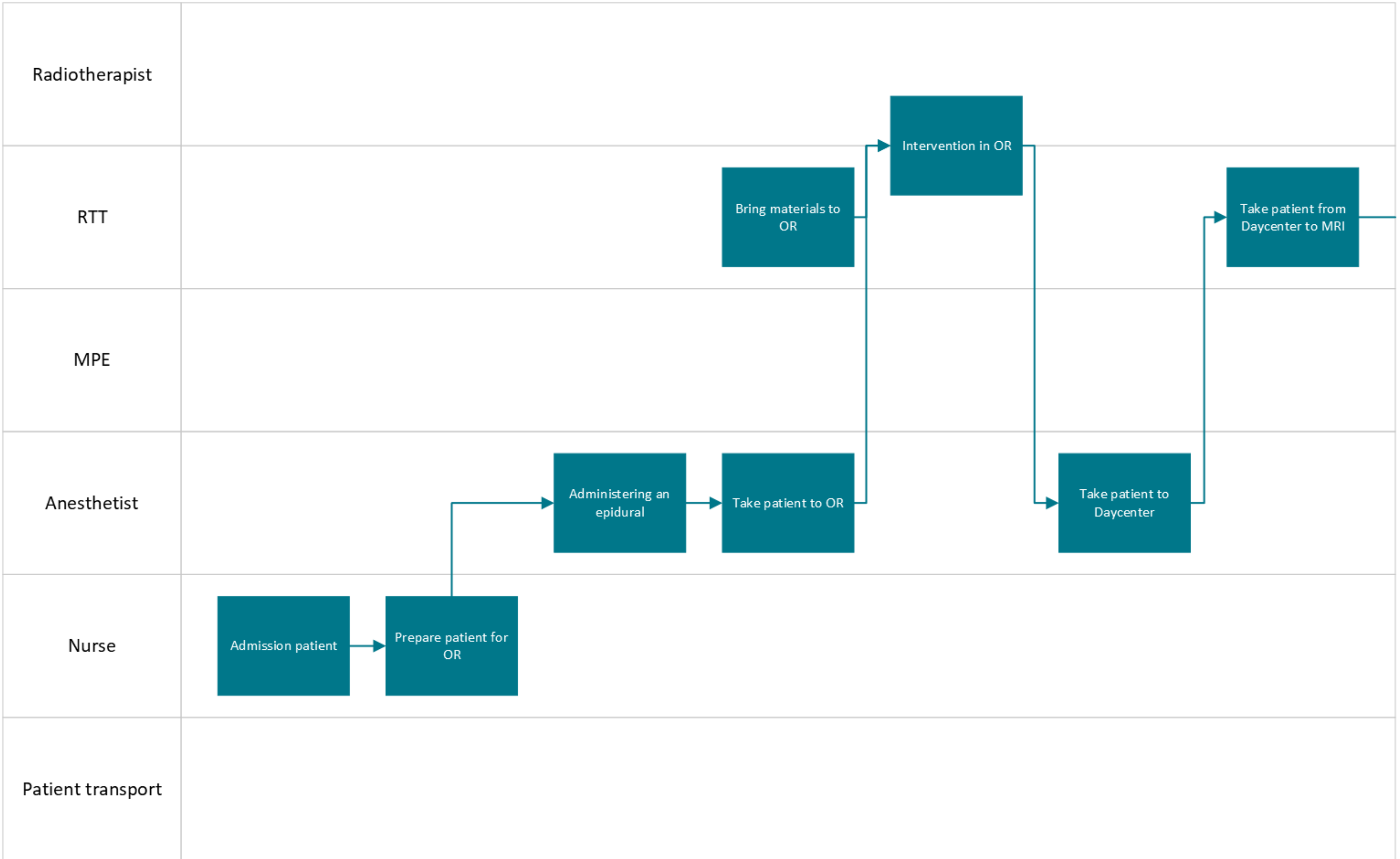

Figure A.8: Workflow of the treatment day of PDR GYN

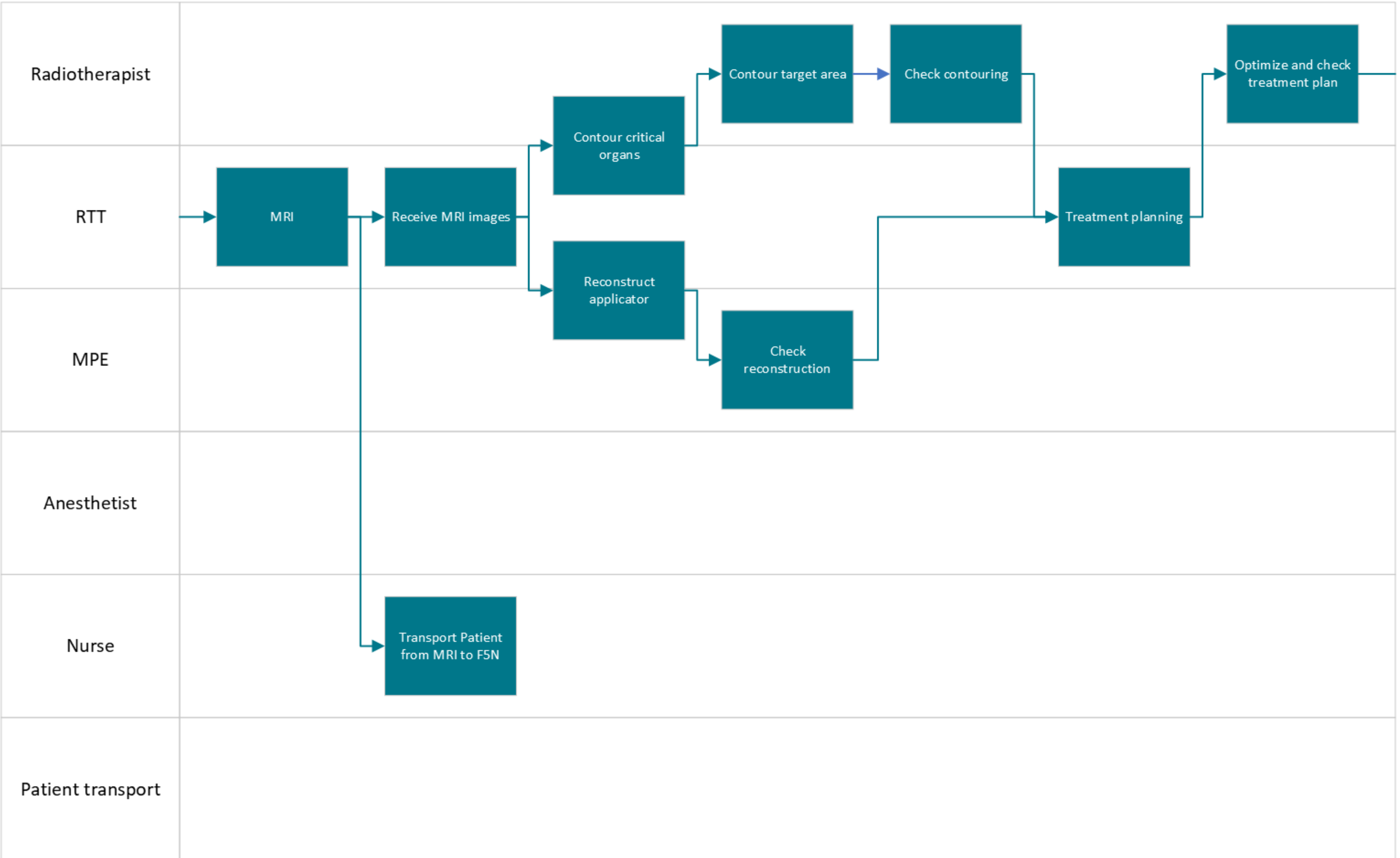

Figure A.8: Workflow of the treatment day of PDR GYN (*cont.*)

Figure A.8: Workflow of the treatment day of PDR GYN (*cont.*)

A.6 Patient flow of PDR gynecology

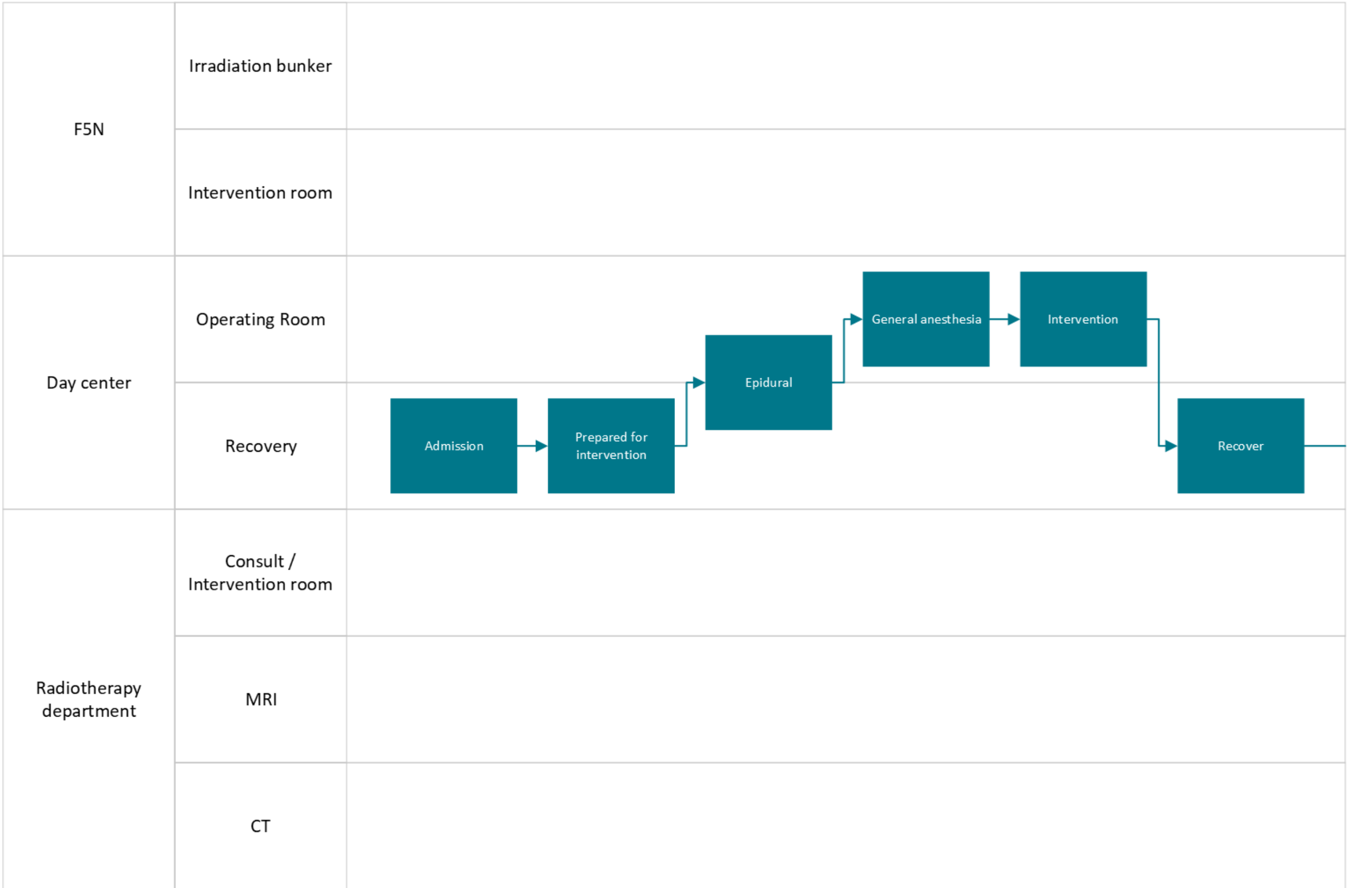

Figure A.9: Patient flow of the treatment day of PDR gynecology

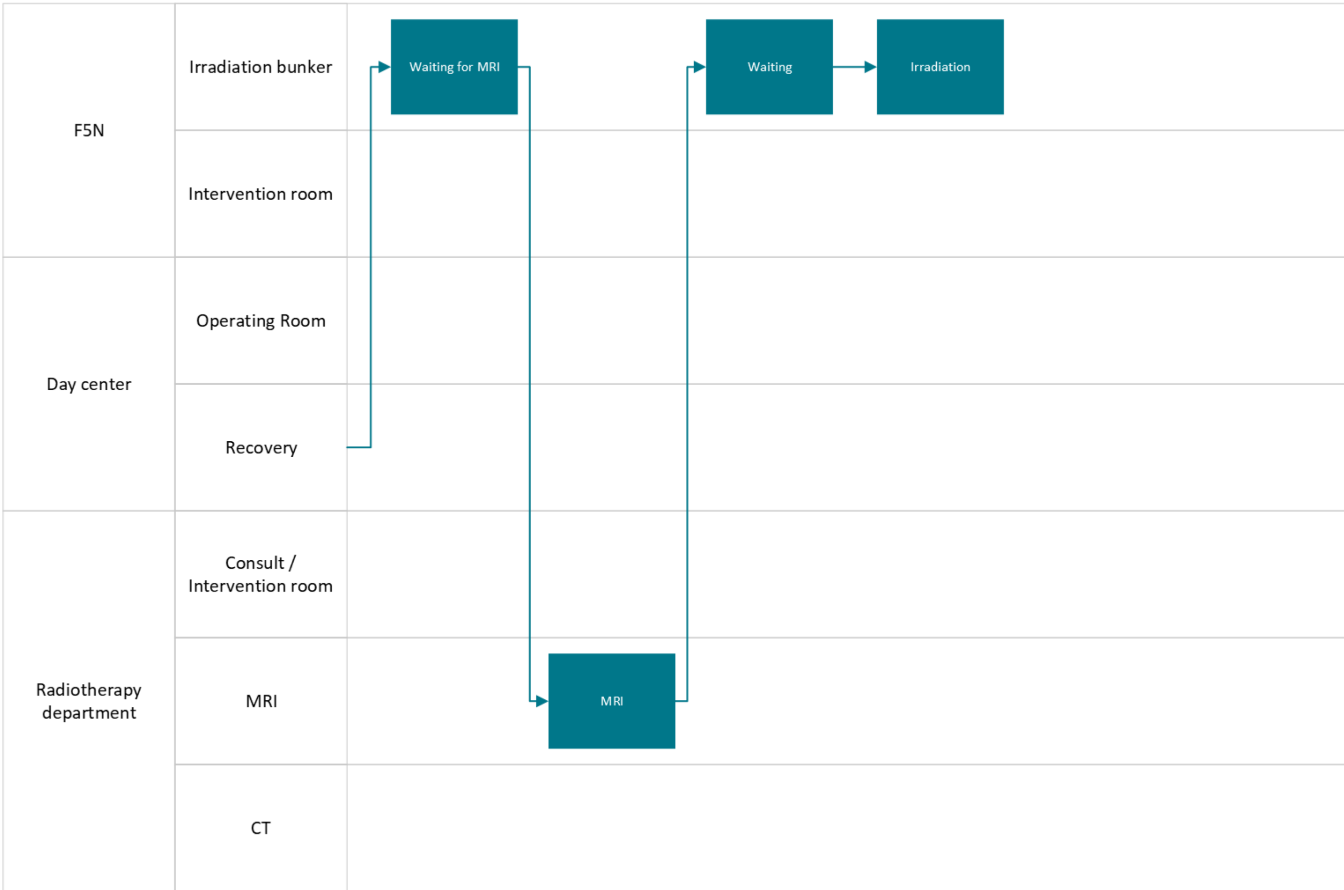

Figure A.9: Patient flow of the treatment day of PDR gynecology (*cont.*)

A.7 Workflow of HDR Ring

A.7.1 Preparation

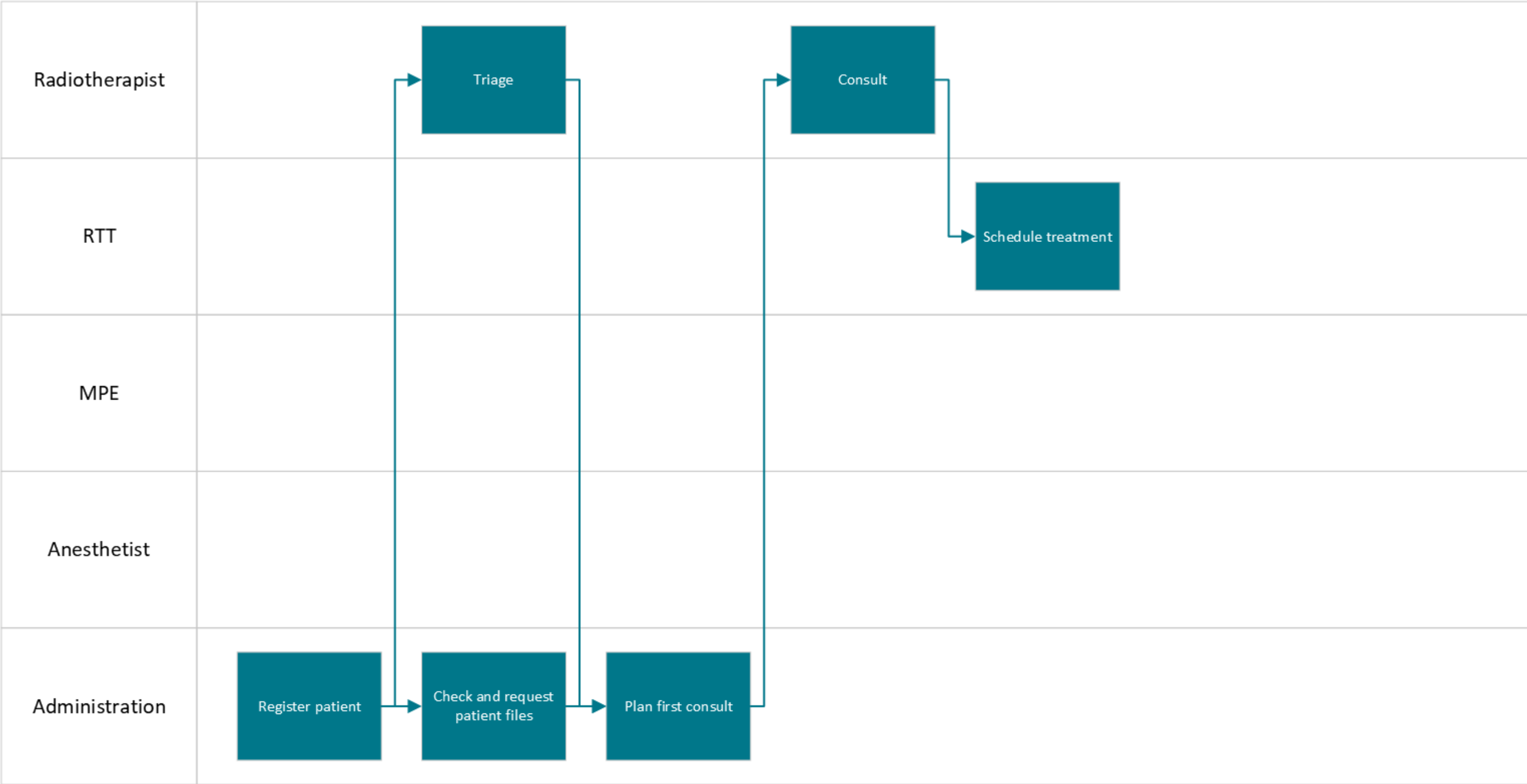

Figure A.10: Workflow of the preparation of HDR ring treatment

A.7.2 Treatment day

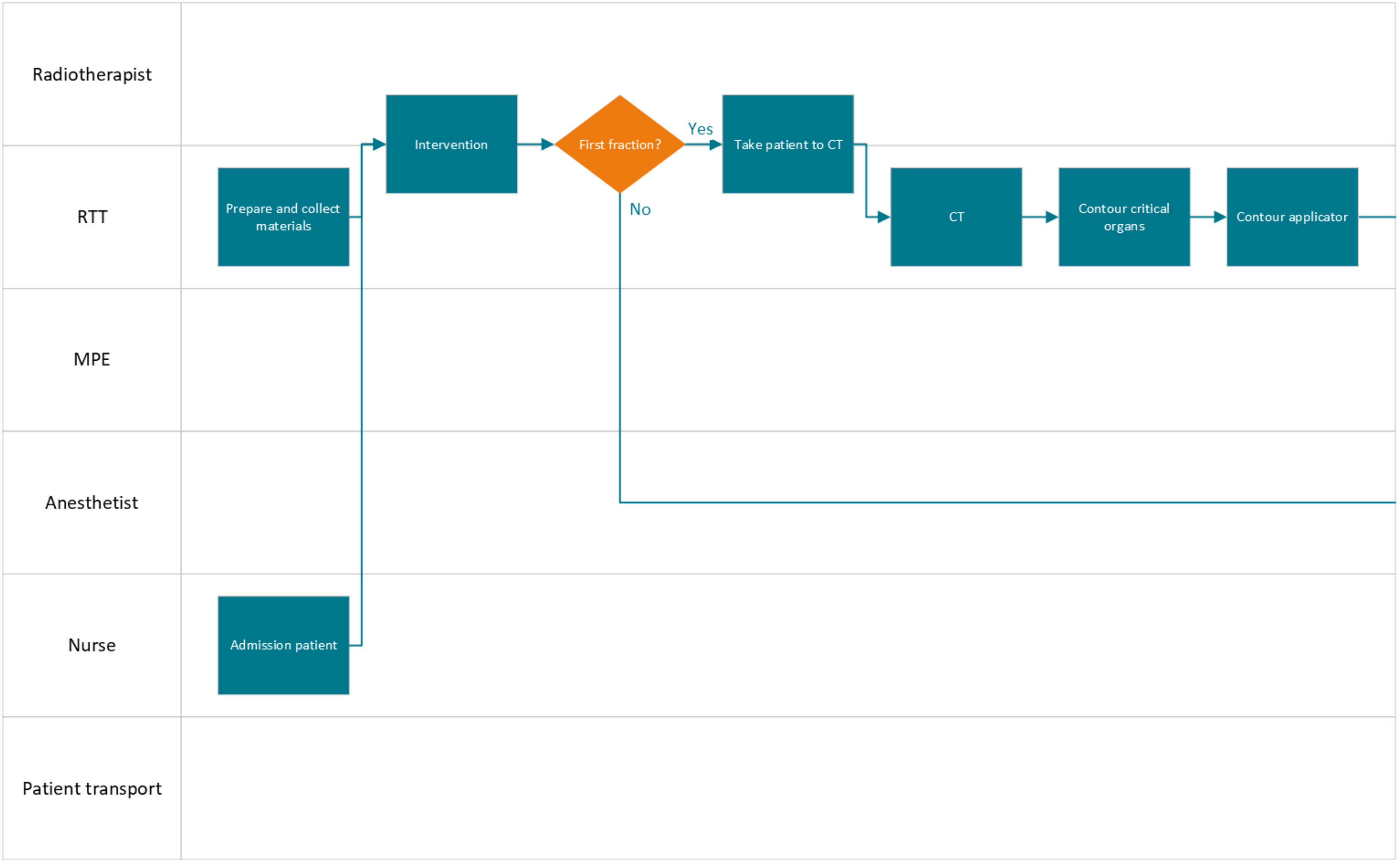

Figure A.11: Workflow of the treatment day of HDR ring

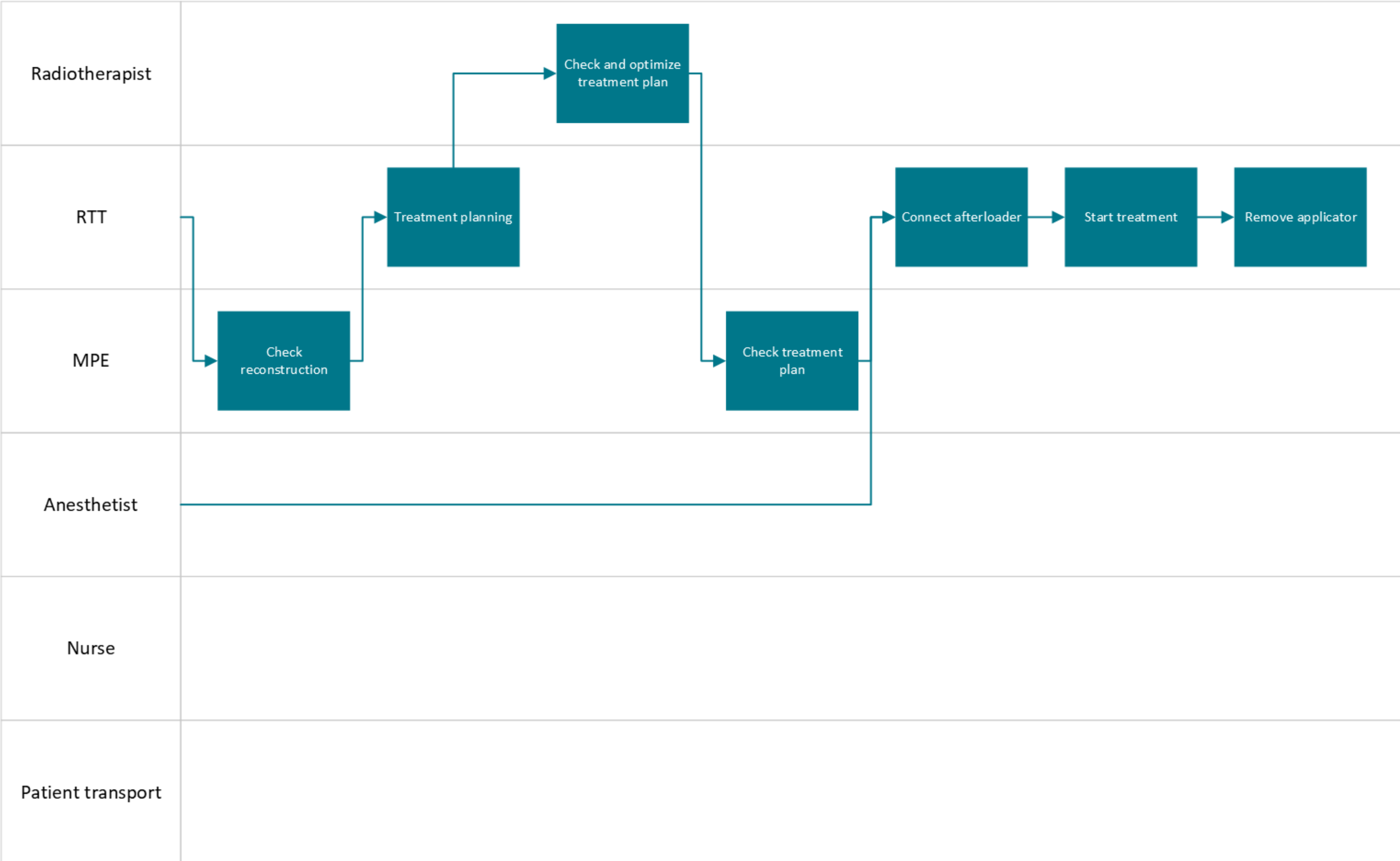

Figure A.11: Workflow of the treatment day of HDR ring (*cont.*)

A.8 Patient flow of HDR ring

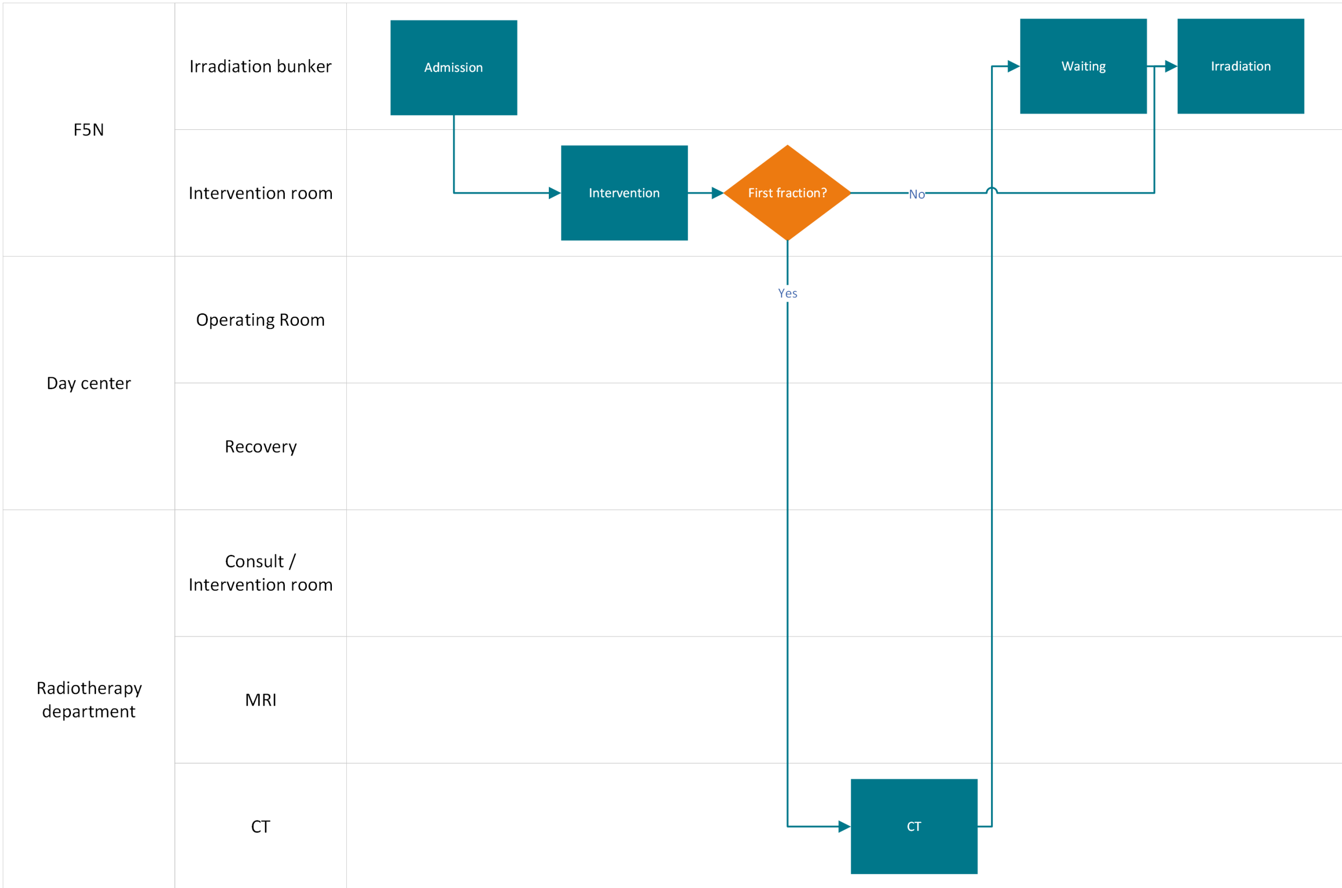

Figure A.12: Patient flow of the treatment day of HDR ring

Appendix B

Systematic literature review

This appendix contains information about the systematic approach used to conduct the literature review. The database used for this literature review is Scopus.

B.1 Multi-disciplinary scheduling

The following search terms are used to search within articles' titles, abstracts, and keywords.

- (multi-disciplinary OR multi-appointment)
  AND
- ("appointment scheduling" OR "appointment planning" OR "capacity planning")
  AND
- (healthcare OR "health care" OR clinic OR hospital)

This search resulted in 9 articles. After the abstracts were read, 4 articles were selected for which a forward and backward search was conducted. This eventually led to a sample of 13 articles.

B.2 Master surgery scheduling

The following search terms are used to search within articles' titles, abstracts, and keywords.

- ("master surgical schedul*")
  AND
- ("procedure type*" OR "patient type*" OR "surgery type*")

This search resulted in 7 articles. After the abstracts were read, 6 articles were selected for which a forward and backward search was conducted. This eventually led to a sample of 7 articles.

Appendix C

Technical description DES model

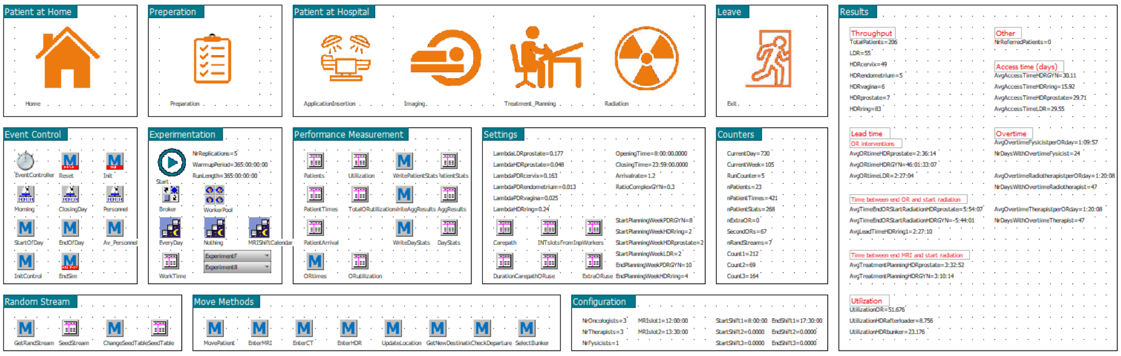

Figure C.1: Control Panel in Plant Simulation

Figure C.1 represents the control panel in Plant Simulation. The four boxes on top, Patient at home, Preparation, Patient at hospital, and Leave, contain the frames where patients move between. In the Home frame, the patients arrive, appointments are scheduled, and patients wait between appointments. In the appointment frame, patients have appointments before the treatment day. The box Patient at Hospital contains four frames, each representing a part of the process during a treatment day. When a patient has no appointments, it will move to the Exit frame. All patient data are written to a table in this frame, and then the patient leaves the system.

The Event Control box contains all the information and methods that manage the simulations and time. All of the variables for the experiments are located in the Experimentation box. The random stream box generates random numbers. This will allow you to compare the systems more statistically efficiently. The box Move Methods contains all methods that ensure a patient moves between different procedures. The performance measurement box includes methods that record statistics about patients, staff, days, and experiments in their respective tables. The settings box includes all the variables and tables needed to create scenarios. In the Configuration box, all the required variables are located to create a configuration. The Counter box comprises all the necessary counters for the simulation, while the Results box contains the crucial output variables.

Appendix D

Distribution fitting

In this appendix, an example shows how a distribution is fit to the collected data. In this example, the OR time of LDR prostate I-125 is fit. For all other distributions that are fit, the same approach is used.

Step 1 - Hypothesizing families of distributions

The first step is to make a hypothesis of the distribution. This hypothesis is based on descriptive statistics and a histogram of the distribution. In this step, first, the data is inserted in a Microsoft Excel worksheet. Then, using the add-in Analysis Toolpak, the descriptive statistics of the data are constructed (see Table D.1). Based on the number of data points available, in this case 82, the number of bins for the histogram is determined. This is calculated by $\lceil \sqrt{count} \rceil$. Accordingly, the bin width is calculated by $range/\#bins$. Then, for each bin, the number of observations is determined using the Analysis Toolpak histogram function. Based on these frequencies, a histogram is constructed. Figure D.1 shows this histogram. Based on this histogram and the descriptive statistics, the hypothesis is made that the OR time of LDR prostate is lognormal distributed.

Table D.1: Descriptive statistics

Descriptive Statistics	
Mean	149.4924
Standard Error	2.1751
Median	149.89
Mode	138
Standard Deviation	19.6968
Sample Variance	387.9629
Kurtosis	−.6139
Skewness	.0789
Range	84.63
Minimum	107.55
Maximum	192.18
Sum	12258.38
Count	82

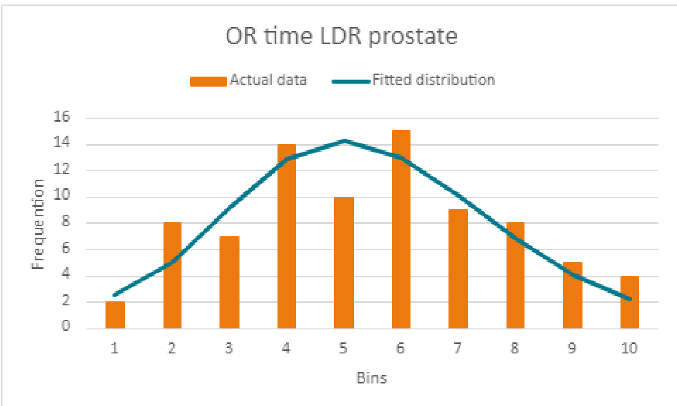

Figure D.1: OR time distribution LDR prostate

Step 2 - Estimation of parameters

The next step is to estimate the lognormal parameters μ and σ. The estimate of the σ is calculated by $\sqrt{\ln\left(\frac{\text{Sample Variance}}{\text{Mean}^2}+1\right)}$ and the μ is estimated by $\ln(\text{mean}) - \frac{\sigma^2}{2}$. In this example the $\sigma = 0.1312$ and $\mu = 4.9986$

Step 3 - Representativity of fitted distribution

First, graphicly it is accessed how representative the fitted distribution is. To do this, a density over plot is made on the previously assembled histogram (see Figure D.1). The number of data points within a bin is calculated based on the distribution for each previously determined bin.

Step 4 - Chi-square test

The last step is to perform a Chi-square test. For each bin j, the interval is determined for which the probability that a datapoint falls within a bin is equal for each bin j. Thus, in this case of 10 bins (k), the probability a data datapoint falls in a bin is 0.10 (p_j). Then, the number of data points in the dataset is counted per interval and compared with the expected number of data points np_j. The dataset contains 82 data points in this case, so $np_j = 82 \cdot 0.10 = 8.20$. Then, the test statistic χ^2 is calculated by $\sum_{j=1}^{k} \frac{(N_j - np_j)^2}{np_j}$. After calculating the test statistic, it is compared to the value of $\chi^2_{9,0.95}$. The value of $\chi^2_{9,0.95}$ is 16.9190. Since the calculated test statistic does not exceed this value, the null hypothesis (H_0) is not rejected at the significance level of $\alpha = 0.05$.

Table D.2: Chi-square goodness-of-fit test

j	**Interval**	N_j	np_j	$\frac{(N_j - np_j)^2}{np_j}$
1	$[0, 125.28)$	10	8.20	0.3951
2	$[125.28, 132.72)$	7	8.20	0.1756
3	$[132.72, 138.36)$	10	8.20	0.3951
4	$[138.36, 143.37)$	5	8.20	1.2488
5	$[143.37, 148.21)$	7	8.20	0.1756
6	$[148.21, 153.22)$	7	8.20	0.1756
7	$[153.22, 158.77)$	10	8.20	0.3951
8	$[158.77, 165.51)$	9	8.20	0.0780
9	$[165.51, 175.35)$	8	8.20	0.0049
10	$[175.35, \infty)$	9	8.20	0.0780
				$\chi^2 = 3.1220$

Appendix E

Feasible OR days

E.1 Process time reduction of 10 percent

Table E.1: Results feasibility OR days based on finish time in OR

Combination	HDR Prostate	HDR GYN	LDR	Percentage finished on time	Average finish time *(hh:mm:ss)*
1	0	0	3	82.69%	15:54:36
2	0	1	2	98.08%	14:50:52
3	0	2	1	100.00%	14:08:10
4	0	3	0	100.00%	13:27:07
5	1	0	2	90.38%	15:42:53
6	1	1	1	99.01%	15:00:49
7	1	2	0	100.00%	14:03:33
8	2	0	1	85.58%	15:56:28
9	2	1	0	98.08%	15:13:50
10	3	0	0	82.69%	16:00:49

Table E.2: Results feasibility OR days based on finish time in OR with four interventions

Combination	HDR Prostate	HDR GYN	LDR	Percentage finished on time	Average finishing time *(hh:mm:ss)*
α	0	4	0	93.88%	15:28:01
β	0	3	1	60.44%	16:25:52
γ	1	3	0	55.88%	16:32:13
δ	1	2	1	5.83%	17:18:57
ϵ	2	2	0	4.17%	17:21:03
ζ	0	2	2	2.88%	17:21:24
η	2	1	1	1.92%	17:38:52
θ	1	1	2	0.00%	17:45:55

E.2 Process time reduction of 25 percent

Table E.3: Results feasibility OR days based on finish time in OR

Combination	HDR Prostate	HDR GYN	LDR	Percentage finished on time	Average finish time *(hh:mm:ss)*
1	0	0	3	100.00%	14:46:53
2	0	1	2	100.00%	14:05:33
3	0	2	1	100.00%	13:24:17
4	0	3	0	100.00%	13:04:07
5	1	0	2	100.00%	14:38:16
6	1	1	1	100.00%	14:05:23
7	1	2	0	100.00%	13:24:32
8	2	0	1	100.00%	14:40:38
9	2	1	0	100.00%	14:01:10
10	3	0	0	100.00%	14:44:31

Table E.4: Results feasibility OR days based on finish time in OR with four interventions

Combination	HDR Prostate	HDR GYN	LDR	Percentage finished on time	Average finishing time *(hh:mm:ss)*
α	0	4	0	100.00%	15:06:44
β	0	3	1	100.00%	15:52:32
γ	1	3	0	97.09%	15:55:03
δ	1	2	1	84.62%	16:14:41
ϵ	2	2	0	79.41%	16:14:00
ζ	0	2	2	79.81%	16:13:13
η	2	1	1	59.62%	16:27:30
θ	1	1	2	47.12%	16:33:16