MASTER THESIS

INDUSTRIAL ENGINEERING AND MANAGEMENT

USING DISCRETE EVENT SIMULATION TO OPTIMIZE THE BRACHYTHERAPY TREATMENT PROCESS: A CASE STUDY

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Management Summary

Research goal and context

Amsterdam UMC recently started as a merger from two Amsterdam academic hospitals, Academic Medical Centre (AMC) and VU medical center (VUmc). Due to the merger, the radiotherapy department will primarily be concentrated at the VUmc location. The radiotherapy department includes external radiotherapy, brachytherapy, and hyperthermia. Brachytherapy is a form of radiotherapy that involves irradiating with a closed source placed in the tumor in the body. This research focuses solely on the brachytherapy treatment process. Moving the radiotherapy department to a new location gives opportunities to change and improve the design of the treatment process. Currently, the brachytherapy department treatment is not as efficient as desired, resulting in long access times and lead times. This makes it undesirable to continue the same process at the new location. However, it is not clear why the treatment process is inefficient. Therefore, it is important to gain insight into the bottlenecks to set up a better process at the new location. This research revolves around answering the following question:

"How do we set up the brachytherapy treatment process at the new location so that timely treatment and an efficient and patient-friendly treatment process can be realized for all patients while guaranteeing high tumor control and a low risk of (late) toxicity?"

Modeling approach

Analyzing the brachytherapy treatment process and its performance is done by means of interviews, observations, and data analysis. This analysis sheds light on the following topics. First, the access time of patients that need brachytherapy is exceeding the national norm. Second, the current amount of OR days is not sufficient for the patients. Third, MRI appointments are static and often do not correspond well with the time a patient is ready to undergo the MRI. Fourth, there is waiting time for other departments and specialists at different moments in the treatment process. Fifth, the treatment planning takes long, caused by protocols not being updated, waiting for other personnel to assist or perform a task, and not fully trained personnel. Sixth, the hospital's layout creates much distance between the required departments, resulting in lost time. Finally, fluctuating agendas of radiation oncologists make it challenging to plan patients in time for smaller (outpatient) interventions.

An extensive literature search is done for all topics discussed in the context analysis. The subjects are divided into various levels of planning and control. At strategic level, the focus is on capacity dimensioning, including hospital layout, resource capacity planning of rooms, material, and personnel. At tactical level, the focus is on how to use the given capacity, for example, the OR and MRI time, and the scheduling of small interventions. At operational level, the focus is on patient-to-appointment scheduling and daily patient flow. Due to the complexity of the brachytherapy process and the many topics that need to be addressed, we chose to perform a discrete-event simulation study using Tecnomatix Plant Simulation software from Siemens. Discrete-event simulation is widely used to address dynamic and complex systems and allows for complex decision-making rules and testing of multiple scenarios. Based on the simulation, we determine the most significant bottlenecks and analyze various scenarios of strategic, tactical, and operational choices.

The simulation study consists of three phases, starting with a simulation of the current situation, followed by a simulation of the bridging phase, a period where the brachytherapy cannot go to the new location yet, but also cannot stay at the current location, and a simulation of the situation at the new location. A simulation model is made for all phases. In every phase, the same performance indicators are evaluated, namely the average access time, average waiting time for patients during the treatment day, average waiting time for personnel during the treatment day, overtime of personnel, lead time of the treatment, and utilization of OR-time, afterloaders, and bunkers.

Results

The simulation model of the current situation showed that MRI times and amount of personnel is not the first bottleneck. But OR capacity and the speed of the treatment planning process are a bottleneck. Current OR capacity guarantees that patients cannot be treated within the access time norm. Treatment planning tasks guarantee that the average lead time of patients is long and that also results in overtime. 92% of the time a patient waits during the OR-day is due to the treatment planning. Working with two half OR-days instead of one full day can reduce the access time by almost 14%. An additional benefit is that the number of OR-slots borrowed from the gynecology department decreases by 77%. Two scenarios based on future technical improvements, such as automatic planning and automatic contouring, and trained personnel are used to evaluate the impact of a faster treatment planning process. The best scenario decreases the average lead time by 20%, and with that the average overtime reduces by 60%.

The bridging phase brings a few changes to the treatment process. The biggest difference is that there are no PDR treatments possible. Those treatments will be replaced by an adjusted variant of the HDR treatments. 62% of the OR patients usually follow the PDR treatment. Changing from treatment means they need two OR appointments one week after another. That is an increase of 62% in OR interventions. A revised agreement with the OR complex can only support such an increase. Besides a great change in OR interventions, the workflow of HDR treatments is more labor-intensive and takes two days. A suggestion is to make use of 1.5 OR days every week. This way the access time does not rise more. Which days do not affect the access time much if there is a day between the OR-days because of the two-day treatment of most patients. For the same reason, a Friday is not advised to use as OR-day. The new situation has a significant impact on the amount of overtime. The best speed scenario for the treatment planning can reduce the average overtime by 57%, but barely the number of days worked in overtime. Almost every time two interventions are performed in the OR, overtime is needed to complete the treatment of the second patient. Without improving the speed, the average overtime is 1:44h and occurs 100 times a year.

No PDR treatments are still in place when designing the treatment process for the new location. There is more freedom regarding OR-time, as a dedicated operating room is available every day. The use of this room is restricted by hiring anesthesia personnel. Another significant change is performing an MRI under anesthesia directly after the intervention. Having the OR available all days will result in an average access time of 20.5 days, but this is not a realistic situation. Experiments are performed using different available days for the OR. The best performing experiment has the OR available on Monday, Tuesday, and Thursday mornings and results in 26.1 days access time. Implementing a rule where every patient with an access time exceeding 35 days will be planned on an additional OR slot will decrease the average access time to 24.1 days. The average lead time of the treatment will be 4:30h, which is a decrease of 28% against the current situation because of the recovery being concurrent with the treatment planning. Even with the new treatment process and the best treatment planning scenario, there will be on average 20 minutes of overtime that occurs eight times a year. This can only be further eliminated with the help of other departments by reducing the waiting time for anesthesia every morning for the first patient at the OR.

Conclusion and discussion

Analysis of the results shows that the MRI slots and amount of personnel are of less impact than expected. The biggest bottleneck for the access time not being under the norm is the amount of OR time. This report suggests which usage of OR-time would be advised for each phase and provides input for discussion with the OR complex and anesthesia personnel. The biggest bottleneck for the long lead time is the treatment planning process. Reducing that time by employing auto contouring, auto planning, and personnel training can reduce the lead time by 20%. In every phase, overtime plays a role. Overtime is mainly caused by the second patient on the OR day. It is impossible to only perform one OR intervention per day because of the dependence on the OR complex, anesthesia personnel, own personnel, and in later phases, the number of OR interventions required. The best way to reduce overtime is to shorten the treatment planning time and perform the MRI under anesthesia. Working in shifts is recommended before the ultimate treatment planning speed can be achieved.

There are possible biases in the results. This can be caused by using input data provided by experts' opinions instead of actual data, due to the lack of documentation, and by assumptions made to simplify the real situation for the simulation model. Important simplifications are the availability of personnel and the lack of assigning personnel to specific tasks and patients. The simulation model uses the amount of personnel available during a standard week and only plans patients when there is sufficient personnel. This study contributes to an increased understanding of the bottlenecks and possibilities for improvement. Therefore, an innovation request is filed and approved to extend this simulation study to hyperthermia and external radiotherapy.

For future research, we recommend studying the process in a more personnel-focused manner. We also recommend optimizing a roster for small interventions and volume measurements for the DBL situation as the number of OR interventions will increase and get more labor-intensive. It is also recommended to log more times regarding patients by means of patient tracking. And more consequent logging of times of the treatment planning process can gain better insights into the use of personnel and time for certain steps and care plans.

Acknowledgment

Dear reader,

With this thesis, I finish my master Industrial Engineering and Management, and with that, I conclude my time as a student at the University of Twente. My life as a student in Enschede was wonderful thanks to the unforgettable moments I got to experience. I am grateful for the great friends that I have met, and I am very proud of the personal and professional development that I have achieved.

I would like to express my appreciation to my supervisors from Amsterdam UMC. I thank Rob and Danique for the opportunity to graduate at the brachytherapy department and observe as much as possible to learn about brachytherapy, despite the COVID-19 regulations. It was a challenging assignment. I thank all colleagues for their collaboration and input.

Furthermore, I thank my supervisors at the University of Twente. Erwin and Gréanne helped me conduct this research by sharing their academic perspective during meetings and providing helpful feedback on my work, as this would guide my thesis in the right direction.

Finally, many thanks to all the people that were involved in their way. My study mates, friends, and family offered me great support along the way and listened to all my thoughts and ideas.

Pleun de Bruijn
Tilburg, February 2022

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List of abbreviations

Abbreviation	Definition
AMC	Amsterdam medical center
CRAFT	Computerized relative allocation of facilities techniques
DA	Doctor’s assistant
DBL	Location of Amsterdam UMC at de Boelelaan, formerly known as VUmc
FWLP	Fixed ward layout problem
HDR	High dose rate, type of brachytherapy
ILP	Integer linear program
KPI	Key performance indicator
LDR	Low dose rate, type of brachytherapy
MBD	Location of Amsterdam UMC at Meibergdreef, formerly known as AMC
MDO	Multidisciplinary consultation
MILP	Mixed-integer linear program
NVRO	Dutch association for radiotherapy and oncology
OR	Operating room
OTL	Operating theatre layout
PDR	Pulsed dose rate, type of brachytherapy
QAP	Quadratic assignment problem
RO	Radiation oncologist
RT	Radiation therapist
VUmc	VU medical center, former name of de Boelelaan location of Amsterdam UMC
VWLP	Variable ward layout problem

Chapter 1: Introduction

This report describes the result from the graduation assignment of the Master program Industrial Engineering and Management at the University of Twente conducted at Amsterdam UMC, department of radiotherapy. This chapter introduces the research topic. Section 1.1 covers the organization description, Section 1.2 the research motivation, Section 1.3 the problem description, Section 1.4 the research objective, and Section 1.5 concludes with the research design.

1.1 Organization description

Amsterdam UMC recently started as a merger from two Amsterdam academic hospitals, Academic Medical Centre and VU medical center. Amsterdam UMC belongs to one of the eight university medical centers in the Netherlands. As a university medical center, it has three main tasks. First, the treatment of patients is paramount. In addition, a lot of medical-scientific research is carried out. The third main task is to provide education and training.

In 2013, the two hospitals announced they wanted to work closely together. To improve complex patient care, excel in research and education at the European level, and deploy people and resources more efficiently (Amsterdam UMC, 2018). In September 2017, the merger between AMC and VUmc was approved, and since June 2018, both UMCs will continue together as Amsterdam UMC. Amsterdam UMC represents the two universities' medical faculties: The University of Amsterdam and the Vrije Universiteit Amsterdam. Amsterdam UMC is a leading medical center that combines complex high-quality patient care, innovative scientific research, and education of the next generation health care professionals (Amsterdam UMC, n.d.).

More than 15.000 professionals work on good and accessible care (Amsterdam UMC, 2018b). Every year they treat more than 350.000 patients at both their locations. They offer medical treatments and facilities that are only allocated at a limited number of hospitals. These top clinical functions include kidney dialysis and kidney transplantation, open-heart surgery, radiotherapy, neurosurgery, neonatology, and nuclear medicine. With the merge, Amsterdam UMC wants to give a new impulse to the quality of patient care and guarantee the sustainable availability of complex patient care. Part of that is bringing together specific patient groups at one of the two locations. The radiotherapy department, specifically brachytherapy, is the main topic for this research.

1.2 Research motivation

Radiotherapy is one of the three most occurring treatments for cancer patients in the Netherlands. This form of therapy is offered at Amsterdam UMC at both location AMC from now on called MBD and location VUmc from now on called DBL. Due to the merger, the radiotherapy department will primarily be concentrated at the DBL location. In addition to external radiotherapy, internal radiotherapy called brachytherapy is also offered. Brachytherapy is a form of radiotherapy that involves irradiating with a closed source placed in the tumor. This treatment is characterized by local high dose delivery into the tumor while sparing the surrounding healthy tissue. This form of therapy is now mainly performed on location MBD. MBD has become a leading center for brachytherapy.

Long access times and rising healthcare costs are major social problems. To provide good, fast care with the current resources, hospitals must plan their care processes more efficiently. At MBD, the various components of the brachytherapy process have become spread throughout the hospital over the years. This situation results in an inefficient process, in which patients must be transported back and forth throughout the hospital. Besides that, the lead time of a patient is longer than necessary due to waiting time during the process. In addition, there is a lot of interdependence between stages in the treatment process. If a stage suffers from delay, it can result in a bullwhip effect on subsequent stages.

Amsterdam UMC decided to concentrate oncological care at the DBL location. As a result, the brachytherapy will have to move to that location. A renovation will be carried out at the DBL location to realize the new department. Moving the brachytherapy to a new location gives opportunities to change and improve the multidisciplinary chain care, which is the motivation for this research. The brachytherapy currently offered at DBL is almost negligible compared to what MBD offers in terms of complexity of the treatments and number of patients. For that reason, this research will only map the current situation of the MBD location. These treatments and number of patients are the starting point for the new situation.

1.3 Problem description

Yearly, around 2.000 new patients come to the radiotherapy department at the MBD location, of which 1 out of 10 is eligible for brachytherapy. Depending on the tumor diagnoses, patients may also get external radiotherapy, hyperthermia, chemotherapy, or surgery before they receive brachytherapy. For the treatment to be successful, all different treatments must start as soon as the previous one is finished. Some treatments are even performed concurrently. This results in the departments having to coordinate and communicate well to let the entire multidisciplinary treatment succeed.

Brachytherapy consists of several successive steps: consultation, pre-MRI scan, intervention at the OR, verification/planning MRI scan, reconstruction applicator, contouring critical organs, making a treatment plan, and irradiation. This makes a brachytherapy treatment a complex process, which in contrast to external radiotherapy and apart from the preparations, is entirely carried out in one day. In addition to the facilities in the radiotherapy department, the brachytherapy process also uses the OR complex, anesthesia, imaging (MRI), and nursing care for each patient. Figure 1 simplistically depicts the brachytherapy process. The consult and pre-brachy MRI are on different days before the grey-colored process start.

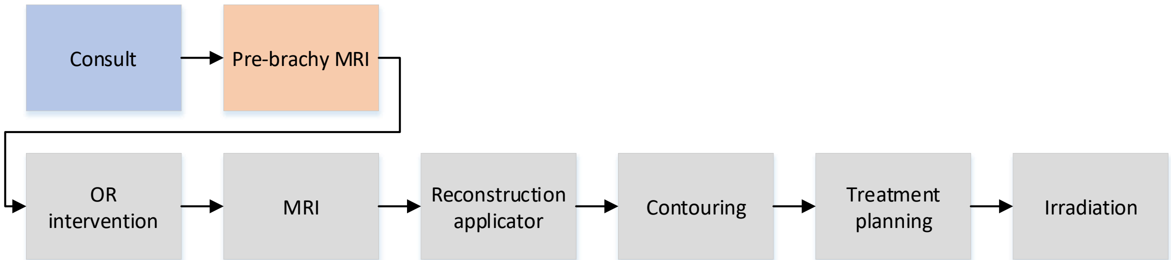

Figure 1. Schematic representation of the brachytherapy process

Many factors affect the lead time of the brachytherapy treatment. However, due to the interdependence between different stages in the treatment process, it is not entirely clear which influence is caused by which factor. To shorten the lead time, it is necessary to gain insight into these factors and identify organizational and logistical bottlenecks.

The goal is to treat more patients in less time with the available resources, which is crucial for an effective result of good tumor control with a low risk of (late) toxicity and limitation of psychological complaints.

1.4 Research objective

After a preliminary problem diagnosis, we define the research objective as follows:

"How do we set up the brachytherapy treatment process at the new location so that timely treatment and an efficient and patient-friendly treatment process can be realized for all patients while guaranteeing high tumor control and a low risk of (late) toxicity?"

Due to the many interdependent stages, target areas, priorities, and types of brachytherapy treatments, the problem size is large. Therefore, we focus on specific brachytherapy treatments. Together with the stakeholders involved in this research, a distinction is made into four main groups:

1. LDR (permanent iodine implantation)
2. PDR (gynecological, bladder, head & neck)
3. HDR complex (prostate)
4. HDR simple (vagina top)

LDR, PDR, and HDR indicate the level of intensity of the irradiation delivered to the surrounding medium. A more detailed explanation of the treatment groups will follow in Chapter 2.

1.5 Research design

The following knowledge questions have been defined to answer the main research question:

1. What is the current situation concerning the brachytherapy process at AMC in terms of workflow, patient flow, and scheduling, and what is the performance of these processes?

1.1 *What do the workflow and patient flow of the different brachytherapy treatments look like?*

1.2 *How can the planning and control mechanisms be described?*

1.3 *What is the performance of the brachytherapy process?*

1.4 *What are the core problems that prevent brachytherapy from treating more patients faster?*

Chapter 2 answers question 1 by employing interviews with professionals of the brachytherapy team, as well observations made during several activities, and by using available data to evaluate performance indicators.

2. What literature is available that relates to our main research question?

2.1 *What is known by literature regarding strategic resource capacity management and facility layout problems?*

2.2 *What approaches are presented in the literature regarding capacity allocation in the healthcare sector?*

2.3 *What methods are used in the literature to schedule patients?*

2.4 *What methods are used to model healthcare trajectories?*

Chapter 3 answers question 2. The literature study is divided into strategic, tactical, and operational level and describes the methods and approaches found in the literature and how they can contribute to this research.

3. How can the brachytherapy treatment trajectory be modeled?

3.1 *What does the conceptual model of the treatment trajectory look like?*

3.2 *Which data and input variables are needed for a realistic model?*

3.3 *Which scenarios should be evaluated?*

Chapter 4 answers question 3. The concept model describes the problem formulation, objectives of the study, performance measures, the model's scope, modeling assumptions, system structure, input parameters, model validation and verification, and the experimental design. This chapter is based on the ten-step approach of Law's simulation modeling and analysis book (2014).

4. What are the results of the model?

4.1 *What is the improvement of the treatment trajectory using the model?*

4.2 *What are the results of the various scenarios?*

Chapter 5 answers question 4. The simulation model is made for three phases: the current situation, the bridging phase, and the new location. All phases make use of various scenarios that are evaluated with the use of multiple performance indicators.

5. In which way can the model help improve the brachytherapy process?

Chapter 6 answers question 5, concluding the research and reflecting on the results.

Figure 2 depicts a visual display of the report structure.

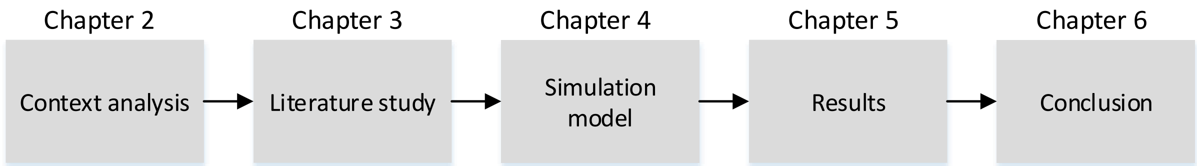

Figure 2. Outline report structure

Chapter 2: Context analysis

This chapter answers the first research question as stated in Section 1.5 regarding the current situation of brachytherapy at AMC. First, an introduction to brachytherapy is given in Section 2.1. Second, Section 2.2 describes the brachytherapy process at AMC explained from work- and patient flow points of view. Then, Section 2.3 describes the planning and control, followed by the performance of the brachytherapy department in Section 2.4. Next, the problems and bottlenecks are explained using a problem cluster in Section 2.5. Finally, we conclude with the demarcation of the core problem in Section 2.6.

2.1 Introduction brachytherapy

Shortly after the discovery of radioactivity, ground-breaking techniques were developed in the early 20th century to apply brachytherapy by bringing the radioactive sources into the tumor. At that time, the personnel was exposed to the radiation because they had to insert the radioactive sources manually. Over the years, remote-controlled afterloading systems have been developed so that employees and patients are not unnecessarily exposed to radiation. Nowadays, brachytherapy is a treatment in which radiation oncologists place radioactive sources in or against a tumor to destroy cancer cells. This can happen in two ways. One is placing the sources directly into the tumor. The other is to use source conductors such as needles accompanied by an applicator. These source conductors ensure that the radioactive source arrives precisely at the right place. The LDR treatment is the type of treatment where the sources are put directly into the tumor, mainly done by early-stage prostate cancer. Tiny radioactive capsules or seeds are permanently placed into the prostate using fine needles. Figure 3 depicts the imaging of radioactive seeds placed in a patient. After the intervention and some time at recovery, the patient can go home. This is different for the PDR and HDR treatment, where they use source conductors to deliver the treatment. For both PDR and HDR, the patient must stay after the applicator and needles are placed to receive the irradiation. Figure 4 depicts a patient connected to an afterloader. For HDR treatments, the treatment time is typically 15 to 20 minutes, where they receive a high dose. Using PDR, the patients receive a lower dose of irradiation for 15 to 20 minutes each hour, but they get 24 to 48 pulses in a row. This means 24 to 48 consecutive hours in bed connected to the afterloader. The afterloader is the device that provides irradiation to the needles. HDR and PDR require a different afterloader. Using them can only take place in bunkers which keep the radiation from going through the walls. PDR has been used for patients where the surrounding healthy tissue suffers a lot of irreversible damage with the irradiation process. With the hourly lower dose, the healthy surrounding tissue gets the chance to heal during the treatment.

Figure 3. Radioactive seeds placed in a patient (source= Amsterdam UMC)

Figure 4. Patient connected to an afterloader (source= Amsterdam UMC)

As an academic hospital, Amsterdam UMC is at the forefront of bringing brachytherapy to the highest level together with international collaboration. The team consisting of four radiation oncologists, five radiation therapists, and two medical physicists is highly specialized. Brachytherapy is part of the radiotherapy department, resulting in the radiation oncologists being partly reserved for the brachytherapy and partly for the external radiotherapy. The same applies to medical physicists. The radiation therapists are entirely devoted to brachytherapy. In addition to seeing new patients and treating patients, it is also necessary to do research and side activities to keep improving and stay a leading hospital.

2.2 Process description

In this section we answer Question 1.1 *What do the workflow and patient flow of the different brachytherapy treatments look like?*. Brachytherapy is part of the radiotherapy department, where patients usually only come on referral from specialists in or outside Amsterdam UMC. All patients will get registered at desk 1. The DA (doctor's assistant) will ensure that all documentation comes with the referral. The radiation oncologist, one specialized for brachytherapy or one specialized for external radiotherapy, will triage the patient and inform the desk employee on the right radiation oncologist. Then, the desk employee will schedule an appointment for the new patient. During the first consult, the radiation oncologist will discuss the patient's needs and wishes. After examination, the radiation oncologist and the patient together will decide which treatment to opt for. Sometimes there are no choices, and sometimes further examination will be needed to know the possibilities. Some patients only get brachytherapy, but it is also possible that multiple treatments like external radiotherapy, hyperthermia, chemotherapy, or other treatments will be combined. The brachytherapy treatment must connect seamlessly with the other treatments. This means that the treatment must start within 1 to 10 days after the previous treatment, depending on the place of the tumor and the type of treatment. Steps needed for other treatments are not described in this process description. After the first consult, there will be differences in the workflow for LDR, PDR, HDR-complex, and HDR-simple, which are explained in the sections below together with the patient flow.

Treatment types	**2016**	**2017**	**2018**	**2019**	**2020**
Brachytherapy AMORE	2	7	7	3	0
Brachytherapy Anus	4	4	6	3	1
Brachytherapy Bladder	1	3	3	1	2
Brachytherapy Cervix Fletcher	40	44	44	49	35
Brachytherapy Endometrium	16	33	34	35	38
Brachytherapy Endometrium Moulage	3	1	2	1	0
Brachytherapy Skin	3	0	0	1	2
Brachytherapy Keloid	19	5	8	6	2
Brachytherapy Lip	0	1	0	0	0
Brachytherapy Esophagus	1	0	0	3	1
Brachytherapy Eye	2	5	3	1	5
Brachytherapy Perineal implant	1	0	0	1	0
Brachytherapy Prostate HDR	16	15	11	15	14
Brachytherapy Prostate I125	40	48	53	45	41
Brachytherapy Vagina	4	10	3	14	12
Brachytherapy Vagina top Ring	27	27	41	21	17
Brachytherapy Vulva	0	0	0	1	2
Total	**179**	**203**	**215**	**200**	**172**

Table 1. Number of brachytherapy patients per treatment type (n=969; data from 2016-2020; source=Amsterdam UMC)

Table 1 depicts the number of brachytherapy patients over 2016 up to and including 2020. The largest group of patients treated with brachytherapy are patients with tumors at the gynecological organs such as cervical, endometrium, or vagina cancer or patients with prostate cancer. The number of treatments is fluctuating over the years. A reason why fewer treatments were done in 2020 may arise from COVID-19. Fewer public health surveys were conducted, and people feared getting COVID-19 at the general practitioner or hospital.

Prostate I125 is the only form of LDR treatment. PDR can be used for multiple locations: bladder, anus, eye, lip, vulva, cervix, and endometrium. HDR can be used for skin, lip, keloid, esophagus, prostate, and vagina top. Figure 5 shows the patients divided into LDR, PDR, HDR, and a few can be treated either with PDR or HDR. HDR complex refers to the treatment where a patient needs anesthesia in an OR to place the applicator and needles. HDR simple refers to the treatment without anesthesia and OR, which results in fewer steps in the work- and patient flow.

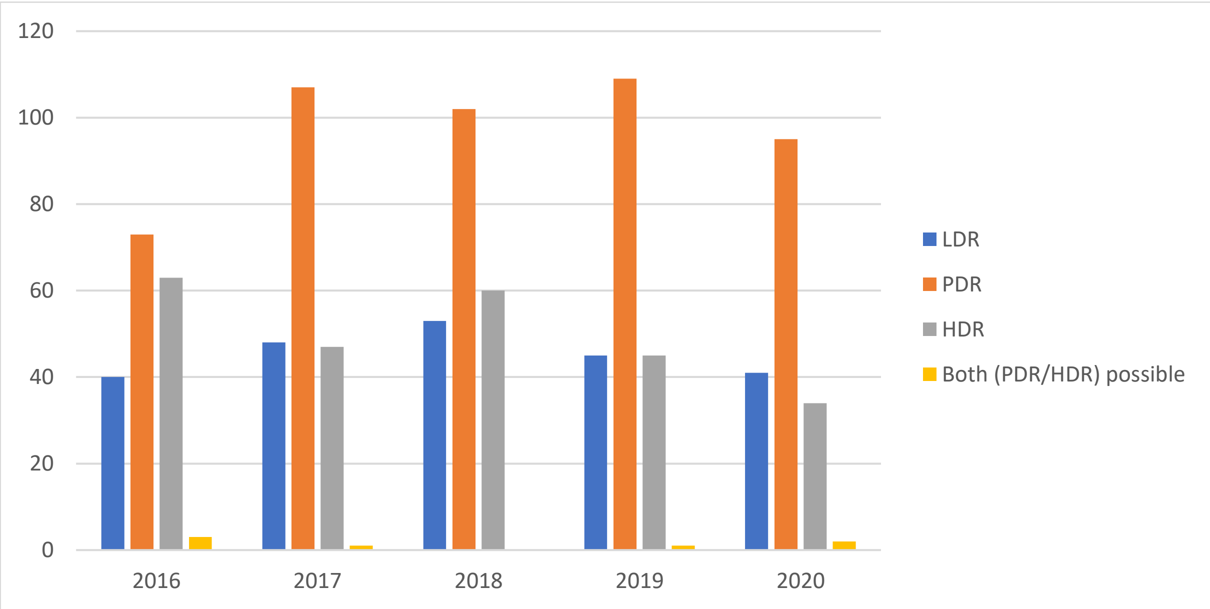

Figure 5. Patients divided into LDR, PDR, and HDR (n=969; data 2016-2020; source=Amsterdam UMC)

2.2.1 LDR

This section described the work- and patient flow of the LDR treatment. This treatment differs from other treatments because it does not involve irradiation using an afterloader. Therefore, this is the only treatment that does not take place on the nursing ward F5N where the brachytherapy bunkers are, but at the day center.

Workflow

As depicted in Appendix A.1: Workflow LDR, the workflow is divided into the preparation phase and treatment phase. Different lanes of the workflow indicate other jobs. The previous section largely explained the preparation stage. The only difference is a volume measurement of the prostate. After the first consultation, the radiation therapists plan a volume measurement. Directly after the volume measurement, another consultation is scheduled to discuss the measurement results and make a treatment plan. In contrast to the first consult, the radiation therapists schedule those appointments. After deciding to have an LDR treatment, the radiation therapists plan the patient in detail. Anesthesia is necessary for this treatment; thus, a consultation with the anesthesiologist must be scheduled. The case manager gives general information about the treatment. The permanent iridium sources must be ordered for each patient; this process is discussed in detail in Section 2.3.3. The last step for the preparation phase is preparing and collecting all material for the OR.

The patient needs to arrive a few hours before the intervention takes place. The treatment phase starts with admitting the patient to a bed, after which he gets prepared for the intervention. The epidural can be given at the day center or in the OR. Then, anesthesia will guide the patient to the OR while the radiation therapists take the material to the OR. One radiation oncologist and two radiation therapists are needed for this intervention, besides the anesthesia team and OR assistants. When the intervention is finished, the patient is taken back to the day center and can go home after a short recovery. After the intervention, the radiation therapists will register the used iridium sources and bring the other sources to the vault.

Apart from the preparation and treatment phases, the patient will return after four to six weeks for a consultation with the radiation oncologist and a CT scan. The radiation therapists use this CT scan to map out the placement of the sources to evaluate the treatment and count whether all the sources are still in the prostate. This procedure often takes place when a CT scan of several patients has been done so that the activities can be clustered.

Patient flow

The patient flow (Appendix A.2: Patient flow LDR) is also divided into the preparation phase and treatment phase. The lanes indicate the different departments. The preparation phase starts with a consult at the radiotherapy department, followed by a volume measurement and consult on another day. When the treatment plan is drawn up, an information session with the case manager and consult with the anesthesiologist will follow before starting the treatment phase.

The patient will only see two departments in the treatment phase: the day center for admission and recovery, and the OR for the intervention.

2.2.2 PDR

There is a difference between the PDR treatments for various tumor types. Therefore, we describe the work- and patient flow of the treatment with the largest number of steps. Those are the gynecological treatments. These treatments are often performed, and given the aggressive form of cancer, it is important to treat in time.

Workflow

Apart from other treatments, the workflow starts with an examination in anesthesia (Appendix A.3: Workflow PDR). The gynecologist performs this and a radiation oncologist is asked to attend. This way, they can decide together what the possible treatments are. Sometimes the patient will not go further in this workflow but get a treatment performed by the gynecology department. After the patient is referred to radiotherapy, she follows the usual route. Different from that route is a pre-brachy MRI after the first consultation. Based on the MRI imaging, it can be needed to make a preplan and custom build an applicator.

The treatment phase starts with admitting the patient. When the intervention is early in the morning, the patient is asked to get admitted to the nursing ward F5N the evening before, otherwise in the morning. On the day of the intervention, the patient will be prepared at recovery and get an epidural. While the nurses prepare the patient, the radiation therapists will take all material to the OR. One (or two in complex situations) radiation oncologist and two radiation therapists are needed for this intervention. When the intervention is performed, the patient will be brought to recovery by the nursing team. The MRI takes place after the patient is recovered. A nurse from F5N comes to recovery to transfer patient records and together with a radiation therapist the patient is brought to the MRI. The nurse from F5N will go back as soon as the patient arrives at the MRI. After the MRI is done, the patient is brought back to F5N with patient transport. The radiation therapist goes back to the radiotherapy department and starts with contouring critical organs and reconstructing the applicator after receiving the MRI images. The radiation oncologist contours the tumor, and another radiation oncologist second reads the contouring. It is also possible that the radiation oncologist starts with contouring critical organs. Next, the medical physicist checks the reconstruction. After that, the radiation therapist can make the treatment plan, which must be reviewed and optimized by the radiation oncologist. The medical physicist must check the treatment plan before sending it to the afterloading system. The afterloader will be connected when everything is approved and the treatment starts. At the end, the applicator needs to be removed by a radiation oncologist or ward doctor. The radiation therapists will clean all materials and bring them to sterilization. Some administrative tasks concerning the patients will close this workflow.

Patient flow

From the patients' point of view, this is a busy flow (Appendix A.4: Patient flow PDR). The preparation phase starts with the examination in anesthesia at an OR. Then a consult at the radiotherapy department, pre-brachy MRI, anesthesia consult, and information session from the radiotherapy department.

The treatment phase consists of admission at F5N, intervention preparation at recovery, the intervention at an OR, recovering, MRI, and the treatment and recovery from that at F5N. For the patient, the most waiting time occurs at F5N after the MRI scan, waiting for the treatment to start.

2.2.3 HDR-complex

A complex HDR treatment is the prostate. There is a difference between treatments for the prostate. The treatment with the most steps is chosen for this work- and patient flow. That treatment consists of three fractions. The second and third fractions are usually given on the second consecutive day in the hospital.

Workflow

Appendix A.5: Workflow HDR-complex depicts the workflow. The preparation phase starts the same as for the LDR, except for the volume measurement. This volume measurement is combined with placing gold markers. The gold markers are for external radiotherapy. The planning desk thus plans the appointment instead of the radiation therapists. The execution of the appointment is done by personnel of external radiotherapy. However, a radiation oncologist and radiation therapist must be available to look during a part of the volume measurement. This way, they can assess what will and will not be possible during the intervention. The treatment plan will be discussed in a consult afterward. Then the radiation therapists can schedule the patient for the intervention, a consult with anesthesia, and the patient will receive information about the procedure from the case manager.

The first day of the treatment is the same as for PDR. Typically, one radiation oncologist and two radiation therapists are needed for the intervention. Afterward, an MRI is performed, and both the radiation oncologist and therapist will check the position of the applicator. As opposed to PDR, the radiation oncologist and therapist will do the treatment planning together. After that, a CT scan will be made. Again, the applicator's position needs to be checked to ensure the irradiation is accurate. The images of the MRI and CT will be matched before the treatment plan can be finalized and inspected by the medical physicist. The second and third fractions take place on the second day. In the morning, the patient gets another CT scan. The location of the applicator is checked again. Then, the MRI and CT images can be matched to optimize the treatment plan and start the irradiation for the second and third time. Finally, the radiation oncologist must remove the applicator.

Patient flow
From the patient perspective, this is the flow with the most steps (Appendix A.6: Patient flow HDR-complex). The preparation phase starts with a consult followed by an appointment to place the gold markers and get a volume measurement. Then, a consult with anesthesia occurs, and they get informed about the treatment procedure.

They see many departments on the first day of the treatment. Starting with F5N for admission, then recovery for intervention preparation, the OR for the intervention, back to recovery before the MRI can take place, then F5N to wait for the CT-scan on the radiotherapy department, and finally back to F5N where the treatment will take place. The next day starts with a new CT scan followed by fraction two and eventually fraction three. After some recovery time, the patient is discharged.

2.2.4 HDR-simple
A simple HDR treatment is the vagina top ring. Such treatment consists of multiple fractions which are given on different days. This is a treatment without needles, only an applicator. Therefore, the patient can come to the hospital shortly before the appointment and go home immediately after the appointment.

Workflow
Appendix A.7: Workflow HDR-simple depicts the workflow. The preparation phase consists of the same steps regarding registration, triage, and consultation as the other treatments. The material needed for this intervention can be prepared in the morning or the day before the treatment. The patient is admitted to F5N, and the intervention is performed by one radiation oncologist and one radiation therapist. A CT scan will be made for the first fraction, which is necessary for making a treatment plan. The CT, contouring critical organs, reconstructing the applicator, and making the treatment plan are all done by the radiation therapists. The radiation oncologist checks the treatment plan. The medical physicist reviews the reconstruction and the treatment plan as soon as the radiation oncologist has approved. Then the treatment can start. The applicator for this treatment can be removed by the nurses; thus, the radiation oncologist does not need to wait during the treatment. The second and third fractions are going faster. There is no CT scan to be made. The applicator will get placed and the irradiation can start immediately. The same plan as for fraction one will be used. The case manager will call the patient for information between the first and second fractions.

Patient flow
Looking from the patient's point of view, this flow has the fastest route (Appendix A.8: Patient flow HDR-simple). The patient will only be in the radiotherapy department for the consult and information. In the treatment phase, everything will take place on F5N, except for the CT for the first fraction, which takes place at the radiotherapy department.

After treatment
After the irradiation and the patient has recovered from that, the work- and patient flow stop. However, this may not be the end of the treatment. A patient will get aftercare in the form of telephone consultation a few days after the treatment, multiple follow-up checks weeks after the treatment, and standard check-ups with their original physician (gynecologist, urologist). This is not included in the process descriptions.

2.2.5 Summary work- and patient flows
Table 2 summarizes the work- and patient flows into important process steps of each care plan. This table emphasizes the differences between all flows. For example, the HDR-simple treatment has the

least steps and takes the least time. On the other hand, the LDR treatment also has a short workflow on OR-day but requires preparation and work a few weeks after the OR intervention.

Process step	LDR	PDR	HDR-complex	HDR-simple
Consult in anesthesia		X		
Pre-brachy MRI		X		
Preplan		X		
CT	X (4-6 weeks later)		X	X
MRI		X	X	
Volume measurement	X		X	
Single-day admission	X			
Multi-day admission		X	X	
Single-day admission multiple times				X
Ordering iridium sources	X			
Applicator removal by radiation oncologist		X	X	

Table 2. Summary of essential process steps of each care plan

2.3 Planning and control

In this section answer is given to Question *1.2 How can the planning and control mechanisms be described?*. The planning and control of the brachytherapy is discussed based on the Healthcare Planning and Control framework of Hans et al. (2011). This framework uses a hierarchical decomposition between strategic, tactical, offline and online operational planning and uses the following managerial areas: medical planning, resource capacity planning, materials planning, and financial planning. The main area for this research is resource capacity planning, but it also takes some aspects of other areas.

2.3.1 Strategic level

The strategic level addresses the structural decision-making with a long planning horizon. Decisions made in this phase affect all other decisions that can be made in the coming phases. Due to the relocation of the radiotherapy department, new strategic decisions must be made. One of those decisions is the layout of the department and how many imaging machines like MRI and CT to buy. How many brachytherapy bunkers to install and whether to equip them with HDR or PDR afterloaders and maybe even a mobile CT. Whether to place an MRI in the OR room or a separate room. How many recovery rooms to make and with how many beds. Whether to perform smaller interventions in a separate invention room or a bunker. All those decisions and acquisitions are long-term and are not easy to change once the department is built. Those decisions will also determine a new workflow and how quickly and how much patients can be served.

The mission of brachytherapy is to achieve the highest chance of healing with the lowest chance of permanent damage. They do this with attention to the individual patient and using state-of-the-art techniques. While designing the new department, they must take possibilities for new techniques into account. One of those new techniques will be operating with CT-imaging instead of the current ultrasound guiding to adjust while implementing the needles. This implies that medical intervention protocols will change to adaptive brachytherapy. The vision of brachytherapy is to create the possibility to treat new indications. Therefore, it is necessary to be able to treat more patients in a year. This growth must be calculated when designing the department on a strategic level. This can result in more beds and brachytherapy bunkers, and a hospital layout that creates an optimal work- and patient flow.

2.3.2 Tactical level

Block scheduling of the radiation oncologists is an essential aspect at tactical level. While writing this report, the department has made a new block schedule for the radiation oncologists, including time windows for small interventions in an intervention room, prostate volume measurements, gynecological examination under anesthesia, and new patient consults. The first two activities are important because the radiation therapists experienced difficulties planning radiation oncologists for those activities. Tuesday is the OR day; all radiation oncologists have an empty schedule for this day. Therefore, other work tasks like new patient consults, staff meetings, research, supervision, et cetera are planned on other days. As a result, almost no space is left unplanned for most radiation oncologists, which makes it difficult for radiation therapists to plan small interventions and volume measurements.

The new block schedule is now made so that every day there are two possibilities for a small intervention or volume measurement equally distributed among the radiation oncologists, including a backup radiation oncologist for each time block. This has been done so that the number of small interventions and volume measurements can continue every week without having issues placing such activities in the agendas of radiation oncologists. However, the work of the radiation therapists has not been examined here. They can schedule up to two volume measurements in a row. But to perform a volume measurement, ultrasound equipment must be set up. It would save time for the radiation therapists to plan multiple volume measurements in succession. However, this is not possible with the current scheme. This does not apply to small interventions since applicators, afterloaders, and beds must also be available.

Besides block scheduling of the radiation oncologists, block scheduling is also done for patients that need an OR intervention. When those patients come into the system for appointment planning, the radiation therapists will look right away for the first available OR date. The patient will already be planned for this date in Outlook without detailed planning and without planning it into the OR system, Snapboard. Just to know that it is possible to treat the patient in time. If this is not the case, they may still be able to switch places with less urgent patients. Or they look for another option, such as asking OR time from gynecology. As soon as it is clear that the patient needs brachytherapy, it should be immediately apparent whether they can be scheduled in time. This way, external radiotherapy knows when to start their treatment if the patient needs that. External radiotherapy is rarely the bottleneck for planning a patient. For that reason, external therapy waits for brachytherapy to plan the patient first. If the patient also needs chemotherapy, those treatments will be planned in cooperation with external radiotherapy. If it is not possible to schedule a patient in time, the radiation oncologist needs to ask for an extra slot on the OR program.

2.3.3 Offline operational level

Operational level planning involves short-term decision-making related to executing the healthcare process. Offline operational level reflects the planning of operations made in advance. One example is scheduling the patients in detail. The radiation therapists perform this task. Every week when new patients have their consult, the radiation oncologist decides what treatment is possible. Sometimes an extra examination in combination with a new consult is needed. The radiation therapists will schedule this. As seen in the work- and patient flows, different types of treatment result in different activities to schedule. For example, there is a big difference between patients who need anesthesia and thus will get the intervention in the OR room and patients who do not require anesthesia and will get the intervention in an intervention room.

Necessary scheduling tasks for patients that go to the OR include:

- Planning the pre-MRI (depending on treatment) using Mosaiq and EPIC,
- Booking an information session about the treatment using EPIC,
- Claiming a spot on the pre-assigned OR-room using Snapboard,

- E-mailing anesthesia with the OR date to let them plan a consult to see whether the patient is fit for the intervention using Outlook,
- Booking a consult with the radiation oncologist for a few weeks after the intervention in cooperation with Desk 1.

All those appointments need to be planned simultaneously because there are rules for the number of days or weeks that need to be between a consult and OR intervention. If one of those appointments cannot be made, they might need to shift the whole process by a week since there is only one OR day available per week. Brachytherapy must look at the agendas of the radiation oncologists, the agenda of nursing ward F5N, and the agenda of the OR. Also, if the applicator and afterloaders needed for the intervention are available.

For treatments that can take place in an intervention room, for example, the vagina top ring, the scheduling process is shorter. There is no need for anesthesia and an OR. Besides that, those patients mostly do not need an MRI and only a CT-scan for the first fraction. Thus, there are more possibilities in a week to schedule the patient, but, as explained in Section 2.3.2, the radiation oncologists are more difficult to schedule.

The brachytherapy team uses multiple planning and information systems. Mosaiq is the department-based system needed for all the appointments and billing. EPIC is used throughout the hospitals as the patient file in the OR and at the MRI. Outlook is used as mail and agenda. For example, with the nursing ward F5N, they share an agenda for all the brachytherapy bunkers in which they let the nursing ward know which patient to expect and when they will go to the MRI and the OR. In this case, the nurses know what to expect and when the patient will return to the ward. There is communication between EPIC and Mosaiq, but that is limited. This results in double work for the radiation therapists and the risk of errors. To avoid making mistakes, all appointments of every scheduled patient are checked by another radiation therapist.

Most scheduling activities relate to resource capacity planning, as the appointment and workforce need to be planned. But it also involves medical planning to a certain level. The radiation oncologists fill in the type of treatment, but the radiation therapists will also consult the patient file to see if they must consider certain things. For example, a patient with diabetes needs to go first on an OR-day because staying sober for the intervention can be a difficult combination with diabetes. There are planning protocols for each treatment, but it still needs extra work and customization. This customization makes planning an enormously time-consuming activity.

The necessary materials will also have to be ordered. This is especially important for the LDR treatment, where the iridium sources must be ordered. When they arrive at the goods receipt hall in the hospital, the radiation therapists must go and pick them up. Then register the sources in the system Jetspeed and take them to the vault. On the day of the intervention, the sources need to be picked up from the vault. After the sources have been placed, it must be registered how many and which sources have been placed, and the other sources must return to the vault. Knowing that the vault, the radiotherapy department, and the OR complex are not on the same floor in the hospital, it takes much time to execute these steps.

2.3.4 Online operational level

The online operational level addresses process monitoring and reactive decision-making. An example from the materials planning managerial area can be rush ordering the sterilization of an applicator. It does not often happen because the availability of applicators is considered when planning the patients, and sterilization usually takes two days. But if two patients need the same applicator close behind each other, an urgent procedure can be requested, meaning 24 hours. If there is even more urgency, it is possible to walk to the sterilization department and request a rush order of, for example, 2 hours.

Another online operational level difficulty that is battled frequently is the workflow on an OR day. An OR day is usually filled with three interventions. The first two interventions are PDR or HDR and require many activities after the intervention, as is shown in Section 2.2. The last intervention is typically an LDR because this patient does not need any more time from the radiotherapy department after the intervention is done. As soon as the PDR and HDR patients are ready in the OR, they will go to recovery. An attending radiation therapist will leave the OR to wait for the patient to be ready for the MRI. He or she takes the patient to the MRI to help with making the scans. And will start working on those as soon as the MRI is done. The speed with which the patient is ready in the OR and how fast the patient has recovered and been discharged from recovery is determining whether they need to wait on the MRI slot they booked or are getting late for that slot. The first is not ideal since the process could have been faster if the MRI slot had been earlier. The second is also not ideal because this brings a lot of stress, calling to recovery hoping they release the patient soon, calling with the MRI to defend their spot on the MRI although they are too late. MRI is a fully booked program, where scanning one patient can take approximately 45 minutes. That does not make it easy to shift with patients. And at the end of the day, MRI will not start a scan in overtime. As soon as the MRI is done, the radiation therapists have back control of the workflow, and they can start with the treatment plan phase. And how fast they go through contouring the critical organs and reconstructing the applicator will determine at what time the treatment plan is ready. The radiation oncologist needs to contour the tumor and optimize the treatment plan; thus, he or she needs to be back from the OR. Optimization of the treatment plan cannot start earlier than the radiation therapists have worked everything out. When all previous activities took longer than planned, it can be the case that the radiation oncologist is not completely available anymore because of scheduled MDOs in the afternoon. A lot can happen during the process that slows down the whole process because many steps can only be performed successively. In the end, the patient is waiting in bed with all needles in place for the treatment to start, which is not a very pleasant position. This waiting time needs to be minimum to serve patient-friendly and to treat as many patients as possible.

Patients may cancel the intervention, but this does not happen on a day's notice. The same holds for emergencies. There are patients with a fast-growing tumor that need to be helped as soon as possible, but this process will belong to offline operational planning since those patients do not come in and must be treated the same day.

2.4 Performance

Question *1.3 What is the performance of the brachytherapy process?* is answered in this section. As described in the introduction, the goal is to be able to treat more patients faster with the available resources, which is crucial for an effective result of good tumor control with a low risk of (late) toxicity and limitation of psychological complaints. Performance indicators for the brachytherapy process can be divided into waiting time for the patient, waiting time for employees, and utilization.

2.4.1 Patient waiting time

Patient waiting time is divided into entry time, access time, and Lead time. The entry time is the time between referral and the first consult. Access time is the time between the first consult and the first day of treatment. With lead time we mean the time between the end of the intervention and the start of the irradiation.

Entry time

Patient-related waiting time starts with the entry time. The entry time is measured from the moment the patient's file is made at the radiotherapy department until the date of their first consult. Table 3 depicts the average entry time for the first consult. We conclude from this table that there has been a small increase over the years, but the increase in the number of days is not significantly high. The radiotherapy department aims to schedule the consultation within seven days.

	2016	2017	2018	2019	2020
Average entry time	6.8	5.1	7.1	7.4	7.3

Table 3. Average entry time in days (n=969; data from 2016-2020; source=Amsterdam UMC)

Access time

According to the NVRO (n.d.), 80 percent of the treatments must take place within 21 days and 100 percent of the treatments within 28 days. This norm has been drawn up for radiotherapy and not for brachytherapy specifically. Nevertheless, the department tries to aspire to this standard. In many cases, the first treatment is external radiotherapy. For calculating the access time, the following treatments are considered: cervix fletcher, endometrium, prostate HDR, prostate I125, vagina, and vagina top ring. These account for 83% of the total treatments. Figure 6 depicts the access time for the years 2016 up to and including 2020. The first column of each year includes the treatments: cervix fletcher, endometrium, prostate HDR, vagina, and vagina top ring. The second column is the same as the first, but with the prostate I125 included. This distinction is made because the prostate I125 treatment is not planned with the same urgency rules, as they use 12 weeks instead of 21 days as standard. For that reason, the overall picture deteriorates. Treatments with an access time longer than 80 days were considered as outliers, except for prostate I125. Treatments postponed due to the patient's choice are not considered. Treatments without complete data and the possibility to calculate the access time were also omitted. We conclude from Figure 6 that the norm of 80% in 21 days and 100% in 28 days is not realized.

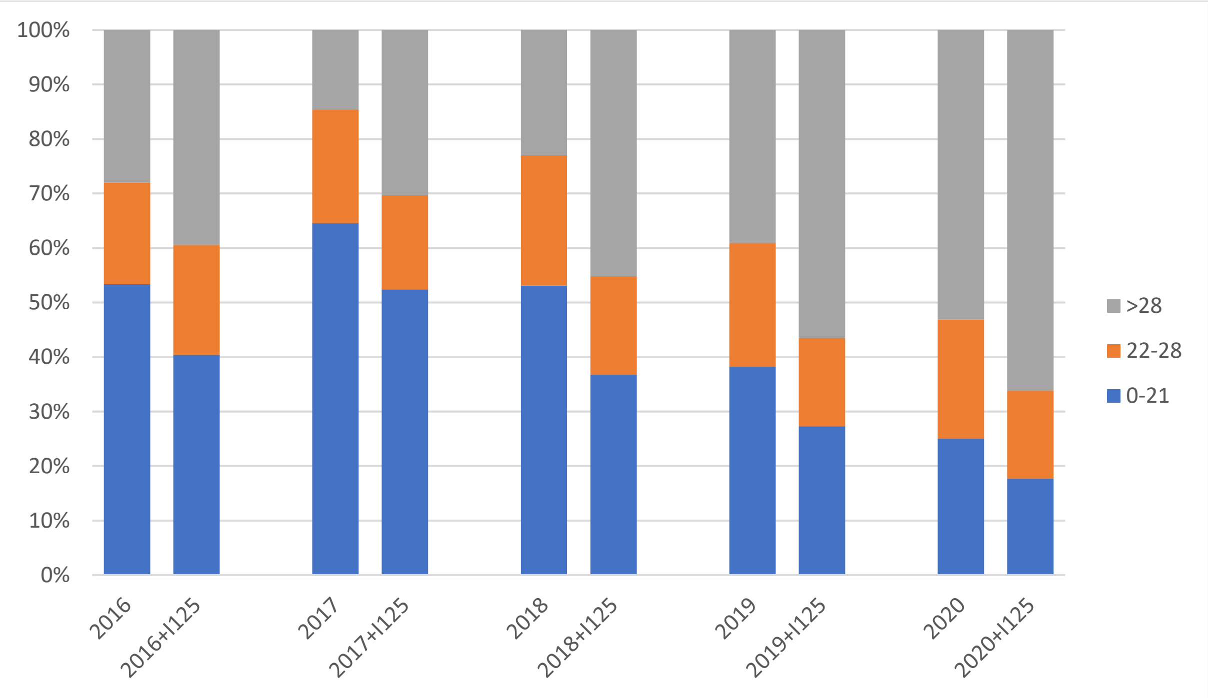

Figure 6. Access time for brachytherapy patients (n=711 ; data from 2016-2020, source= Amsterdam UMC)

To give an idea of the average access time each year, this is also calculated without prostate I125 and with prostate I125. Table 4 depicts the average access time in days. From Figure 6 in combination with Table 4, we conclude that the average access time is too long, except for 2017. There are too many patients with too long access time, and there is a negative trend over the years.

	2016	2017	2018	2019	2020
Without prostate I125	24.9	21.0	23.5	30.2	30.6
With prostate I125	31.6	33.6	39.8	56.9	55.0

Table 4. Average access time in days (n=711; data from 2016-2020, source= Amsterdam UMC)

For patients that do not need brachytherapy the average access time is also calculated. This way we can see if the long access time is caused by the brachytherapy or plays a role there too. Table 5 depicts the average access time of treatments for patients that do not need brachytherapy. Treatments postponed due to the patient's choice are not considered. Treatments without complete data and the possibility to calculate the access time were also omitted.

	2016	2017	2018	2019	2020
Access time	15.6	11.8	12.7	14.0	19.8

Table 5. Average access time radiotherapy in days (n=5600; data from 2016-2020, source= Amsterdam UMC)

The average access time is within 21 days for all years. Figure 7 depicts the percentage of treatments within 21 days and 28 days. It seems to follow the same trend as Figure 6 for the brachytherapy patients, with 2017 as the best year and from then a descending trend. We conclude that patients that do not get brachytherapy can be treated within the NVRO norm.

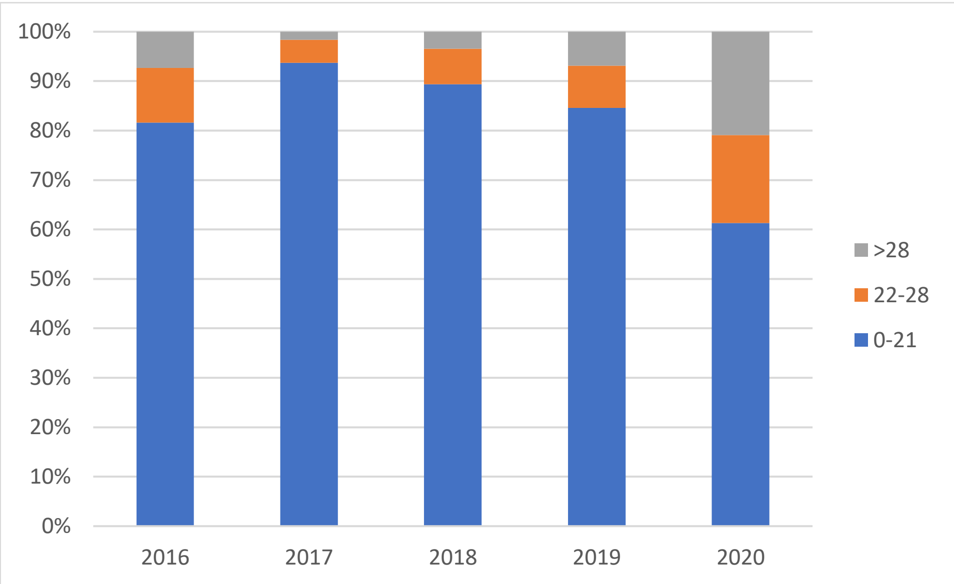

Figure 7. Access time for non brachytherapy patients (n=5600; data from 2016-2020, source= Amsterdam UMC)

Lead time

Besides waiting for the treatment, another performance indicator can be calculated, namely the lead time of the treatment, which is from the end of the intervention until the irradiation starts. The irradiation time is not included since that time cannot be changed and varies per patient and treatment plan. Lead time can only be calculated for OR interventions and not LDR treatments because they do not have more treatment steps after the OR. There is also no need to calculate this for interventions in the intervention room because those patients are less dependent on irregularities as their flow is shorter and involves fewer departments and personnel. The average lead time over the years is depicted in Figure 8.

	2016	2017	2018	2019	2020
Lead time	6:08	5:40	6:04	5:56	5:39

Figure 8. Average lead time in h:mm (n=372; data from 2016-2020, source= Amsterdam UMC)

2.4.2 Personnel waiting time

Waiting times indicated by personnel includes three types of waiting time: waiting for the MRI timeslot, waiting for the intervention to start at the OR, and waiting for approval on the treatment plan.

Waiting for MRI

Because the interdependence of the radiotherapy department with many other departments is high, processes may be put on hold due to reasons outside the radiotherapy department. One of those interdependencies is with the radiology department for using the MRI. There are many time windows the brachytherapy can schedule their patients. But when there are time windows left, the radiology will fill them with other patients to fully utilize the MRI. The brachytherapy department does not deliver many interventions per year, and many of these interventions are very complex and have variability in the operation times. This makes it difficult to choose a good time slot for the MRI. Because as soon as the intervention runs out of time, the MRI slot is gone, and if you structurally book the MRI late, this causes a lot of unnecessary delay in the process. For this reason, we choose to look at the time between the actual ending time at the OR and the MRI time slots booked.

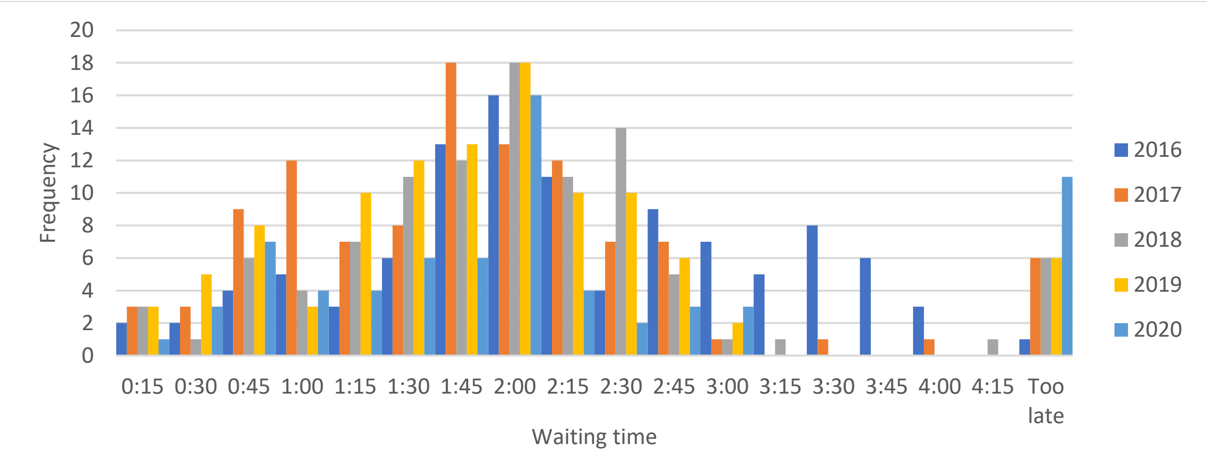

Figure 9. The time between OR and MRI (n=491; data from 2016-2020, source= Amsterdam UMC)

Figure 9 depicts the time between the end of the OR intervention and the booked MRI slot. We see that often there is a long period between the OR and MRI. But, as seen from the patient flows, the patients are recovering from the intervention. An acceptable recovery time is one hour. This means that all treatments with a shorter waiting time than an hour cannot reach the MRI on time. That is in 18% of the cases. In 6% of the cases, the patient has precisely one hour at recovery. In the other 76% of the cases, the patients waiting time between the OR and the MRI was longer than one hour, which causes undesirable waiting time.

Waiting for start intervention at the OR

Besides waiting for the MRI, employees mentioned that there is waiting time at the OR. They are waiting for the anesthesiologists to have the patient ready. When looking at the difference between the planned starting time of the intervention and the actual starting time documented in EPIC, the difference is minimal. Knowing that waiting times caused by the previous intervention taking longer than calculated are included. Table 6 depicts the average difference between the actual starting time and planned starting time for each year.

	2016	**2017**	**2018**	**2019**	**2020**
Average difference	0:09:47	0:11:04	0:11:51	0:20:56	0:18:45
Standard deviation	0.0065	0.0086	0.0073	0.0284	0.0161

Table 6. The average difference between actual starting time and planned starting time at OR in h:mm:ss (n=723; data from 2016-2020, source= Amsterdam UMC)

Waiting to approve the treatment plan

It is also indicated that waiting for the radiation oncologists to optimize and approve the treatment plan sometimes occurs. This usually occurs when the whole process has run out, and the radiation oncologists are scheduled with other tasks when the treatment planning should be finished. However, this cannot be verified with data since the programs in which they work remain open, and it is not possible to make clear when the radiation therapists are ready and when the radiation oncologists join. Radiation oncologists confirm this feeling. They indicate that they have a certain time off for brachytherapy, and as soon as the brachytherapy is planned, other tasks are assigned, for example, external radiotherapy. If the process is running on schedule, the scheduled time should be sufficient. However, it often happens that there is a delay somewhere in the process.

2.4.3 Utilization resources

When evaluating the utilization of resources, we focus on the utilization of the brachytherapy bunkers, the afterloaders, the OR-time, and the MRI.

Utilization of brachytherapy bunkers and afterloaders

For the brachytherapy bunkers, a distinction is made between PDR and HDR. Currently, there are two PDR and one HDR afterloaders available. The number of interventions performed in 2016 up to and including 2019 has been examined. For each type of intervention, a time indication has been given for having the bunker in use. The number of interventions times the number of hours determines the utilization of the bunkers. Table 7 depicts the utilization of the bunkers. The utilization includes admission in advance, waiting time, treatment time, recovery, and aftercare. This is the time a patient is in the bunker, even though the afterloader is not in use all the time.

	2016	**2017**	**2018**	**2019**
Utilization HDR-bunker	64%	56%	61%	62%
Utilization PDR-bunkers	77%	89%	78%	76%

Table 7. Utilization of brachytherapy bunkers (data from 2016-2019, source= Amsterdam UMC)

The utilization of the afterloaders is lower because there is a lot of waiting time before the irradiation starts and recovery time after the irradiation has ended. For interventions executed in the OR, this difference will be higher since there is more preparation time needed. This can be done more efficiently by using a separate room for admission and recovery but comes at the cost of lower patient comfort since they will need to switch rooms. Table 8 depicts the utilization of the afterloaders. This is calculated by the actual time the afterloader is connected to the patient. For both tables, the available time has been calculated considering time for maintenance, holidays, patient changes, and cleaning.

	2016	**2017**	**2018**	**2019**
Utilization HDR-afterloader	6%	7%	7%	7%
Utilization PDR-afterloaders	42%	48%	42%	42%

Table 8. Utilization afterloaders (data from 2016-2019, source= Amsterdam UMC)

Utilization OR-time

The utilization of OR time is evaluated in two ways. One evaluates the use of the available time on the assigned OR days, and the other looks at the number of patients treated in relation to the assigned treatment places in the OR. Data is used from 2016 up to and including 2019. Data from 2020 is not used because there have been many temporary adjustments to the OR program due to COVID-19.

The operating room is available from 8:00-16:30, which is 8.5 hours, and OR management does not want overtime. The last intervention can start if the expected duration fits before closing time. If that is not possible, it is up to the medical coordinator that day to determine whether the last intervention can still be started. The actual ending time of the last intervention minus the actual starting time of the first intervention is the used OR-time. This is used to calculate the utilization. To detect outliers, boundaries are set on 95% of the data. The lower bound of a single operation time is 1:04 hours and the upper bound 3:17 hours, with a mean of 2:04 hours and a standard deviation of 38 minutes. Calculating with the mean plus standard deviation, only three interventions fit in a full OR day with little time left. This means that if there is 68% utilization or less, another intervention could have been performed. And if there is 36% utilization or less, even two more interventions could have been performed. Figure 10 shows the number of OR days that fall into such utilization grades. When the utilization was more than 100%, there was a violation of the OR closing time. Each year between 13-23% of the assigned OR slots is not used. This is mainly caused by a shortage of personnel or place in the bunkers. Unfortunately, the reasons for not using the assigned OR-time are rarely noted.

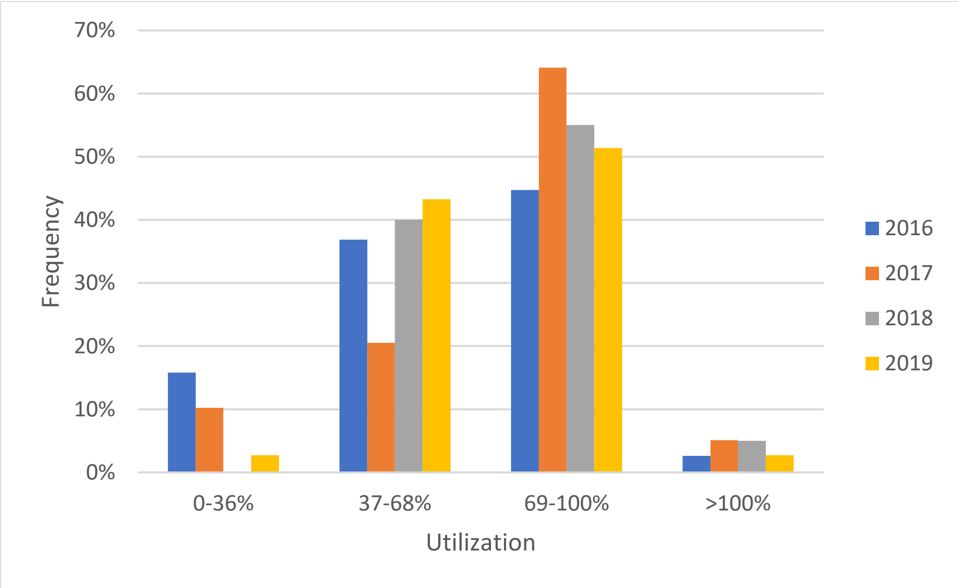

Figure 10. Utilization of OR time (n=154 ; data from 2016-2019, source= Amsterdam UMC)

Figure 11 depicts the ratio between the concept number of intervention slots, which are the interventions from the concept OR schedule, the assigned number of intervention slots, those are approved by the OR planner a few weeks before the actual OR day, and the number of interventions performed. The OR planner only assigns whole days to the brachytherapy department, which is equivalent to three interventions. The concept planning can deviate from the actual OR days, which can be caused by a changed situation at the OR complex or, for example, due to maintenance in the brachytherapy department. In 2016, the concept planning was much lower, resulting in many additional OR days. We conclude that the assigned days are structural to low for the performed number of interventions. This, in combination with not using the days to their full capacity, results in doing a lot of interventions on other days. This gap is mainly solved by using or exchanging time from the gynecology department.

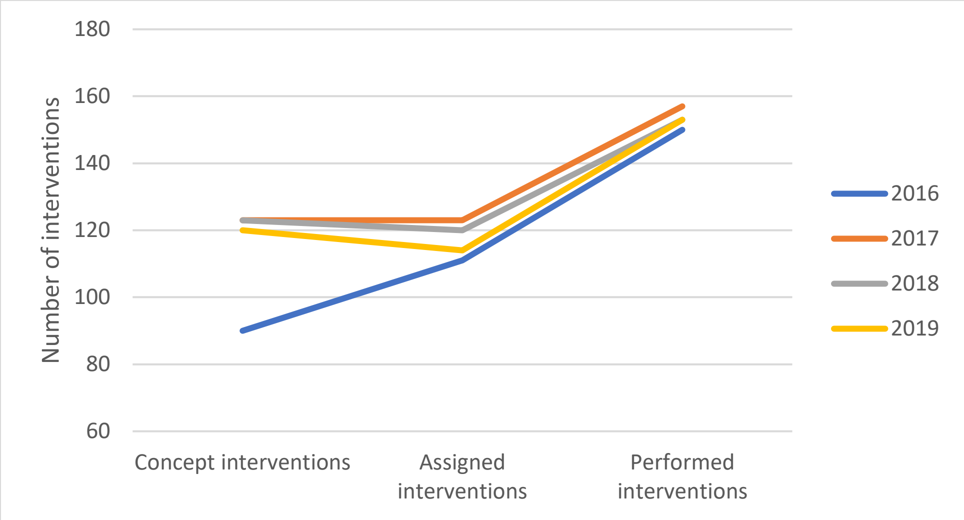

Figure 11. Interventions at OR (data from 2016-2019, source= Amsterdam UMC)

Utilization MRI

The radiotherapy department has bought an MRI in cooperation with radiology. Before COVID-19, they had a schedule of 14 hours where radiotherapy could book MRI slots. During COVID-19, that is brought back to 12 hours because there is a shortage of personnel at radiology and less OR time available. Due to a lack of data and the fact that the MRI time is shared with the entire radiotherapy department, it is not possible to calculate the utilization rate of the MRI for brachytherapy. But it is clear that the available times are not fully used. It is possible to negotiate more time with the radiology department because both departments are entitled to 50% of the time. However, this is not necessary because the given hours are not fully utilized.

The availability of applicators does not raise many questions yet. But must be taken into consideration when thinking of serving more patients per week.

2.5 Problems and bottlenecks

After looking at the workflow, patient flow, and the performance of the department, problems and bottlenecks became clear. These are mapped in a problem cluster in Figure 12. The problem cluster helps to connect causal links between various problems. The main problems are the long lead time of the treatment, low patient comfort, the department not being future-proof, and long access time. The grey, orange, and yellow boxes are causes, core influencable problems, and non-influencable problems. After this section, an answer can be given to Question *1.4 What are the core problems that prevent brachytherapy from treating more patients faster?*.

To answer which factors affect the lead time of the treatment, we can read from the problem cluster that excessive waiting time of the patients is one factor. This is a consequence of the MRI time window that does not fit with the time a patient is discharged from recovery. This is due to the low flexibility of the MRI time slots, which is agreed upon with radiology. On the other hand, making a treatment plan takes a long time. This is caused by protocols that are not up to date, radiation oncologists that are not always directly available, and radiation therapists that are not fully trained. It is also possible that there is no nurse available to hand over the patient from recovery to the nursing ward F5N. This stagnates the process and will cause a longer lead time of the treatment.

The causes for low patient comfort are partly the waiting time of the patient and partly the layout of the hospital. Patients that have an intervention in the OR complex must travel through many departments. The layout of the hospital is a strategic level decision and should be considered while designing the department for the new location.

The department not being future-proof is partly caused by the layout of the hospital limiting the space for new or extra equipment. Besides that, there are some capacity problems. There is not enough OR time available. However, the data also shows that the OR time is not fully utilized. That is caused by the under-capacity of the radiation therapists. This problem could be solved by rearranging the available OR time. If there is not enough staff available to work in the OR for a whole day, it may be possible to work in the OR during parts of the day.

The last problem depicted in the cluster is the long access time. We identified a few reasons. First is the trouble of finding an OR slot caused by having too little OR time. Second, the under-capacity of radiation therapists holding back utilizing the full OR-time. And the knowledge gap of the radiation therapists, caused by not being fully trained yet, results in a slower process than can be. As explained earlier, finding a radiation oncologist for the small interventions is difficult, which results in treating fewer patients a week. Besides that, the radiation therapists lose time because of the ad hoc working environment and the complex and time-consuming activity of making detailed patient planning. It might be possible to make the working environment less ad hoc by making use of more block scheduled activities to some extent.

Concluding, given the complex process which involves many steps, and some of those steps are in collaboration with other departments, many problems can be identified as root causes. Not all core problems can be handled internally, but there are a few core problems that can be tackled in the current situation or adapted to in the new situation. Those are:

- Cooperation with radiology about the MRI,
- The layout of the hospital,
- Utilization OR-time
- Fluctuating agendas,
- Knowledge gap radiation therapists.

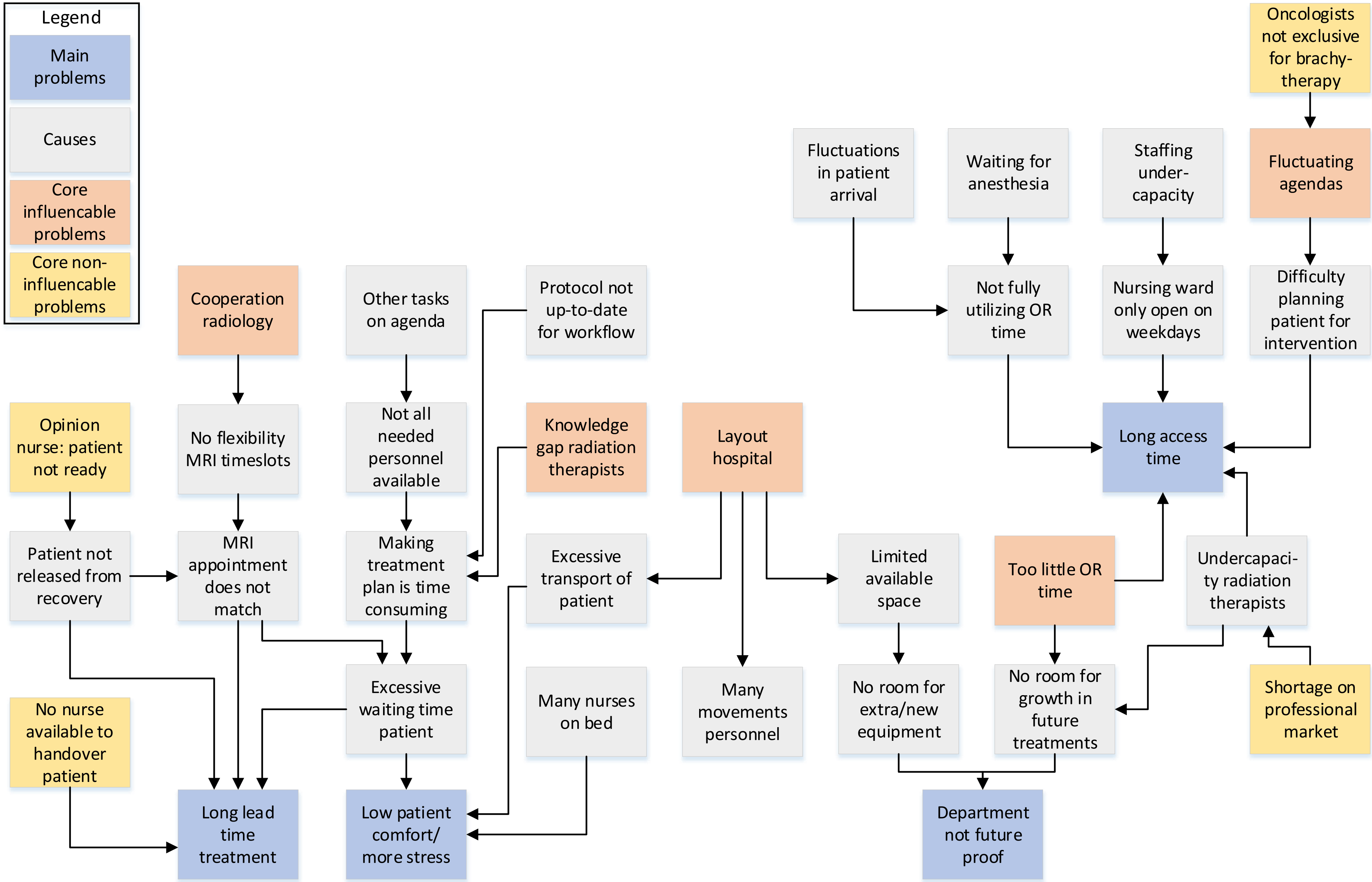

Figure 12. Problem cluster

2.6 Conclusion

In this chapter, the current situation of the brachytherapy department is described. In addition to describing the processes and work- and patient flows, the performance is measured based on patient waiting time, personnel waiting time, and utilization of resources. A few important conclusions are:

- the entry time is around 7 days,
- the access time is too low and has an increasing trend over the years,
- the time between the OR and the MRI varies a lot, which causes that it often does not connect well with the MRI timeslot,
- the utilization of the HDR-bunker is around 7%,
- OR-time can hardly be fully utilized due to, for example, personnel, while there is also too little time available over the year.

Concluding, Amsterdam UMC's brachytherapy department experiences a few problems. Based on these problems, we identified five core problems that can be tackled in the current situation or adapted to in the new situation in the context of this research. Those are:

- Cooperation with radiology about the MRI,
- The layout of the hospital,
- Utilization OR-time,
- Fluctuating agendas,
- Knowledge gap radiation therapists.

To address these core problems, we look at the various levels of planning and control. At strategic level, we focus on how to design the new department; how to make a resource capacity planning concerning the brachytherapy bunkers, afterloaders, recovery beds, and applicators; and how to make a workforce planning that utilizes the OR-time. At tactical level, we look at resource capacity planning concerning block scheduling of small interventions and volume measurement. At operational level, we look at the patient-to-appointment assignment and daily patient flow. In Chapter 3, we focus on models and methods available in the literature regarding resource capacity management at strategic, tactical, and operational level to address these problems.

Chapter 3: Literature study

This chapter discusses the literature related to our main research question. Section 3.1 covers the literature at strategic level, Section 3.2 at tactical level, and Section 3.3 at operational level. Finally, Section 3.4 provides the conclusion of the literature study.

3.1 Strategic level

Following from the previous chapter, facility layout and capacity dimensioning are the main topics at strategic level.

3.1.1 Facility layout

Facility layout concerns the positioning and organization of various physical areas in a facility (Hulshof et al., 2012). For example, the positioning of departments in a hospital and the different rooms and machines in a department. For the brachytherapy, it includes consultation rooms, intervention rooms, treatment bunkers, position of imaging machines, offices, et cetera.

There are various forms of facility layout, namely the static facility layout problem and the dynamic facility layout problem. The static approach assumes constant material flow between pairs of departments. The dynamic approach is based on a multiperiod time horizon, where the material flow changes and layout rearrangements may be planned (Balakrishnan & Cheng, 1998). The dynamic approach consists of selecting a static layout for each period of changed flows. Multiple algorithms can be used to solve the dynamic facility layout problem. Balakrishan and Cheng (1998) looked at multiple research papers and concluded that the dynamic facility layout problem can be tackled using a variety of algorithms. These are divided into four categories, depicted in Table 9.

Category		Algorithm
Equal size departments	Deterministic material flow	Dynamic programming
		Pairwise-interchange
		Genetic
		Tabu-search
		Comparison, branch and bound
		Bounds and fathoming
	Stochastic material flow	Branch and bound, robustness
		Markov processes
		Simulation
Unequal size departments		Linear programming
		Mixed integer programming

Table 9. Summary of algorithms in the dynamic facility layout problem (Balakrishnan & Cheng, 1998)

Most of the research focused on equal-sized departments and deterministic material flow. When all departments have equal size, the static layout problem can be modeled as a quadratic assignment problem (QAP) (Koopmans & Beckman, 1957). In reality, it is not common to work with equal-sized departments. New algorithms are developed, to handle different sizes. A well-known heuristic is CRAFT (computerized relative allocation of facilities techniques). CRAFT is an improvement heuristic that uses pair-wise interchange to improve the starting solution (Hartl & Gansterer, 2010). The objective is to minimize the sum of the layout rearrangement costs and the material handling costs over the planning horizon. The dynamic facility layout problem can also be solved using tabu-search. Tabu-search uses pairwise interchange while maintaining a tabu-list to prevent cycling and uses the best exchange in each iteration. The procedure stops after a predefined number of unsuccessful moves, or when an iteration limit is reached. Each tabu-search heuristic can be designed with a variety of parameters. Lacksonen and Enscore (1993) proved that a tabu-search can provide a good solution.

All the above-mentioned algorithms came from papers that are not specifically designed for healthcare layout. Therefore, a specific search was made for literature applied in the healthcare sector. Halawa et al. (2020) did a systematic literature review into evidence-based healthcare facility design and identified three categories: *architectural options and concepts, layout modeling and optimization, and workflow and resource planning*. Figure 13 depicts the various research topics found in the literature.

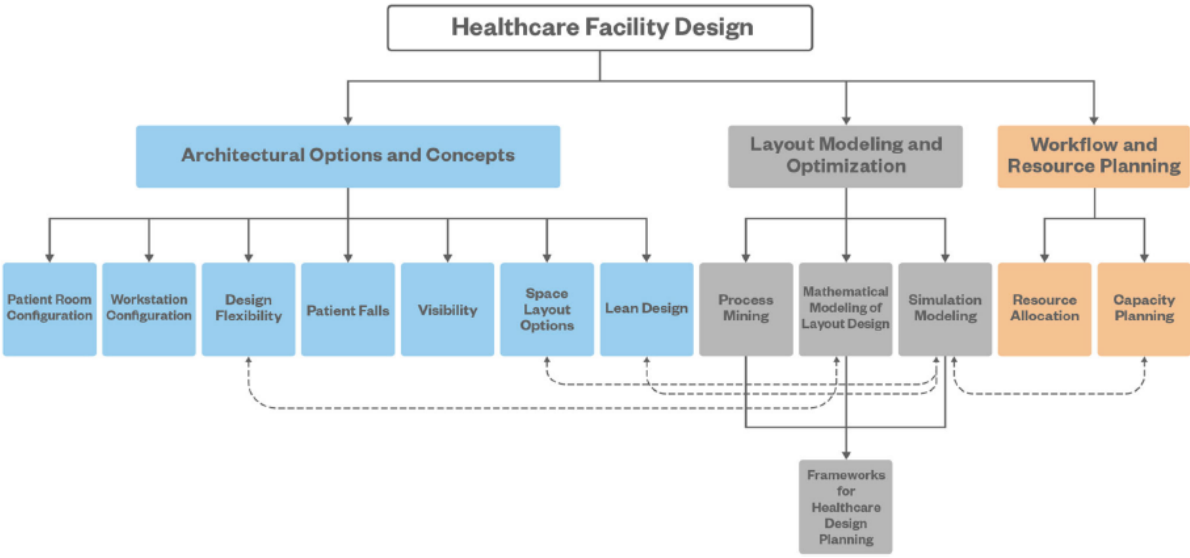

Figure 13. Concept map of healthcare facility design literature showing the relationships and research topics of focus (2008–2018) (Halawa et al., 2020)

Regarding *architectural options and concepts*, literature is found about patient room configurations. These go into detail on patient comfort, such as care disruptions, patient falls, lack of privacy, and poor acoustics. Other papers concern staff workstation configurations. Besides that, multiple layout options are proposed for several departments, such as the inpatient unit, emergency department, and clinic.

The most contributing category for this research is *layout modeling and optimization*. The most common methods applied in *layout modeling and optimization* are mathematical modeling, heuristics, and simulation modeling. As mentioned before, QAP can be used for problems with equal-sized departments and the aim is to assign departments to locations. Mixed-integer linear programming (MILP) can be used if the aim is to generate an optimal layout for departments with variable sizes. Objective functions used in literature are minimal traveling costs and maximal proximity. Facility layout problems are often computationally expensive and hard to solve for large instances (Cheng & Lien, 2012). Heuristics can search in significantly less time to near-optimal solutions. Cheng and Lien (2012) developed a particle bee algorithm that can be efficiently employed to solve practical facility layout design problems with high dimensionality. Gai and Ji (2017) proposed an integrated method with mathematical programming to generate feasible alternatives and experts' opinions to consider both quantitative and qualitative criteria to get a synthesized rank of the feasible alternatives. Rismanchian and Lee (2016) used goal programming to find a layout that satisfies several objectives, namely minimized traveled distance of patients, and minimized relocation costs caused by changing the design. The model is applied for an emergency department and resulted in improved distances traveled by non-critical and critical patients by 42.2% and 47.6%, respectively. Simulation modeling is an effective tool to test layouts (Halawa et al., 2020), but it does not search for an optimal layout. Su and Yan (2015) designed a hybrid simulation-optimization tool to quickly find an optimal design applicable for architectural use. The model is built as a decision-making tool. The objective is to minimize nurses' travel distance and maximize daylighting performance in patient rooms. Arnolds and Nickel (2013) described the multi-period layout planning of hospital wards. Medical and organizational factors change over time, which hampers the process of designing a sustainable layout. They proposed two models, the variable ward layout problem (VWLP) and the fixed ward layout problem (FWLP). The VWLP used non-movable and movable walls and has possibilities for adaptions in the layout plan to satisfy the demand. Where FWLP had only non-movables walls and a robust layout. The objective of the VWLP was to minimize the costs for installing movable and non-movable walls as well as layout adaptions. This was modeled with a binary linear program. The FWLP had as objective to minimize costs for installing non-movable walls and maximize patient satisfaction. This was modeled with an integer linear program (ILP). The designed models were intended to use as a decision support tool for hospital planners. The costs of both models can be compared, and the different kinds of demand violations can be used as input for choosing a layout.

The last category covered by the literature review of Halawa et al. (2020) is *workflow and resource planning*. Within this category, Du et al. (2013) primarily focused on optimizing the scheduling of clinical pathways. They proposed a combination of a genetic algorithm with particle swarm optimization to distribute resources and schedule the treatments. The hybrid genetic algorithm can improve patient efficiency. Ozcan et al. (2016) also aim to improve the clinical pathways, by building a decision tool using a simulation-optimization model for the surgery department. Objective functions of the model are OR utilization rate, bed utilization rate, number of patients operated, and the maximum time before treatment. Multiple configurations are tested. The changing parameters were the number of OR blocks, the opening hours of each block, and the number of ward beds.

In addition to Halawa's literature review, there are a few more papers found that contribute to the facility layout problem. K.E.K. et al. (2020) discussed the development of a hospital layout. Unlike many other papers, they do not use mathematical programming or simulation to design the facility layout. They used Apple's layout procedure to design possible layouts and ELECTRE as multi-criteria decision analyses. This research included the layout of an entire hospital. The designed layouts are tested on seven criteria; interdepartmental satisfactory level, the average distance traveled for staff flow, the average time required for staff flow, the average distance traveled for patient flow, the average time required for patient flow, the average distance traveled for material flow, and the average time required for material flow.

Chraibi et al. (2016) proposed a model for solving the multi-objective operating theatre layout (OTL) problem. The model makes use of a particle swarm algorithm to solve the OTL problem approximately. The particle swarm algorithm used a constructive solution to explore and search to find an effective solution in efficient computation time. The goal of the OTL consisted of two sub-functions, on the one hand minimizing the material handling costs and on the other hand minimizing the desired closeness rating factor based on international standards. To achieve a better outcome faster with the particle swarm algorithm, a heuristic is used to make initial solutions. The intelligence used in the heuristic is based on frequencies of internal and external flows. In later work, Chraibi et al. (2019) presented a decision-making tool using multi-agent's systems where agents' skills were exploited to cover a wide research space, accelerate the decision-making process, and deal with real-life problem sizes. This research is also conducted for operation theatres and has proven effective for several problem instances with over 80 facilities. With facilities is meant all the different rooms needed, such as operating room, scrub room, cleaning room, et cetera. The decision-making tool was based on several mixed-integer linear programming models. The objective was minimizing traveling costs, maximizing adjacency, and minimizing layout rearrangement costs.

A summary of all mentioned references, their used technique with the main outputs and variables are depicted in Table 10.

Reference	Topic	Technique	Main outputs	Main variables
Lacksonen and Ensore (1993)	Dynamic hospital layout	Tabu-search	Minimize total costs: flow costs, rearrangement costs	Place of departments

Gai and Ji (2017)	Healthcare facility layout problem under area constraints	Mathematical programming	Operation costs, traveling distance	Area size, place of areas
Rismanchian and Lee (2016)	Emergency department layout	Goal programming	Traveling distance, relocation costs	Place of departments
Su and Yan (2015)	Layout planning	Genetic algorithm	Traveling distance, daylighting performance	Place of rooms
Du et al. (2013)	Workflow planning and resource allocation	Genetic algorithm, particle swarm optimization	Time of clinical pathway	Scheduling of tasks
Ozcan et al. (2016)	Workflow planning and resource allocation	Discrete-event simulation, Reactive Thermostatistical Simulated Annealing algorithm	OR utilization rate, bed utilization rate, number of patients operated, and the maximum time before treatment	Number of OR blocks, opening hours of each block, and number of ward beds
Arnolds and Nickel (2013)	Multi-period hospital ward layout planning	Binary linear programming, integer linear programming	Costs for variable layout, movements	Variable or fixed layout
K.E.K et al. (2020)	Hospital layout	Apple's layout procedure, ELECTRE outranking technique	Traveling distance, adjacencies,	Place of departments
Chraibi et al. (2016)	Multi-objective operating theater layout problem	Particle swarm algorithm	Traveling costs, adjacencies, material handling costs	Place of activities
Chraibi et al. (2019)	Operating theatre layout	Mixed-integer linear programming	Traveling distance, adjacencies	Place of activities

Table 10. Summary of layout models

Conclusion Strategic level – Facility layout

Much research is done on layout models, also with a specific use in hospital settings. Several techniques are used to model the layout, varying from heuristics to mathematical programming. Most references only change the place of department or activities while searching for the best configuration. Traveling costs and traveling distance between activities/ departments, rearrangement costs, and preferred adjacencies are considered while doing so.

3.1.2 Capacity dimensioning

Capacity dimensioning concerns the decision of which number of resources to purchase. Resources can include personnel, equipment, and space. Resources are most of the time costly, thus the objective is often to maximize throughput while maintaining high resource utilization and staff and patient satisfaction.

Joustra et al. (2011) investigated the acquisition of one additional linear accelerator for the radiotherapy department. The department already planned on purchasing one linear accelerator, assuming the number of linear accelerators where the bottleneck in not achieving the access time targets. A simulation study was performed to prove whether that assumption was right. The percentage of patients treated within 21 days was higher than with one linear accelerator less, but still, the target was not met. Instead, the simulation model showed that the outpatient department was of more importance in not meeting the target. Queuing theory is used to provide insights into the variability of the outpatient department. As result, the combination of increased outpatient department capacity with one extra consultation per week, and reduction of the preparation time should meet the target. Besides that, if the outpatient department capacity would be stable, with the same weekly capacity 34 consultations would be sufficient to meet the target. The researchers suggested that the additional accelerator might not have been necessary after all, but they continued the experiments with a fourth linear accelerator as it was already purchased.

Thomas (2003) did research in the field of capacity and demand models for radiotherapy machines, and specifically the degree of utilization. To predict the number of linear accelerators required for radiotherapy treatments it is common to assume that capacity needs to equal demand. To avoid the build-up of waiting times, queuing theory shows that capacity needs to exceed the mean demand. With the use of Monte-Carlo simulation, Thomas calculated the percentage of spare capacity required to keep the average access time short. The aim was to start radiotherapy within 10 days after the consultation. Before radiotherapy can start with the treatment several pre-treatment processes need to be finished. The duration of those processes varies and is dependent on numerous departments and issues outside the scope of the research of Thomas. Therefore, an assumption is made that the pre-treatment steps can be completed in five days. The simulation showed that the linear accelerators cannot exceed a utilization rate of 90% without causing delays to patients' treatment because of random demand fluctuations.

Elkhuizen et al. (2007) developed a model that analyzed the capacity needed in appointment-based outpatient departments neurology and gynecology. Queuing is used to get insight into the capacity needed to meet the norm of seeing 95% of the new patients within two weeks. Computer simulation is used for a more detailed analysis including the daily variations in demand and capacity schedules. The neurology department needed 26 extra consultations per week for two months to eliminate the backlog and a permanent increase of consultations to keep the access time within two weeks. After the analyses, the department added one extra doctor with a capacity of 25 extra consultations per week. This extra capacity was not available until the backlog had been eliminated completely. The result of the temporarily extra, but too little, capacity was that the average access time was less than 10 days, but the 95% percentile was not. The permanent extra capacity was created half a year later. The backlog was increased slightly in the meantime. The temporary extra capacity will still be needed to eliminate the last part of the backlog. The gynecology department did not have any backlog and a mean access time of 1.2 working days. The model proved that the same service level could be achieved with 14% less capacity. Less capacity would drive the utilization rate from 82% to 89%. Which changes in capacity are used is not stated in the paper.

Edward et al. (2008) used a simulation model to determine the capacity needed to achieve and maintain a proposed service level at a preoperative assessment clinic. The used service levels were access time and waiting time. Multiple scenarios were tested to find the actual capacity needed to meet demand and a temporary extra capacity to eliminate the backlog. Rohleder et al. (2010) also used a simulation model to determine the capacity needed in an outpatient clinic. The main performance indicators were the waiting time and lead time of the treatment. The simulation model resulted in one more employee and different patient scheduling rules. Proposed changes are implemented and significantly improve the lead time of the treatments. Swisher and Jacobson (2002) also made use of simulation to improve a healthcare clinic regarding staffing and resource levels. Indicators tested upon were patient and physician satisfaction and clinic profit. Configuration varied in the number of physician assistants/ nurse practitioners, nurses, medical assistants, and exam rooms. Their study showed that the optimal configuration depends on the preference of the decision-maker in trading clinic profit for patient and physician satisfaction.

A summary of all mentioned references, their used technique with the main outputs and variables are depicted in Table 11.

Reference	**Topic**	**Technique**	**Main outputs**	**Main variables**
Joustra et al. (2011)	Purchase of extra linear accelerator	Queuing and simulation	Reduced access time	Outpatient department capacity, preparation time
Thomas (2003)	Utilization of linear accelerators	Monte-Carlo simulation	Utilization, access time	Opening times
Elkhuizen et al. (2007)	Consultation capacity	Queuing and simulation	Access time	Number of consultations
Edward et al. (2008)	Consultation capacity	Simulation	Access time, waiting time	Number of consultations
Rohleder et al. (2010)	Capacity of outpatient clinic	Simulation	Waiting time, lead time	Staff and scheduling rules
Swisher and Jacobson (2002)	Staffing and resource capacity	Discrete-event simulation	Patient and physician satisfaction, clinic profit	Staff and exam rooms

Table 11. Summary of capacity dimensioning models

Conclusion Strategic level – Capacity dimensioning

Various authors investigated various aspects of capacity dimensioning in radiotherapy settings. All authors used a simulation to mimic the complex situation of healthcare. Simulation techniques prove useful for complex situations, regardless of the indicators to measure and configurations used. Two papers additionally used queuing theory prior to the simulation. Queuing theory can also provide insights into the capacity needed but often lack the ability to take the complexity of the system into account.

3.2 Tactical level

At tactical level, we look at how to execute strategic decisions thus how to allocate the available resources. Tactical level issues that were identified in Chapters 1 and 2 are the allocation of radiation oncologists for volume measurements and small interventions, and the allocation of OR and MRI times.

3.2.1 Staff and appointment scheduling

The allocation of staff and appointments is discussed in this section. Multiple papers discussed the topic of blueprint schedules. A blueprint schedule describes the amount of capacity on a day or time slots that can be used for specific patient types or specific tasks in the operational planning (Leeftink et al., 2018). The block schedule of the radiation therapists for volume measurements and small interventions is thus a blueprint schedule. Multiple objectives can be used while designing a blueprint schedule; minimize waiting time on a day and minimize access time or throughput time. Bikker et al.

(2015) reduced access times for radiation treatment by designing a new blueprint schedule. The blueprint is designed using an integer linear programming model and depicts when radiation oncologists can best have consultation time slots and contouring time slots.

Minimizing waiting time on a day is researched by Liang et al. (2014). They focused on scheduling patients who need an appointment with an oncologist followed by chemotherapy. They proposed a mathematical model with two objectives. The first objective balanced the workload over the chemotherapy chairs, the second objective balanced the workload over the exam rooms. The proposed scheduling method improved patient flow by reducing patient waiting times and provided a smoother workload with lower total clinic working times.

Dharmadhikari and Zhang (2013) had the objective to plan multiple consultations on one day. Instead of the traditional first come first serve planning rule, they made use of block scheduling with priority. The proposed policy helped with scheduling multi-clinic appointments in a single day, by keeping slots open for those appointments. The policy is carried out with a heuristic. Simulation is used to compare the first come first serve policy with the block scheduling with priority policy and proved to make a better planning.

Conforti et al. (2007) addressed appointment scheduling, by optimizing the outpatient schedule within the radiotherapy department. The multiple goals used in the optimization model were; all the activities are scheduled as soon as possible, patient access time is minimized, and device utilization is maximized. The model, formulated with linear programming, outperformed human scheduling by scheduling more patients in a week and delivered a blueprint with possible timeslots for appointments.

A summary of all mentioned references, their used technique with the main outputs and variables are depicted in Table 12.

Reference	Topic	Technique	Main outputs	Main variables
Bikker et al. (2015)	Blueprint schedule	Integer linear programming	Reduced access time	Changed schedule radiation oncologists (consults, contouring)
Liang et al. (2014)	Blueprint schedule oncology with chemotherapy	Mathematical programming	Reduced waiting times, lower clinic working times	Changed schedule oncologists and use of chemotherapy chairs
Dharmadhikari and Zhang (2013)	Multi-clinic blueprint schedule	Simulation	More consults on one day, less traveling for patients	Changed policy to block scheduling with priority
Conforti et al. (2007)	Blueprint patient appointments	Linear programming	More patients planned per week	Scheduling of time slots

Table 12. Summary of staff and appointment scheduling techniques

Conclusion Tactical level – Staff and appointment scheduling

Most papers made use of mathematical programming to make the blueprint schedules. Besides changing the blueprint schedule, the literature showed that another scheduling policy might also improve the performance indicators.

3.2.2 Capacity allocation machines

Literature on the capacity allocation of machines gives useful insights on planning OR and MRI times.

Utley and Worthington (2011) reflected on using queuing models in healthcare organizations to determine the level of resources to make available. They described two steps, first to model the situation with unfettered demand. This means to model the situation with no restrictions on resources. This gives insights about capacity requirements but cannot explicitly account for the impact of having finite resources available. Second, it is necessary to model with finite resources. This can be done by analytical queuing models or simulation queuing models. The first is typically represented by formulae and often provides valuable insights. Where simulation models evaluate what-if scenarios and produce quasi-empirical results rather than direct insights. Analytical queuing models as single-server queues, multi-server queues, network of queues, and time-dependent queueing models are described in the paper of Utley and Worthington (2011). For the application of queuing models, it is key to decide to what level of detail the situation should be modeled. Where using additional complexity and detail can add value, it will also make the model more complex and take longer time to develop and perform.

Fung Kon Jin et al. (2011) looked into a trauma department to choose optimal planning and distribution of CT scanners to diagnose trauma patients as fast as possible. They used a simulation model to evaluate six clinically relevant configurations of CT scanners, CT location, and different patient categories on the CT scanners. The best configurations reduced waiting times and overtime while increasing idle time. The simulation brought insight into the optimal patient flow and lends for decision-making. Vermeulen et al. (2009) also used simulation techniques for resource allocation. They proposed an adaptive resource scheduling approach applied to CT scanners of a radiology department. The actual realization of patient arrivals does not match the allocation, which results in inefficient use of the capacity and/or long access time for patients. A simulation was used to analyze the case and evaluate approaches. An adaptive method was added to change the given resource blueprint to use available time more efficiently and free-up not used time slots for other patient groups. Dynamically adjusting the capacity allocation showed to be more efficient than the static capacity allocation. Zheng et al. (2011) discussed the allocation of operating rooms in a hospital. With the use of discrete-event simulation, the current situation was analyzed. Indicated problems in current OR's management were unreasonable manpower resources and insufficient bed capacity for recovery. Suggestions for improvement were more beds for recovery, more anesthesiologists and nursing workers, and fewer nurses.

Zhou et al. (2015) researched the capacity allocation of MRIs. Instead of using simulation techniques, they used integer linear programming to allocate limited MRI capacity to various patient groups. The objective was to minimize costs including patient waiting costs, reject costs, and machine idle costs. Multiple experiments with various machine working times and setup time duration were developed to indicate the efficiency of the proposed method. The new method performed better than the single queue method.

A summary of all mentioned references, their used technique with the main outputs and variables are depicted in Table 13.

Reference	Topic	Technique	Main outputs	Main variables
Utley and Worthington (2011)	Resource planning	Queuing models	Waiting time, queuing time	Single-server, multi-server
Fung Kon Jin et al. (2011)	Allocation of CT's	Simulation	Reduced waiting times and overtime	Number of CT's, place of CT's

Vermeulen et al. (2009)	Allocation of CT's	Simulation	Access time, utilization	Opening hours,
Zhou et al. (2015)	Allocation of MRI's	Integer linear programming	Waiting cost, reject cost, machine idle cost	Allocation of MRI hours over patient groups
Zheng et al. (2011)	Allocation of OR	Discrete-event simulation	Utilization, lead time	Beds, medical personnel

Table 13. Summary of capacity allocation techniques

Conclusion Tactical level – Capacity allocation machines

Utley and Worthington (2011) described the use of queuing models in healthcare organizations. Nevertheless, the literature on capacity allocation mainly used simulation or mathematical programming. Commonly used performance indicators were waiting time or waiting costs of the patients and utilization of the resources.

3.3 Operational level

Chapter 2 showed that the detailed planning of the patients is a complex process. Besides that, the current patient flow was identified as a bottleneck on the operational level.

3.3.1 Patient-to-appointment assignment

A patient-to-appointment assignment is a process that comes after making a blueprint with possible appointment slots. Here the patients are scheduled on an available slot.

Bikker et al. (2018) discussed capacity planning with resource compatibility restrictions for radiation treatments. They designed a model to plan the patients considering the complexity of the patient treatment courses, the varying linear accelerator requirements, variable demand, and limited treatment capacity. Due to this complexity, the designed model consisted of approximate dynamic programming with Langrangian relaxation. The proposed method significantly increased the service levels, thus reduced patient access time, and with that decreased clerical rework and free up staff.

Another case study where patients are scheduled was done by Braaksma et al. (2014). Braaksma et al. (2014) used integer linear programming to make an integral multidisciplinary planning for rehabilitation treatment. Patients that need rehabilitation often see multiple care providers from different disciplines, thus need a series of appointments. This multidisciplinary nature complicates the planning process. The objective function of the ILP minimized penalty costs of eleven factors. These factors included the number of unscheduled appointments, spreading of the appointments over the week, access time, exceeding of prescribed duration, and the number of appointments that caused a break in the schedule of the therapists. Each treatment plan received its blueprint of appointments per discipline. All factors got a weighted factor, defined by the specialists. The model was evaluated using performance indicators, such as access time, combination appointments, and therapist utilization. The results showed a significantly higher percentage of patients treated within the access time with retaining or improving the therapist utilization. The model can be used as a decision-making tool for resource capacity planning and control.

Another technique used for scheduling patients are heuristic methods. Vlah et al. (2011) formulated the scheduling problem as a binary integer program and designed a reduced variable neighborhood search heuristic for solving the program. The variable neighborhood search is a metaheuristic whose basic idea is to systematically change the neighborhoods in search of the optimal solution. The goal was to plan the patients efficiently, with low access time and minimal work in overtime for staff. The proposed model can find optimal solutions for small-sized problems, up to 40 patients, and will still find solutions for large-sized dimensions in acceptable computational time. Chien et al. (2008) used a genetic algorithm for rehabilitation patients' scheduling. To benchmark the genetic algorithm a mixed-integer program was modeled. The objective was to minimize the maximum waiting time and to minimize the makespan. The makespan is the time to complete all therapies for a patient. Minimizing the makespan improved the operation efficiency. Weights were given to indicate the importance of both goals in the objective function. The genetic algorithm and the mixed-integer program found a solution with identical waiting times. Thus, the genetic algorithm proved to be useful for scheduling patients. Several scenarios regarding scheduling rules were tested to find the scheduling rule that yields the best objective.

A summary of all mentioned references, their used technique with the main outputs and variables are depicted in Table 14.

Reference	Topic	Technique	Main outputs	Main variables
Bikker et al. (2018)	Patient scheduling with resource compatibility restrictions	Approximate dynamic programming, Langrangian relaxation	Reduced access time, free up staff	Patient scheduling
Braaksma et al. (2014)	Patient scheduling in multidisciplinary form	Integer linear programming	Reduces access time, better combination treatments	Patient scheduling
Vlah et al. (2011)	Patient scheduling	Binary integer programming with reduced variable neighborhood search	Near-optimal schedules	Patient scheduling
Chien et al. (2008)	Patient scheduling	Genetic algorithm	Utilization, waiting time	Patient scheduling rules

Table 14. Summary of scheduling techniques

Conclusion Operational level – Patient-to-appointment assignment

Most papers used mathematical programming to make a patient schedule. Mathematical programming is often used for various scheduling problems because of its capabilities in presenting the nature of combinatorial optimization problems (Chien et al., 2008). Chien et al. (2008) and Vlah et al. (2011) showed that using heuristics such as genetic algorithms can also provide a good solution within reasonable computation time.

3.3.2 Patient flow

There is much literature available on simulating patient flows in hospitals. Also, on the specific topic of radiotherapy is plenty of literature available, but not for brachytherapy. One paper is found discussing the simulation of the entire radiotherapy department, including brachytherapy (Kapamara et al., 2007). They used discrete-event simulation to model the radiotherapy department, analyze the patient flow, and point out the bottlenecks. After modeling the current situation and validating the output, they experiment with various scenarios. The scenarios were reducing the staff, extending the staff and machine hours, patients do not necessarily have to attend their own doctor, and machine downtime due to breakdowns. For all scenarios, the access time was compared with the current situation. The utilization of the machines in the current situation was analyzed, and the model showed that the most congestion was for the linear accelerators. A similar study was conducted by Proctor et al. (2007). Different scenarios were increased patient demand, additional machines, extra machine hours, and a reduced percentage of patients that need to see their own doctor. The output is only depicted in access time. Using more machines or extending the operating hours of the treatment machines enabled more patients to be treated with lower access time.

Miranda and Miranda (2021) did similar research into the radiotherapy process. The goal was to maximize the throughput and reduce access time. Besides changing staff and machine hours, different staff scheduling and adjusted time slots for treatments are used in the configurations. The optimal result of the model was to schedule some linear accelerator technicians earlier and adjust the slot length from 10 to 9 minutes. Babashov et al. (2017) analyzed the planning process of a radiotherapy department to only reduce access time. A discrete-event simulation was used to model the patient's flow from referral to a radiation oncologist to the start of the radiotherapy. Multiple experiments with varying oncologists, technicians, and resources were carried out. Increasing the number of radiation therapists by one reduced the mean access time by 6.55% to 84.92% of patients being treated within the 14 days target. Adding one more oncologist decreased the mean access time from 10.83 to 10.55 days, whereas a 15% increase in arriving patients increased the waiting time by 22.53%. Another paper that purely focused on reducing the mean access time is from Werker et al. (2009). The scenarios varied in using standard plans instead of individual, double the required time by radiation therapists for the main tasks, arrivals increase and decrease by 20%, and productivity increase and decrease of the radiation oncologists by 20%. The scenarios showed that the model was most sensitive to the change of radiation therapists' time. The scenario with one less radiation therapist increased the access time. The scenario with more consistent (not dependent on the oncologist's schedules) and shorter radiation oncologist delays reduced the access time by more than one day. Unfortunately, it is not clear how and which delays to shorten.

Unlike the above-described research, Vieira et al. (2019) investigated the scheduling strategy for the first irradiation session: pull strategy and push strategy. The pull strategy means that all pre-treatment workflow and irradiation sessions are planned after the first consultation. Push strategy schedules the irradiation sessions after the pre-treatment workflow has been completed. The current practice is a hybrid strategy with 40% pull and 60% push. Discrete-event simulation allows to research the effect of changing to a 100% pull strategy, which resulted in 41% fewer patients breaching the targeted access time. Besides this, an additional scenario in which consultation slots are evenly spread throughout the week is conducted. Resulting in a 21% reduction in access time.

When searching for the use of simulation models in healthcare, many more articles can be found in areas other than radiotherapy, namely emergency departments (e.g., Kenny et al., 2021; Steward et al., 2017; Ahmed and Alkhamis, 2009; Lal et al., 2015; Best et al., 2014), and outpatient clinics (e.g., Kulkarni et al., 2021; Demirli et al., 2021). Kenny et al. (2021) used discrete-event simulation to get better insights into adequate resources for future demands. Historically informed synthetic data was used to feed the simulation model. The hospital performance measures of an emergency department were tested using what-if scenarios. The performance measures used were the overall length of stay and queuing time of emergency patients. The result of the simulation model was that adding a single bed with the associated resources would decrease the average patient treatment delay by 23%. While there were many discrete-event simulation studies carried out in the healthcare sector, only Kenny et al. (2021) discussed the use of synthetic data modeled from historical data. This allows to look at resources not historically included in the data or to extend the time frame of the historic data. To validate the synthetic data, the generated and actual data were used in the simulation. However, it was not described how representative the synthetic data was.

Different from others Steward et al. (2017) used a simulation model for a newly constructed facility to look at the workflow, variables, resources, structure, process logic, and associated assumptions. The goal of the research evolved. Before opening the emergency department, the main goal was of strategic level and to train personnel, where after opening the emergency department the main goal was to continue with improving the department. The key performance indicator used was the length of stay of emergency patients. The described results only included a variation of emergency rooms and interarrival times. Whilst the paper also stated they looked at different workflows with parallel and series events.

Simulation can also be used in combination with optimization, which was for example done by Ahmed and Alkhamis (2009) for an emergency department. The objective was to maximize patient throughput and reduce patient lead time. They simulated the emergency department and optimized the staffing distribution during the simulation, subject to budget restrictions. The result was a 28% increase in patient throughput and an average of 40% reduction in patients' waiting time when optimal distributing the staff.

A summary of all mentioned references, their used technique with the main outputs and variables are depicted in Table 15.

Reference	Topic	Technique	Main outputs	Main variables
Kapamara et al. (2007)	Patient flow modeling	Discrete-event simulation	Reduced access time	Demand, staff, and machine hours
Proctor et al. (2007)	Patient flow modeling	Discrete-event simulation	Reduced access time	Demand, staff and machine hours, extra machines
Babashov et al. (2017)	Patient flow modeling	Discrete-event simulation	Reduced access time	Demand, staff, and machine hours
Vieira et al. (2019)	Patient flow modeling	Discrete-event simulation	Reduced access time	Push/pull strategy, spreading consultation slots
Miranda and Miranda (2021)	Patient flow modeling	Discrete-event simulation	Reduces access time, increased throughput	Scheduling, demand, staff hours, slot length for treatment
Kenny et al. (2021)	Patient flow modeling	Discrete-event simulation	Shorter length of stay and waiting time	Bed capacity
Steward et al. (2017)	Patient flow modeling	Discrete-event simulation	Length of stay	Interarrival time, rooms
Kulkarni et al. (2021)	Patient flow modeling	Discrete-event simulation	Waiting time, service time, utilization	None
Ahmed and Alkhamis (2009)	Patient flow modeling	Discrete-event simulation + optimization	Lead time, patient throughput	Staffing distribution
Lal et al. (2015)	Patient flow modeling	Discrete-event simulation + mixed-integer programming	Fewer costs	Shift scheduling
Best et al. (2014)	Patient flow modeling	Discrete-event simulation	Length of stay	Staffing distribution

Demirli et al. (2021)	Patient flow modeling	Lean + discrete-event simulation	Utilization, throughput, waiting time	Interarrival times, no-shows, walk-ins

Table 15. Summary of patient flow models

Conclusion Operational level – Patient flow

From the literature, we conclude that simulation techniques, and in particular discrete-event simulation, are common for modeling patient flows. The most common rationale for choosing discrete-event simulation is that it can model the complexity associated with healthcare processes (Lal et al., 2015). Discrete-event simulation is well suited for healthcare where it can tackle problems with, for example, scarce resources and irregular patient arrival times (Mustafee et al., 2010).

The research focused on radiotherapy only evaluates the access time, since that is experienced as a major issue in radiotherapy departments. By adjusting the amount of personnel and machine capacity, researchers try to lower the access time. Changes in demand were to test what the process will be like when demand increases over time. The research focused on emergency departments typically looks at the waiting times and length of stay, since that is the most important factor regarding emergencies. Most papers do not include many performance indicators but focus on the few most important ones.

3.4 Conclusion

The brachytherapy process is very complex, as described in Chapter 2, and therefore well suited for analyzing with simulation techniques. As seen from the literature, these techniques imitate reality well in complex situations. The simulation model itself executes at the operational level but can evaluate various strategic and tactical decisions (see e.g. Kapamara et al. (2007), Vieira et al. (2019), Kenny et al. (2021)). Optimizing strategic or tactical decisions in a specific area is also possible, but typically performed together with a simulation to evaluate the impact on the system. For this reason, we decided to start using a discrete-event simulation to mimic the current situation, which can be extended by incorporating optimization decisions in future work. Contrary to other radiotherapy literature, our main performance indicator will not be access time but a multi-objective including waiting time, lead time of the treatment, overtime, and utilization of resources. The conceptual model for the simulation is discussed in Chapter 4. After that, experiments with strategic and tactical decisions are investigated in Chapter 5.

Chapter 4: Simulation model

This chapter discusses the conceptual model used for the simulation study. The ten-step approach (Figure 14) of Law (2014) is used as guidance for the simulation model. This chapter describes the steps up until step 7 design experiments. The problem formulation is covered in Section 4.1, data collection and modeling assumptions in Section 4.2, model content in Section 4.3, experimental settings in Section 4.4, validation and verification in Section 4.5, experimental design in Section 4.6, and we conclude this chapter in Section 4.7.

4.1 Problem formulation

The first step is to formulate the problem and plan the simulation study. Extensive research into the current situation is described in Chapter 2. This section describes the objectives of the simulation study, the performance measures, and the scope of the model.

4.1.1 Objectives of the study

As described in Chapter 2, the brachytherapy treatment process is complex and seems to be inefficient. The goal of the simulation study is to identify the bottlenecks in the process and to test strategic and tactical decisions to improve the brachytherapy treatment process in such a way that efficient and patient-friendly (less waiting time) treatment can be realized for all patients.

Specific questions to be answered for this study are:

- How is the current situation performing?
- What are the bottlenecks?
- How can strategic and tactical decisions such as extra resources, different layouts, or other scheduling techniques improve the process?
- How can the treatment process be modeled best at the new location?

4.1.2 Performance measures

The performance measures that are used to evaluate the efficacy of the configurations follow from Chapter 3 and are the following:

- Access time,
- Waiting time,
- Overtime,
- Lead time treatment,
- Utilization.

Access time is the time from the first consult to the start of the first treatment. Waiting time regarding personnel waiting for the next step to execute and waiting time for patients in between process steps. Besides that, overtime of personnel will be measured, mean lead time of the treatments, utilization of OR-time, utilization of the afterloaders, and utilization of the bunkers.

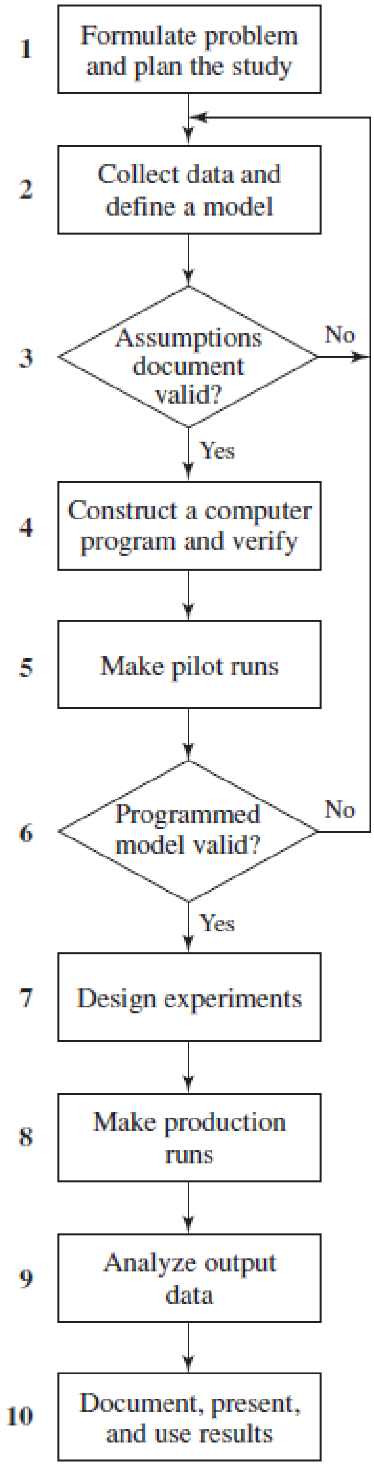

Figure 14. Steps of simulation modelling (Law, 2014)

4.1.3 Scope of the model and level of detail

Due to the complexity of the brachytherapy and its different treatments, the simulation model only evaluates the impact on the brachytherapy department. The four care plans as described in Chapter 2 will be used to simulate the different patient streams.

A lot of personnel is involved in the brachytherapy treatments, such as radiation oncologists, radiation therapists, and medical physicists. But also personnel from other departments, such as nurses, anesthesiologists, patient transport employees, MRI technologists, et cetera. All personnel outside the brachytherapy department are not considered in this research and are expected to always be present when the relevant departments are open and available for the brachytherapy. This choice is made to simplify the situation.

4.2 Data collection and modeling assumptions

The second step is to collect data and define the model. For defining the model, we look at the system structure and operating procedures, model parameters and their probability distributions. Model assumptions are also described in this section.

4.2.1 System structure and operating procedures

The four care plans as described in Chapter 2 are LDR, PDR, HDR-complex, and HDR-simple. LDR and HDR-complex are both prostate cancer patients. PDR and HDR-simple are both gynecology cancer patients. This is a simplification, as 17% of the patients do not fit directly in one of the care plans. This 17% includes AMORE, anus, bladder, eye, skin, keloid, lip, and esophagus. To simulate the total amount of patients the brachytherapy department expects each year, we choose to assign the other patient groups to one of the four defined care plans that suit them best. Figure 15 depicts the high-level flowchart of the care plans. This is a simplified representation of reality. When a patient arrives, he or she is first triaged and then given the first consultation with the most appropriate radiation oncologist. If the patient has gynecologic cancer, a PDR or HDR-simple care plan will immediately follow. If the patient has prostate cancer, a volume measurement must be performed first, followed by the right care plan. Some care plans are repeated several times by the same patient within a certain period. This is explained in Section 4.3.

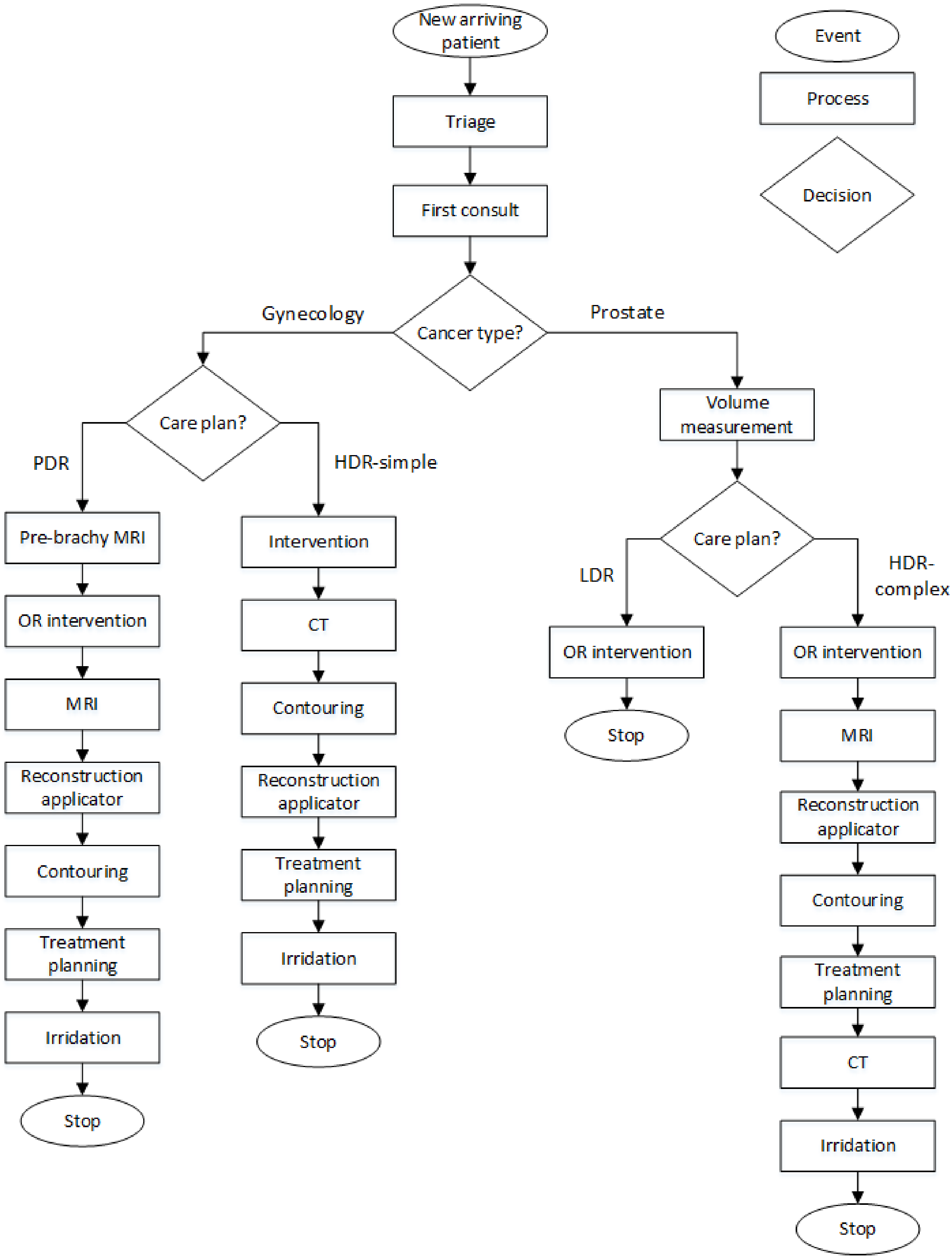

Figure 15. The high-level flowchart of the complete simulation flow

4.2.2 Model parameters and input probability distributions

An important part of the simulation is the model and input parameters. In this section, the working hours of the personnel and opening hours of rooms and equipment are described. Besides that, the time necessary for different process steps dependent on the care plan is described, together with the walking time between departments.

Personnel

The working hours of the radiation therapists are depicted in Table 16. RT1 indicates radiation therapist 1 et cetera.

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
RT1	8.00 – 17.30	7.30 – 17.30	8.00 – 17.30		8.00 – 17.30
RT2	8.00 – 17.30	7.30 – 17.30	8.00 – 17.30	8.00 – 17.30	
RT3	8.00 – 16.30	7.30 – 16.30		8.00 – 16.30	8.00 – 16.30
RT4		7.30 – 17.30	8.00 – 17.30	8.00 – 16.30	
RT5		7.30 – 16.30		8.00 – 16.30	8.00 – 16.30

Table 16. Working times of radiation therapists

We cannot make such a schedule for the radiation oncologists (RO) because they also work for external radiotherapy. Table 17 depicts the blueprint with the small interventions and volume measurements. On Tuesday, all radiation oncologists are always available for interventions at the OR, except for one.

To explain the table below. On Mondays for example, RO1 is available for a small intervention at 10:00 am. This means that there is one slot at 10:00 am. The 9:00 am timeslot in brackets will not be used until RO3 cannot fulfill that timeslot. The timeslots between brackets are reserve timeslots. On Tuesday, RO2 has a place for a small intervention at 11:00 and 12:00. At that time, there is also a possibility to plan three patients for volume measurements because they require a shorter time from the radiation oncologists. However, the radiation therapists must start preparing the materials half an hour before the timeslot. On Thursdays, only one hour is available for the small interventions or volume measurements, so only one small intervention or two volume measurements can be scheduled. The HDR volume measurements on Thursday are intended for the HDR-complex treatments. These are performed by external radiotherapy and require only 10 minutes of the brachytherapy therapist's time. The timeslots on Tuesday can only be used when there are no interventions planned at the OR; otherwise, there will not be enough radiation oncologists and therapists available.

	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
RO1	10:00 (9:00) small int.		13:30 (11:30/12.30) small int.		
RO2		11:00/12:00 small int./volume	11:30/12.30 small int./ volume OW	8:15-9:15 small int./volume 13:00 HDR volume	10.30 small int./volume OW
RO3	9:00 (10:00) small int.	9:00/10:00 small int./volume			9:30 small int./volume
RO4		(9:00-12:00) small int./volume	11:30/12.30 small int./ volume EW	8:15-9:15 small int./vol 13:00/13:30 HDR volume	10:30 small int./volume EW

Table 17. Radiation oncologists' blueprint for small treatments and volume measurements

During an MDO, radiation oncologists are not available. Table 18 shows which radiation oncologists must be present at an MDO.

	Monday	Tuesday	Wednesday	Thursday	Friday
RO1	14:00-16:00	17:00-18:00		8:15-9:00	
RO2		17:00-18:00		12:00-13:00 16:30-17:30	
RO3	14:00-16:00	17:00-18:00			
RO4	14:00-16:00	16:00-17:00		8:00-8:30 12:00-13:00	

Table 18. Radiation oncologists' MDO schedule

Room and equipment

The opening hours of the rooms and equipment can be found in Table 19. The CT can be booked the entire day. There is no personnel needed besides the brachytherapy radiation therapists. Thus, the available time is the working day of the radiation therapists. The MRI can be booked between 12:00 and 14:00 every day. The MRI can be freely booked in those hours but not later than three days in advance. The radiology department will then start with filling up empty slots. On a Tuesday it is typically divided into two timeslots because of the interventions at the OR.

The OR is available on Tuesdays from 8:00 till 16:30, approximately 39 Tuesdays in a year. Brachytherapy cannot always use the entire OR day. As a result, interventions are regularly performed on other days as well. Normally an extra OR slot will be opened by the gynecology department if a gynecology patient must wait too long. All other patients must be treated on regular Tuesdays.

The HDR-afterloader may only be used during working hours because of the high irradiation. A radiation oncologist must be available in case of error messages and removal of the applicator. The PDR-afterloader can only be connected during working hours but does not have to be disconnected at night, as the treatment can continue. Once every four weeks, the nursing department F5N is open until 10.30 pm on Saturday, allowing to start later in the week with the treatment of patients. The intervention room has the same opening hours as the personnel has working times since the interventions depend on the personnel of the brachytherapy department.

	Monday	Tuesday	Wednesday	Thursday	Friday
CT	8:00-17:30	8:00-17:30	8:00-17:30	8:00-17:30	8:00-17:30
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		8:00-16:30			
Afterloader HDR	8:00-17:30	8:00-17:30	8:00-17:30	8:00-17:30	8:00-17:30
Afterloader PDR 1	8:00-17:30	8:00-17:30	8:00-17:30	8:00-17:30	8:00-17:30
Afterloader PDR 2	8:00-17:30	8:00-17:30	8:00-17:30	8:00-17:30	8:00-17:30
Intervention room	8:00-17:30	8:00-17:30	8:00-17:30	8:00-17:30	8:00-17:30

Table 19. Opening hours rooms and equipment

Activities

Table 20 shows the times for the different process steps involved in the brachytherapy treatment trajectory. The time for a step differs between the care plans. For most steps there is no data available; these times are composed by the brachytherapy team and are therefore uniform distributed. The OR time is based on data and normally distributed. After realizing there was a large time range for PDR process steps, caused by the difficulty of the procedure that can vary a lot. We decided to break up the care plan into PDR-complex and PDR-simple. They still follow the same path but with different process times.

Process step time in min	LDR	PDR-simple	PDR-complex	HDR-complex	HDR-simple
Waiting time start 1st OR	30 – 45	30 – 45	30 – 45	30 – 45	N/A
Switching patients on OR	20 – 30	20 – 30	20 – 30	20 – 30	N/A
Applicator insertion (OR time)	Avg=155 Stdev=27	Avg=99 Stdev=30	Avg=128 Stdev=31	Avg=153 Stdev=24	15 – 30
Recovery	60-90	60-90	60-90	60-90	N/A
CT	N/A	N/A	N/A	45-60	15
MRI	N/A	45	45	45 – 70	N/A
Contouring critical organs	N/A	50-60	50-60	45 – 60	30 – 45
Contouring tumor	N/A	30 – 55	30 – 55	30 – 45	N/A
Second read tumor	N/A	10 – 20	10 – 20	10 – 20	N/A
Reconstruction	N/A	30 – 55	60-80	60 – 80	15 – 20
Check reconstruction	N/A	15 – 25	30-40	20 – 30	5
Treatment planning	N/A	30 – 55	60-80	40 – 55	2
Treatment plan check	N/A	10	10	10	5
Connect afterloader	N/A	15 – 25	20 – 25	20 – 25	10
Treatment	N/A	total treatment time 36 – 48 hours	total treatment time 36 – 48 hours	30 – 45	10
Applicator removal	N/A	10-15	10-15	10-15	10 – 15
Clean up after treatment	N/A	N/A	N/A	N/A	10

Table 20. Times in minutes for the process steps dependent on the care plan

Besides the process time, some walking times between departments are also important, depicted in Table 21. These times follow from a few manual measurements.

Distance	Time in minutes
Recovery to MRI	15
F5N to CT	5 – 10
Brachy to F5N (without patient)	4 – 6

Table 21. Walking times between departments

4.2.3 Assumptions

The following assumptions are made for the sake of simplicity:

- We assume that the necessary personnel from other departments is present when these various departments are open and available to the brachytherapy department.
- We assume that patients always show up in time for their appointments.
- We use a standard working scheme, thus not including holidays.
- Ideally, the radiation oncologist who performed the intervention will work on the treatment planning of the same patient. If this is not possible and will cause serious delay, another available radiation oncologist will start with the treatment planning. Therefore, the model does not assign tasks to specific employees but only checks if there is personnel available.
- We assume that the first MRI appointment will be booked at 12h and the second at 13.30h.
- We do not consider the time to bring equipment to the OR because that will happen before starting time of the intervention. And we do not take time to clean up that equipment after the last OR intervention into account because that will be done in a way that does not affect patients waiting time.
- We assume that the brachytherapy department and the nursing department are closed on the weekends.

4.3 Model content

There are multiple written and unwritten procedures the brachytherapy team follows when scheduling patients for volume measurement and interventions. These procedures are described in this section.

4.3.1 Scheduling rules and procedures for OR

At most three patients can be treated on a full OR day, of which at most two PDR and/or HDR procedures. At most one HDR can be scheduled because there is only one HDR-afterloader.
The first two interventions are scheduled with the following priority:
1. HDR complex
2. PDR complex
3. PDR simple

After the patient comes into the system, the therapists start scheduling. Most brachytherapy treatments follow other treatments. Depending on the care plan, those previous treatments and the duration can differ. A PDR treatment typically follows an external radiotherapy treatment of five weeks with three weeks of preparation beforehand. It is also important to treat these patients within two weeks after the external radiotherapy. Thus, the patients must be planned within eight to ten weeks after consultation, Table 22. In Chapter 2, we decide to use the HDR-complex treatment with the most steps; for that treatment we do not have to take any time beforehand into account, there are no previous treatments planned when the patient enters the system. The simulation model will use one week to be able to inform the patient timely. LDR treatments need two weeks of preparation due to the ordering of the iodine seeds.

The HDR-complex treatment includes a second and third fraction on the second day of the treatment. These patients will stay at the nursing department to continue the treatment on the second day. The appointment for the CT and the second and third fraction will be planned together with planning the OR appointment.

	Preparation + external radiotherapy	**Start before**
PDR	3+5=8 weeks	10 weeks
HDR-complex	1 week	
LDR	2 weeks	
HDR-simple	2 weeks	4 weeks

Table 22. Planning weeks for interventions

4.3.2 Scheduling rules small interventions

Two weeks after the consultation, a patient needs to be scheduled for a small intervention. This has to do with the four to six weeks that should be between the operation they had before the brachytherapy treatment. The consultation takes place a few weeks after they had the operation, and therefore the small intervention ideally starts two weeks after the consultation. The procedure will be performed three times, with at least three and at most seven days between each intervention. All three dates will be planned simultaneously.

4.4 Experimental settings

Experimental settings affect the accuracy of the simulation. These settings are the warm-up period, run length, and the number of replications.

4.4.1 Warm-up period

The simulation model starts with no patients in the system, which is not representative for observations. Therefore, a warm-up period must be determined. This period of initial output data will be deleted. To determine how many days are needed to get in a steady-state, we observe the KPI access time. As the system is filling with patients, the average access time will rise to a steady level. Welch's graphical method is used for identifying the length of the warm-up period. Five independent runs of five years are done. Moving averages with windows 5, 10, 25, 50, and 100 are calculated over the simulation run. As indicated by the black arrow in Figure 16, around the 120th patient the access time is stable. This number of patients is equal to an average of 38 weeks. Therefore, the warm-up period for the simulation model is set to one year. The run length of the simulation is also one year.

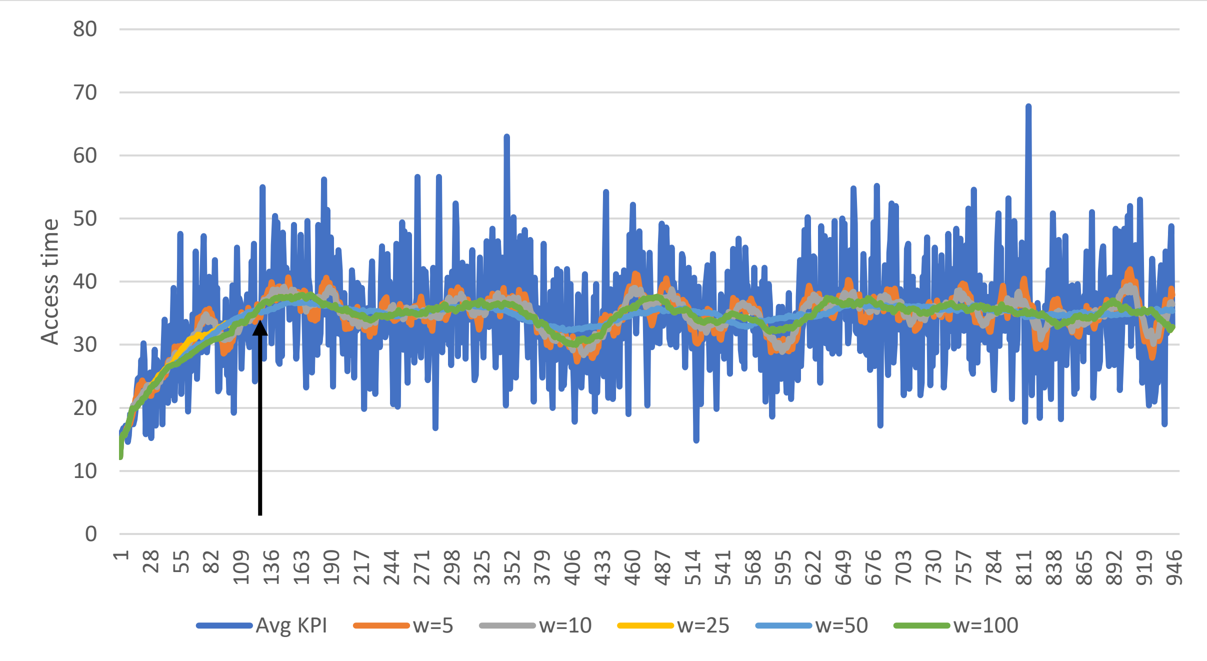

Figure 16. Welch's procedure for the warm-up period

4.4.2 Replications

Multiple replications are required to obtain reliable results. Each replication uses a different random number stream. The significance level of 95% is used with a relative error of 5%. When aiming for a relative error of 0.05, the actual relative error of the model is 0.048. 30 independent replications are performed. After 21 replications, the relative error is below the threshold of the required relative error (Figure 17 & Figure 18). The number of replications per experiment will be 21.

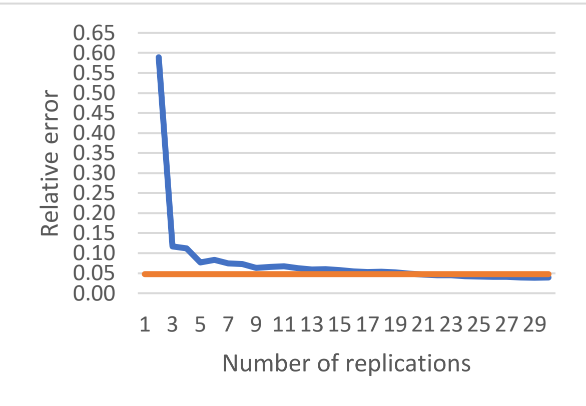

Figure 17. Number of replications

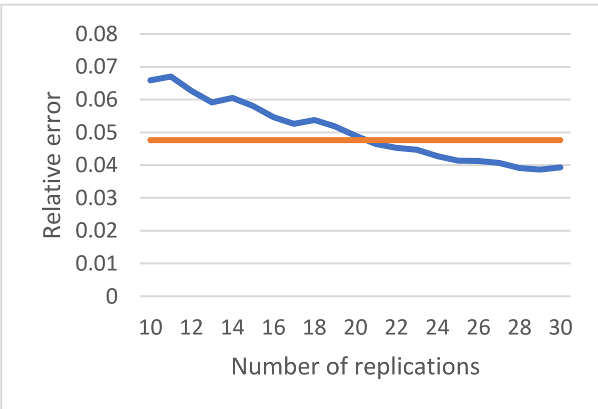

Figure 18. Number of replications close-up

4.5 Validation and verification

Model verification is done by comparing the simulated model to the conceptual model. The model is built part by part and tested after every part. The simulation started with simplified assumptions to see whether the model would behave as expected. At last, we have done a visual verification to see if patients and personnel are having normal realistic behavior during the day.

Model validation is necessary to ensure that the simulation is sufficiently accurate for the purpose of the study. Validation is done in multiple ways, namely by comparing the output of the simulation with the output of the actual situation by looking at several KPIs and with the opinion of experts by doing a walkthrough of the used data, assumptions, and output of the model. Table 23 depicts the output of several KPIs for the simulation model and the reality. The KPIs of the current situation are based on the data of 2016 up to and including 2019. Based on the difference between the KPIs, the simulation model looks to reflect reality well enough. The biggest difference is for the HDR afterloader utilization, which can be a result of the simplification of patients in the simulation model. Experts' opinion is that the model reflects reality adequately and can be used for the study.

KPI	**Reality**	**Simulation model**	**Difference**
Average OR utilization	72.1%	73.4%	▲1.8%
Number of OR interventions	155	159	▲2.4%
Average Access time (days)	30.6	32.6	▲6.4%
Average Lead time (h:mm)	5:59	6:15	▲4.3%
PDR afterloader utilization	43.5%	39.3%	▼9.5%
HDR afterloader utilization	6.9%	5.7%	▼16.9%
PDR room utilization	80.0%	80.4%	▲0.5%
HDR room utilization	60.7%	53.6%	▼11.7%

Table 23. Difference between KPIs of the real situation and simulation model

4.6 Experimental design

To show the effects on the KPIs we define various experiments. For the experimental design, we must make three decisions: which factors to vary, which levels to choose for each factor, and which combinations of factor levels to simulate. In Chapter 3, we discussed experimenting with strategic and tactical decisions. These decisions include the use of OR time, MRI slots, and dimensioning of personnel.

The goal of this study is to identify bottlenecks to be able to improve the brachytherapy treatment process and to build an improved process at the new location. To know what the bottlenecks are, we start with a sensitivity analysis. Sensitivity analysis allows us to investigate the effect of varying input factors. In this analysis, we first alter the MRI slots to an all-day availability, and after that we assume there is always plenty of personnel without having to wait for it. After this sensitivity analysis, we can decide how important it is to set multiple levels on the factor MRI-slots and dimensioning of personnel.

Factor levels to use for OR time instead of one full day is two half days. For the MRI slots, we can vary the times of the slots on an OR day. For dimensioning of personnel, we can add more radiation therapists, radiation oncologists, or medical physicists, depending on the impact given by the sensitivity analysis.

4.6.1 Sensitivity analysis

The first sensitivity analysis is performed for the MRI slots. Currently, the patient that goes first to the OR gets the first MRI slot at 12:00h. The second patient at the OR gets the second MRI slot at 13.30h. For this analysis, we stop using the slots and assume the patient can go to the MRI as soon as recovery is fully done. This led to an average lead time of 5:56h against 6:15h when using the MRI slots. We conclude that this does not make much difference. The time range for patients being ready at recovery and going to the first MRI slot is from 9:55h-13:49h with an average of 11:49h. For patients going to the second MRI slot, the range is from 12:17h-16:43h with an average of 14:15h. A more detailed distribution is depicted in Appendix B: Distribution patient ready for MRI. Given this information, we conclude that the average patient will be ready in time for the first MRI slot, but there are also many patients waiting, and many patients are getting too late. For the second MRI slot, more patients are getting too late than being ready in time. Based on this data, we do not recommend planning the MRI slots earlier since that will only be helpful for a part of the patients.

The second sensitivity analysis is about the availability of brachytherapy personnel. We assume there is plenty of personnel, thus waiting on personnel is not needed. But, waiting at the OR and for the MRI is still in place. This led to an average lead time of 6:13h against 6:15h. Changing the personnel does not mean there are plenty of workplaces for the treatment planning, and it also does not change the speed at which successive steps can be performed, which holds back the little gain that is possible by adjusting the personnel.

4.6.2 Experiments

KPIs can be influenced by configurations. Access time reflects on how many patients are going through the system. Access time can be influenced by changing the OR time in a way that more patients can be treated per week. On the other hand, lead time is a clear KPI that shows how fast a patient can be treated on the day of the intervention.

The sensitivity analysis on the MRI slots and personnel shows that there is not much to gain by changing those parameters. Changing MRI slots cost more effort than it can offer for the average patient. The lead time of the treatment is mostly affected by the time it takes to make the treatment planning. Personnel training and automation of parts of the treatment planning to be able to shorten the period of treatment planning is worth looking into.

The two experimental factors to alter for the current situation are thus OR-time and speed of the treatment planning. There are two alternative scenarios for the speed of the treatment planning, ideal speed, and second-best speed. These two scenarios are estimates based on recent literature on the use of algorithms for automatic planning (Breedveld et al., 2019; Maree et al., 2019; Oud et al., 2020) and automatic contouring (Jong et al., 2021; Savenije et al., 2020) for the brachytherapy or comparable treatments. The ideal speed scenario is not expected to reach very soon, but there are automation processes in progress. Therefore, a second-best speed scenario is made to test what smaller improvements would do for the whole brachytherapy treatment. We decided to do a full factorial design to study the effect of each factor as well as the effects of all interactions between the factors. The experiments are depicted in Table 24.

Experiment	Experimental factor	
	OR-time	*Training*
1	Current full day	Second best speed
2	Current full day	Ideal speed
3	2 half days	Current speed
4	2 half days	Second best speed
5	2 half days	Ideal speed

Table 24. Experiments

After running the experiments, the most promising experiments will be selected for the sensitivity analysis. With the sensitivity analysis patients' arrival rate will be decreased and increased by 10% to see how the system responds to that change. After altering the current situation to find bottlenecks in the brachytherapy process, there are two more important situations to simulate, namely the bridging phase and the new location.

Bridging phase

The bridging phase is a temporary phase for brachytherapy. For a certain amount of time, the current location will not be available anymore and the new location will not be ready. In this phase, the brachytherapy department must move out of F5N and the bunkers. A new location will be used to treat the patients. This has the following consequences for brachytherapy:

- All patients must be treated with HDR.
- Two HDR afterloaders are available, with two bunkers.
- Every patient that currently follows the PDR treatment, will be treated with HDR in two OR sessions a week after another and two irradiation sessions per OR.
- HDR-simple treatments are normally performed in the intervention room, this will change to the bunker.
- Nursing rooms at the gynecology department will be used for patients that wait for the OR need to wait in between treatments.

DBL location

By moving to the new location there is a new workflow possible. Namely, MRI under anesthesia, meaning the patient can recover after the MRI and the MRI is directly after the OR. There is a dedicated OR room available every day of the week if there is anesthesia personnel available. Only HDR treatments are possible with two HDR afterloaders and two bunkers. HDR-simple treatments are performed in the bunkers.

4.7 Conclusion

In this chapter, we described the simulation model and the verification and validation of this model. The key performance indicators identified to analyze the performance of the brachytherapy department are access time, average lead time, waiting time for patients and personnel, overtime, and utilization of OR-time, afterloaders, and bunkers. Furthermore, we described the experimental design that consists of adjusting the OR availability and the speed of the treatment planning processes. At last, we describe two future scenarios that should be evaluated, namely the bridging phase and the DBL location. Chapter 5 discusses the results of the experiments, two scenarios, and the sensitivity analysis.

Chapter 5: Results

This chapter provides the results of the experimental design as stated in Section 4.6. The results of the current situation are covered in Section 5.1, experimentation and results of the bridging phase in Section 5.2, experimentation and results of the DBL location in Section 5.3, sensitivity analysis of all phases in Section 5.4, and we conclude this chapter in Section 5.5.

5.1 Current situation

Experimentation with the current situation is mainly meant to lower the access time and lead time by changing the OR time and speed of the treatment planning process steps. The experiments are evaluated in this section using the performance indicators.

5.1.1 Access time and OR utilization

The use of two half OR days instead of one full day makes a big difference for the access time, as depicted in Table 25. The average access time lowers by almost 25%. For the two half days, we choose to use Tuesday and Thursday to be able to use the extra OR-time from the gynecology department on Monday and Wednesday without having troubles with the afterloader availability.

In the current situation, a gynecological patient is sometimes moved to an extra OR in advance so that the other patients do not incur extreme access time. In experiment 3, there are more OR-slots available, but this rule remains in use, resulting in more unused OR-slots. Experiment 3-1 was carried out to test the same experiment, but where extra OR-slots are less likely to be used when this is not necessarily needed for the gynecological patients. The access time will go up, but the extra use of OR-slots and the unused OR-slots are decreasing.

Experiment	Experimental factor		KPI			
	OR-time	*Training*	*Access time*	*Extra OR-slots*	*OR utilization*	*Unused OR-slots*
Current sit.	Current full day	Current speed	32.6	66	73.4	7
3	2 half days	Current speed	24.7	24	66.6	14
3-1	2 half days	Current speed	28.1	15	69.6	7

Table 25. Access time current situation

5.1.2 Lead time and overtime

The change of treatment planning speed lowers the lead time on an operating day by 13% to 20%, depending on the ideal or second-best speed scenario (Table 26). Highly correlated to that is the average overtime and number of days worked in overtime, which can be reduced with 60% of both the average overtime and the number of days worked in overtime. Two half OR days instead of one full day has only a little impact on the overtime.

Experiment	Experimental factor		KPI		
	OR-time	*Training*	*Lead time*	*Overtime*	*Overtime count*
Current sit.	Current full day	Current speed	6:15	1:19	43
1	Current full day	Second best	5:26	0:49	30
2	Current full day	Ideal speed	4:58	0:33	15
3-1	2 half days	Current speed	6:13	1:12	48
4-1	2 half days	Second best	5:24	0:45	31
5-1	2 half days	Ideal speed	4:56	0:32	14

Table 26. Lead time and overtime of the current situation

5.1.3 Utilization

The change of treatment planning speed has barely impacted the utilization, therefore Table 27 only depicts experiment 3-1.

Experiment	Experimental factor	KPI			
	OR-time	*PDR aft.*	*HDR aft.*	*PDR bunkers*	*HDR bunker*
Current situation	Current full day	39.3	5.7	79.8	53.1
3-1	2 half days	38.9	5.8	79.4	53.8

Table 27. Utilization current situation

5.1.4 Waiting time

There are two types of waiting time: patient and personnel waiting times. Reasons for patient waiting time is the duration of the treatment planning time. After the MRI, the treatment planning process, including contouring and reconstruction, can start. The waiting time is highly correlated with the speed of performing those steps. As seen in the sensitivity analysis of Section 4.6.1, the waiting time for MRI is only for a few patients long. Figure 19 depicts the waiting time divided over waiting for the MRI and waiting for the treatment to be made. Table 28 shows the average time patients wait in each scenario for the MRI and the treatment planning. Regardless of the scenario, the waiting times will stay the same. However, depending on the speed of the treatment planning, the waiting time for that will automatically reduce with it.

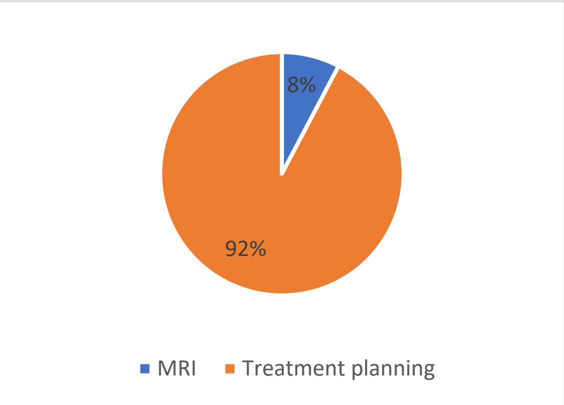

Figure 19. Patient waiting time current situation

Exp	Experimental factor		KPI	
	OR-time	*Training*	*MRI*	*Treatment planning*
Cur.sit.	Full day	Current	0:17	3:29
1	Full day	Second best	0:17	2:42
2	Full day	Ideal	0:17	2:14
3	2 half d.	Current	0:18	3:28
4	2 half d.	Second best	0:18	2:41
5	2 half d.	Ideal	0:18	2:13

Table 28. Patient waiting time current situation in h:mm

Personnel waiting time exists of waiting time for the MRI-slots and waiting time for other colleagues to perform a task. Most of this waiting time comes from waiting for the MRI slot. As the sensitivity analysis of Section 4.6.1 shows, using much personnel will only improve the lead time by a few minutes. Figure 20 depicts the waiting time divided over waiting for the MRI and waiting due to personnel actions. Table 29 shows that the waiting time for personnel is also not very sensitive for the scenarios and will not rise much.

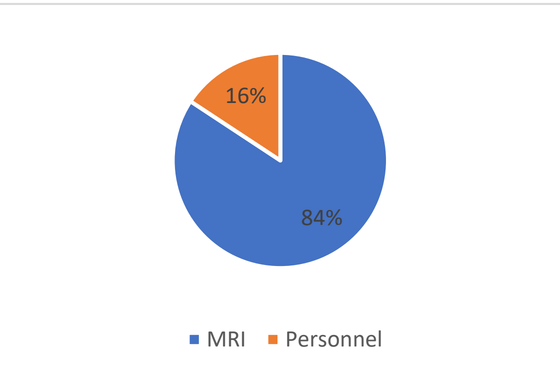

Figure 20. Personnel waiting current situation

Exp.	Experimental factor		KPI	
	OR-time	*Training*	*MRI*	*Personnel*
Cur.sit.	Full day	Current	0:17	0:03
1	Full day	Second best	0:17	0:04
2	Full day	Ideal	0:17	0:04
3	2 half d.	Current	0:18	0:02
4	2 half d.	Second best	0:18	0:03
5	2 half d.	Ideal	0:18	0:03

Table 29. Personnel waiting time current situation in h:mm

5.1.5 Other experimentation

The number of available afterloaders limits the possibility of different scheduling rules. One HDR and two PDR-afterloaders are available, which means that a maximum of one HDR and two PDR patients can be treated simultaneously. But both those treatments also need an MRI and treatment planning before the irradiation can start. Planning three of those treatments on one OR day is very time-consuming as they all have a long workflow after the OR. Besides that, it is not possible to have a third MRI before the closing time of the MRI. The average time a patient would be ready for the third MRI slot is 17:00h with a range between 14:43h-19:13h.

5.2 Bridging phase

The brachytherapy must move out of F5N and the bunkers in this phase. Therefore, the brachytherapy will use a new location which involves a few changes. For starters, all patients will be treated with HDR. Patients that currently follow the PDR treatment will be treated with HDR in two OR sessions a week after another and two irradiation sessions per OR. These OR appointments and irradiation sessions will be planned together. There are two HDR-afterloaders and two bunkers available. HDR-simple treatments will be performed in the bunker instead of a separate intervention room. All patients will leave the bunker to a nursing department after and in between irradiation sessions to treat more patients on the same day.

Changing to only HDR treatments increases the times that OR appointments are requested from an average of 158 to 257 OR appointments per year. This means that a significant change in the use of OR-time is needed because the current number of OR days (39 days of three slots) will only provide 117 appointments. The use of extra OR time of the gynecology department will not close the gap to 257 OR appointments and cannot be a sustainable solution. 1.5 OR days per week, every week of the year will provide 260 OR slots. It is also possible to use another distribution to get the same number of OR slots, for example, two-thirds of the weeks two full OR days and one-thirds of the weeks one full OR day. However, this is disfavored because of the fluctuations in patient arrival. Gynecology patients can only be planned for the first OR in the eighth or ninth week after consultation. If high peaks of these patients come when there is only one full OR day, extra OR time is needed more often, namely 55 times against 19 times when using 1.5 days.

Three experiments based on OR-time are performed. First, the simulation uses a full Tuesday and Thursday morning at the OR. Second, the simulation uses a full Monday and Thursday morning at the OR, and third a full Monday and Wednesday morning at the OR. Friday is not suitable for an OR-day since 82% of the OR interventions are for patients with a two-day treatment, which cannot continue on Saturdays. Because of the two-day treatment, it is preferable to keep a day between two OR days in a week to spread the patients over the week to lower congestion at the bunkers and prevent significant differences in workload. Besides the OR-time, the speed of the treatment planning process steps as used in the current situation experiments is also used here, in combination with all OR-time variations, resulting in nine different experiments.

5.2.1 Access time

The average access time gets only affected by the dedicated OR time. Adjustments were made for all experiments. For experiment 1, the timeslot for the small interventions on Wednesday had to be changed. Those timeslots were in the afternoon, which collided with the use of the bunkers for the patients that go on the OR on Tuesday and have their second irradiation treatment on Wednesday afternoon. For experiments 4 and 7, an adjustment in the availability of personnel is made. The availability from Monday and Tuesday is switched, to have enough personnel to run the OR that day. Besides that, a third MRI slot is added. Table 30 shows the average access time of the scenarios. All scenarios have a slightly shorter average access time in comparison with the current situation.

Experiment	Experimental factor	KPI
	OR-time	*Access time*
Current situation	Current full day	32.6
1	Tuesday full day, Thursday morning	30.8
4	Monday full day, Thursday morning	30.9
7	Monday full day, Wednesday morning	31.2

Table 30. Access time in days of the bridging phase

5.2.2 Lead time

The lead time is mostly affected by the speed of the treatment planning process steps and a little bit by the use of OR-time in combination with the small intervention timeslots (Table 31). Overall, it results in the same as for the current situation with different speed factors.

Experiment	Experimental factor		KPI
	OR-time	*Training*	*Lead time*
Current sit.	Current full day	Current speed	6:15
	Tuesday full day, Thursday morning	Current speed	6:05
2	Tuesday full day, Thursday morning	Second best speed	5:18
3	Tuesday full day, Thursday morning	Ideal speed	4:52
4	Monday full day, Thursday morning	Current speed	6:08
5	Monday full day, Thursday morning	Second best speed	5:19
6	Monday full day, Thursday morning	Ideal speed	4:53
7	Monday full day, Wednesday morning	Current speed	6:10
8	Monday full day, Wednesday morning	Second best speed	5:20
9	Monday full day, Wednesday morning	Ideal speed	4:55

Table 31. Lead time of the bridging phase in h:mm

5.2.3 Overtime

The KPI overtime is mostly affected by the speed of the treatment planning and a little by the use of OR-days. The average overtime and the number of days that are worked in overtime per scenario are given. The average overtime only counts for the days in which is worked in overtime. Table 32 shows that there is a big difference in the number of days worked in overtime for the current situation in comparison with the bridging phase. This is caused by the rise of OR interventions from 158 to 257. The difference in speed has a higher impact on the average overtime than on the number of days.

Experiment	Experimental factor		KPI	
	OR-time	*Training*	*Overtime (h:mm)*	*Count*
Current sit.	Current full day	Current speed	1:19	43
1	Tuesday full day, Thursday morning	Current speed	1:44	100
2	Tuesday full day, Thursday morning	Second best speed	1:00	95
3	Tuesday full day, Thursday morning	Ideal speed	0:46	78
4	Monday full day, Thursday morning	Current speed	1:48	98
5	Monday full day, Thursday morning	Second best speed	1:02	94
6	Monday full day, Thursday morning	Ideal speed	0:46	79
7	Monday full day, Wednesday morning	Current speed	1:50	96
8	Monday full day, Wednesday morning	Second best speed	1:02	96
9	Monday full day, Wednesday morning	Ideal speed	0:46	80

Table 32. Overtime of the bridging phase

5.2.4 Utilization

Utilization of OR-time, afterloaders, and bunkers is measured. The utilization barely differs due to changing the speed of the treatment planning steps. Therefore, Table 33 only depicts the experiments with the current speed. In the bridging phase, there will be two HDR-afterloaders and two HDR-bunkers available compared to one in the current situation. In addition, all patients will be treated with HDR, causing the utilization of the afterloaders to rise. The utilization of the bunkers has decreased compared to the current situation because patients are only in the bunker during the treatments instead of from admission to recovery of the treatment. Solely looking at the utilization rates, two afterloaders and bunkers are unnecessary. Adjusting the treatment blueprint according to the OR day choices will lower congestion at the bunkers to a minimum. However, the impact on personnel is not considered.

The OR time utilization is not very high, namely 68%. Two reasons are that not every possible OR is used and that not all hours on an OR day are used. This poses two questions: why not all OR slots are filled and whether it is possible to perform four interventions at the OR on one day. Not all OR slots are filled even though those are the right amount because of the fluctuation of the patient's arrival. A large part of the patients are gynecological patients who need to be treated in two specific weeks. If many of those patients arrive in the same week, it means they all have the same two weeks they can be planned for their first OR appointment. This means a peak in demand, where the supply remains the same. These weeks the use of extra OR time is necessary. In quiet weeks there will be places left.

Experiment	Experimental factor	KPI				
	OR-time	*Utilization for one afterloader*	*Utilization for one bunker*	*OR utilization*	*Extra OR-slots*	*Unused OR-slots*
Current sit.	Current full day	7.5%	53.6%	73.4%	66	7
1	Tuesday full day, Thursday morning	12.2%	17.7%	67.9%	19	21
4	Monday full day, Thursday morning	12.8%	18.5%	68.1%	19	21
7	Monday full day, Wednesday morning	12.2%	17.7%	68.1%	18	20

Table 33. Utilization bridging phase

It is theoretically only possible to perform four interventions at one OR day if those interventions are all PDR-simple treatments, they do not take more than the average time, and the switch between patients on the OR is swift. It is difficult to determine beforehand if an intervention will take the average time or less and whether the change of patients will go smoothly, which means that it is practically impossible to perform four interventions in one OR day. Figure 21 depicts a boxplot of the end time of OR interventions divided into one, two, or three interventions performed. The data is from experiment 1. For three OR interventions, the average time of being ready at the OR is 15:42h which will cause some time to be leftover. But there are also days where the full OR-time and even more is used. The average end time when performing two OR interventions is 12:42h. 95% of the OR-interventions, when performing two, will be done at 14:05h. The brachytherapy department can use this information to negotiate with the OR management for better use and distribution of OR time.

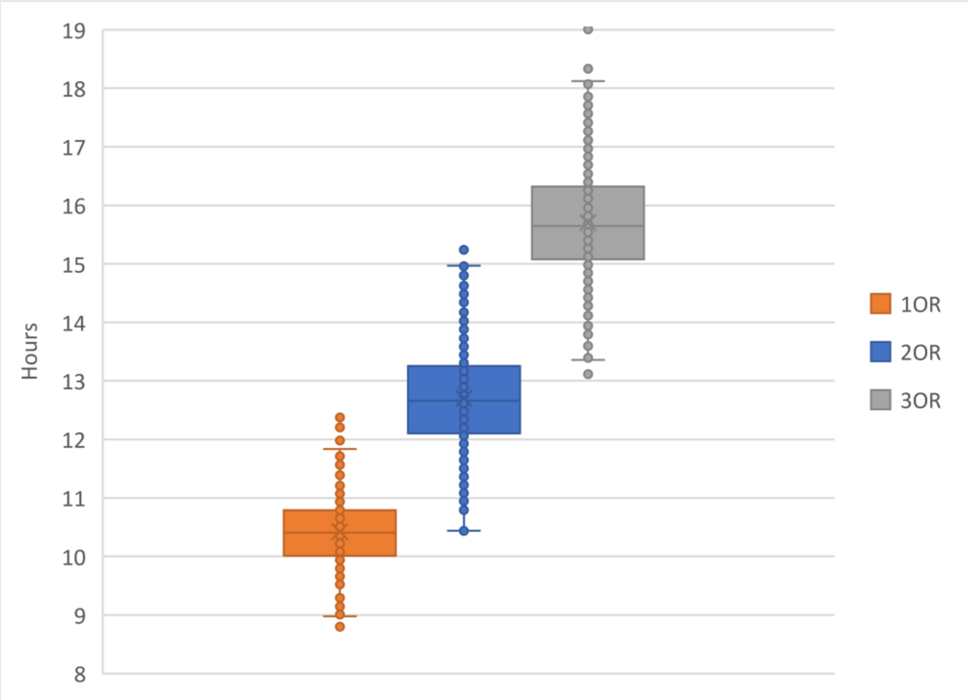

Figure 21. Boxplot of the end time of OR interventions

It is inefficient to leave slots unused but not avoidable. In those situations, the unused slots are given back to the OR in time to give the time to other specializations. Structurally receiving fewer OR slots will improve the utilization of the allocated slots. Peak demand of the gynecology patients is known two months in advance, which leaves the opportunity to ask for extra OR slots in time.

5.2.5 Other experimentation

There is some experimentation done on the scheduling techniques for the OR-day. In the current situation, the afterloaders would restrict other scheduling techniques. But in the bridging phase, the patients will not occupy an afterloader for a long time since the set-up of the treatments will be different. In this situation, it is possible to treat multiple patients after each other with the same afterloader. Therefore, we composed the following OR scheduling rules:

1. HDR and (formerly) PDR allowed on the first two slots, LDR on all three slots
2. HDR allowed on the first two slots, PDR and LDR on all three slots
3. HDR, PDR, and LDR allowed on all three slots

The first experiment is a slight improvement in the utilization of OR time. The second and third experiment makes even better use of OR-time but needs to use a third MRI slot, which is a bottleneck. The time a patient is ready for the third MRI lies in a range of 13:42h-19:22h with an average of 16:12h for the second experiment. For the third experiment, the range is 13:42h-19:56h with an average of 16:21h. The MRI closes at 17:00h, making experiments two and three infeasible. For the same reason, it is not possible to cluster treatments on the OR day. Clustering only HDR-complex treatments or only PDR-complex and PDR-simple treatments on one OR day will give troubles with the third MRI slot. Clustering LDR treatments is possible and is already being done. But LDR treatments are also the only treatments that can be performed as third on the OR and therefore will also be used to fill up OR-time if possible.

5.3 DBL location

By moving to the new location there is a new workflow possible. Namely, MRI under anesthesia, meaning the patient can recover after the MRI, and the MRI is directly after the OR intervention. There is a dedicated OR room available for the brachytherapy every day of the week if anesthesia personnel is available. The use of a dedicated OR room implies that asking for extra OR time dedicated to other specialties does not exist in this situation. Only HDR treatments are possible with two HDR afterloaders and two bunkers. HDR-simple treatments are entirely performed in a bunker.

5.3.1 Baseline measurement

The PDR-patients will follow the same HDR treatment trajectory with two OR interventions as in the bridging phase. 257 OR interventions are requested per year, which is on average five per week. In this case, the OR-room is no longer a restricting factor, but anesthesia personnel who need to be hired will be. We start with a baseline measurement where we use two OR-slots on Monday, Tuesday, Wednesday, and Thursday and plan no small interventions. The current small interventions blueprint will bias the simulation as it is designed to use Tuesday as an OR day. Therefore, decide on the blueprint after assigning the OR days. Friday is left out of the possibility of an OR-day because 82% of the demanded OR-slots consist of a two-day treatment which cannot continue on Saturdays. This baseline gives the best access time achievable. We can compare more realistic scenarios with this baseline to evaluate the impact of different alternatives.

Table 34 shows that the average access time of the baseline measurement is 20 days. In all cases, the patients can be planned in the available OR-time, which is eight slots per week. The average lead time of the new workflow will be 4:31h, which is much shorter than in the current situation (6:15h) because of the MRI that can be performed under anesthesia. This way, the recovery time of on average 60-90 minutes can be simultaneous with the treatment planning, and thus this time does not go to waste. Overtime will occur 46 times a year with 47 minutes on average. The average overtime is also less than in the current situation because of the new workflow.

Experiment	Access time (days)	Extra OR-slot	Lead-time (h:mm)	Utilization for one afterloader	Utilization for one bunker	Overtime (h:mm)	Overtime count
0) Baseline	20.5	0	4:31	11.2%	13.6%	0:47	46

Table 34. Baseline DBL location

5.3.2 OR-time

Making eight OR-slots available per week is not a realistic scenario as we want more structure instead of ad hoc planning, anesthesia must be available for the slots, and it is more than demanded. Therefore, we did experiments with six OR-slots divided into three days. This will still be more than is required but will already restrict the model. Not using Friday as OR-day will result in four possible scenarios, experiments 1, 2, 3, and 4, as depicted in Table 35. All four scenarios result in an access time of around 26 days, which is an increase of 30% with respect to the baseline. But there is still no need to use extra OR time, which means that six OR-slots per week will be enough in demand peaks of gynecological patients. Most other performance indicators stay the same, except for the days worked in overtime. The difference is the most for scenarios 3 and 4, where the OR-days are consecutive. In combination with the two-day treatments results in doing the work concerning OR interventions in fewer days than when there would be a day without OR interventions in between. Distributing the workload evenly with spreading OR-days results in less overtime.

Since six OR-slots per week is still one more than needed, we performed experiments with five OR-slots per week. Alternations on experiment 2 are used because this distribution of OR-days resulted in slightly less lead time and overtime. The three alternations on experiment 2 all gain similar results; therefore, Table 35 only depicts experiment 5. One OR slot is available on Monday, and two on Tuesday and Thursday in that experiment. The most significant impact of changing from six to five structurally available slots is the access time that increases by 50% and is twice as high as the baseline. Besides that, five OR-slots could not provide enough to keep up during peak demand. In the current situation, the brachytherapy department can only arrange extra OR time for gynecological patients by asking for additional OR time at the gynecology department. Experiment 5 still uses this rule, but in the DBL situation, the operating rooms are not a bottleneck because the brachytherapy department has a dedicated operating room of its own. This means that it is possible to plan extra OR-slots in busy weeks and use them for all patients.

Experiment 6 will use a new planning rule to use OR-time outside the structurally planned OR-slots when any patient exceeds an access time of 35 days. Using 22 OR-slots outside the original planning will reduce the access time to 24 days. Remarkable is that mainly prostate patients use the extra OR-slots. The reason is that gynecology patients are planned eight to ten weeks in advance due to the external radiotherapy they receive beforehand. Currently, the model only uses two OR-slots on one day because a third slot is only possible for LDR patients. It is possible to cluster three LDR patients and plan a day with anesthesia to do more interventions when planning manually.

Experiment 7 shows the performance if there is no option to use OR-time outside the five weekly OR-slots as used in experiments 5 and 6. The access time would rise tremendously. Experiments 6 and 7 show what flexibility in OR-slots can do for the access time. A situation where six slots are structurally available or a situation where five slots per week are structurally available combined with the possibility to arrange extra slots in peak demand is needed to keep the access time at a desirable level.

Experiment	Access time (days)	Extra OR-slot	Lead-time (h:mm)	Utilization for one afterloader	Utilization for one bunker	Overtime (h:mm)	Overtime count
0) Baseline	20.5	0	4:31	11.2%	13.6%	0:47	46
1) Monday, Wednesday, Thursday	25.9	0	4:31	11.2%	13.7%	0:48	52
2) Monday, Tuesday, Thursday	26.1	0	4:28	11.2%	13.7%	0:47	52
3) Monday, Tuesday, Wednesday	26.6	0	4:32	11.2%	13.7%	0:50	55
4) Tuesday, Wednesday, Thursday	26.0	0	4:36	11.2%	13.7%	0:50	58
5) Monday1, Tuesday2, Thursday2	38.9	10	4:29	11.2%	13.7%	0:50	47
6) New planning rules	24.1	22	4:28	11.2%	13.6%	0:46	47
7) No extra OR-time	56.5	-	4:28	11.0%	13.4%	0:48	44

Table 35. Results experiments DBL location

5.3.3 Blueprint small interventions

We can decide on the blueprint schedule for small interventions after choosing the OR slots. In case of experiment 2, the first irradiation on the OR-day starts at the earliest at 12:36h and the latest at 20:09h. The second irradiation on the day after the OR starts at the earliest at 10:22h and the latest at 12:50h. The third irradiation of the HDR-complex patients will start at 16:30h. If the goal is to interrupt the treatment process of those patients the least, we should consider the above-mentioned times. Table

36 depicts the irradiation schedule if Monday, Tuesday, and Thursday would be used as OR-days with two OR-slots each day. Every Monday, Tuesday, and Thursday afternoon there can be two irradiation sessions planned. Every Tuesday, Wednesday, and Friday morning the second irradiation session will follow. Looking at that schedule, we would propose to schedule small interventions on Monday morning, Wednesday afternoon, Thursday morning, and Friday afternoon. The first fraction of the HDR-simple treatment can take at most three hours. Therefore, the slots in the morning are set at 8:30 and 9:30 and the afternoon slots are set at 13:30 and 14:30. This way they do not create overtime and they do not fall simultaneously with the irradiation session of the OR patients.

	Monday	Tuesday	Wednesday	Thursday	Friday
Morning		Second irradiation	Second irradiation		Second irradiation
Morning		Second irradiation	Second irradiation		Second irradiation
Afternoon	First irradiation	First irradiation		First irradiation	
Afternoon	First irradiation	First irradiation		First irradiation	

Table 36. Irradiation schedule if Monday, Tuesday, Thursday are OR-days

Table 37 depicts the results of experiment 2 and the same experiment but then with the HDR-simple treatments (experiment 8). We can see that this blueprint schedule indeed does not change anything about the lead time and overtime. As expected, the utilization will rise, and the average access time will drop a bit because the blueprint provides plenty of slots. Experiment 9 is the same as experiment 8 but uses the ideal treatment planning scenario. This results in the best lead time possible and shows that even in that case there will be overtime.

Experiment	Access time (days)	Extra OR-slot	Lead-time (h:mm)	Utilization for one afterloader	Utilization for one bunker	Overtime (h:mm)	Overtime count
2) Monday, Tuesday, Thursday	26.1	0	4:28	11.2%	13.7%	0:47	52
8) With HDR-simple	24.2	0	4:29	12.0%	17.4%	0:47	52
9) With HDR-simple and ideal speed	24.2	0	3:17	12.0%	17.1%	0:21	9

Table 37. Results DBL location with and without HDR-simple treatments

Table 38 depicts the results of experiment 6 in comparison with the same experiment but with scheduling HDR-simple treatments (experiment 10). In this experiment, extra OR time is being used to keep the access time low. Another OR slot is used 22 times. The same applies here as for experiment 2, using the above-defined blueprint will not affect other patients' flow. And using the ideal treatment planning speed (experiment 11) will still result in overtime.

Experiment	Access time (days)	Extra OR-slot	Lead-time (h:mm)	Utilization for one afterloader	Utilization for one bunker	Overtime (h:mm)	Overtime count
6) New planning rules	24.1	22	4:28	11.2%	13.6%	0:46	47

10) With HDR-simple	22.6	22	4:28	12.0%	17.4%	0:46	47
11) With HDR-simple and ideal speed	22.6	22	3:17	12.0%	17.1%	0:20	8

Table 38. Results DBL location with and without HDR-simple treatments

5.4 Sensitivity analysis

The most promising experiments of the current situation, the bridging phase, and the DBL location are selected for a sensitivity analysis. With the sensitivity analysis patients' arrival rate will be decreased and increased by 10% to see how the system responds to that change.

5.4.1 Current situation

The first experiment chosen is where two half OR-days are used with the ideal speed scenario for the treatment planning, here we call it experiment 1. This experiment and the model of the current situation are used in the sensitivity analysis. Figure 22, Figure 23 and Figure 24 only depict the KPIs impacted by the change in arrival rate.

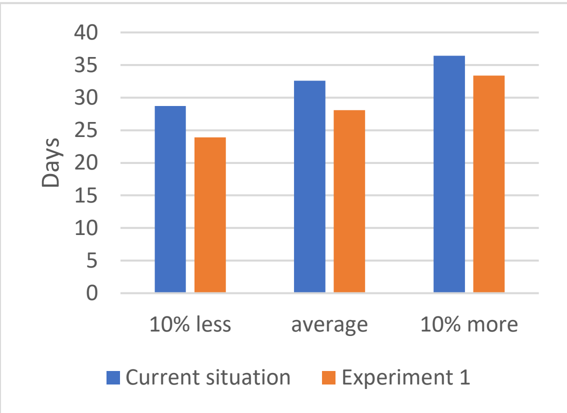

Figure 22. Sensitivity analysis on KPI access time for the current situation

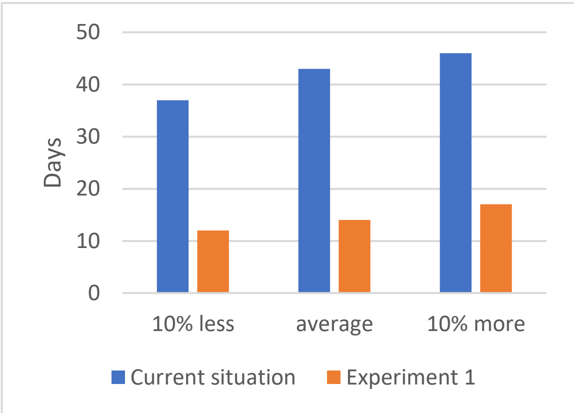

Figure 23. Sensitivity analysis on KPI overtime count for the current situation

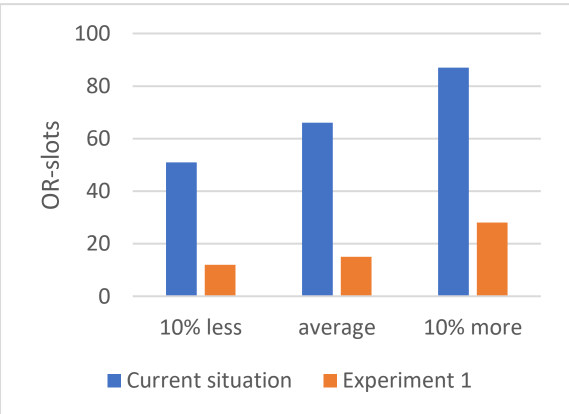

Figure 24. Sensitivity analysis on KPI extra OR-slots for the current situation

This sensitivity analysis shows that the current way of working cannot deal with an increase of patients because the access time is already too high and will only rise more. Using two half OR-days can better handle the increase of patients, but still has too high access time. The current way of working is not equipped for growth and already balancing to treat its patients in time. Using two half OR-days only provides enough improvement for the current patient arrival rate.

5.4.2 Bridging phase

For the bridging phase, we use the experiment where a full Tuesday and half Thursday are available as OR days. The first experiment makes use of the current speed scenario from this experiment, and the second experiment makes use of the ideal speed scenario. The third experiment is where a full Monday and half Wednesday are available as OR days, using the ideal speed scenario. Figure 25 depicts the KPI access time, Figure 26 the KPI extra OR-slots, and Figure 27 the KPI overtime count.

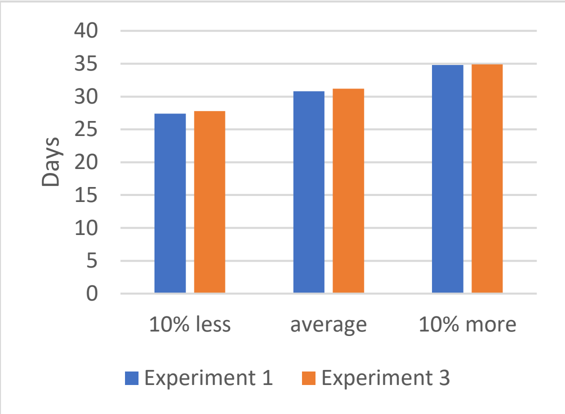

Figure 25. Sensitivity analysis on KPI access time for the bridging phase

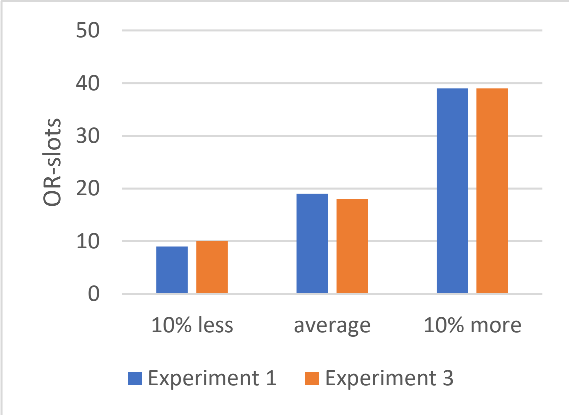

Figure 26. Sensitivity analysis on KPI extra OR-slots for the bridging phase

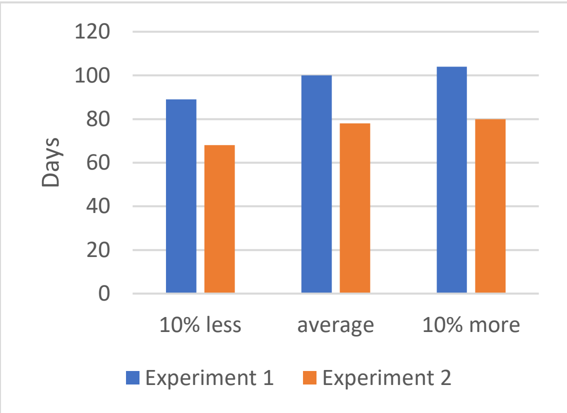

Figure 27. Sensitivity analysis on KPI overtime count for the bridging phase

When the arrival rate decreases, the access time will decrease by 11%. When the arrival rate increases, the access time will increase by 13%. Which is, as the current situation, around the actual change of the arrival rate. The extra use of OR-slots is affected a lot, they double or halve. But comparing it to the in- or decrease of 26 OR-interventions, that is not a strange reaction. The bridging phase is also not equipped for growth, as the increase in patients will rise the access time too much. But the bridging phase is also not designed for more OR interventions. The difference in treatment planning time between experiments 1 and 2 continues to reduce the number of days worked in overtime, regardless of the patient arrival rate.

5.4.3 DBL location

For the first experiment, the baseline measurement is chosen. For the second experiment the configuration that uses two OR-slots on Monday, Tuesday, and Thursday is chosen. For the third experiment the configuration that uses 1 OR slot on Monday and 2 on Tuesday and Thursday, with the modified scheduling rule where 35 days access time or more will not be accepted is chosen. Figure 28 depicts the KPI access time, Figure 29 depicts the KPI extra OR-slots, and Figure 30 the KPI overtime count.

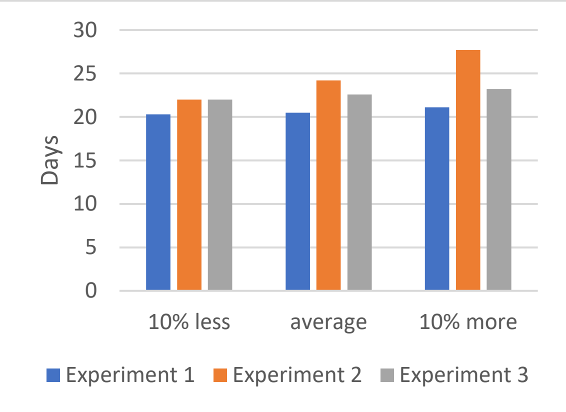

Figure 28. Sensitivity analysis on KPI access time for DBL location

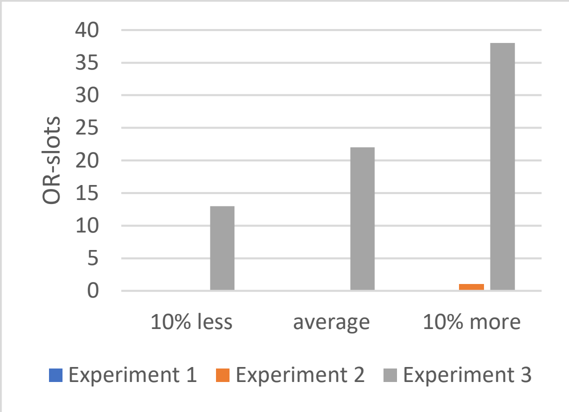

Figure 29. Sensitivity analysis on KPI extra OR-slots for DBL location

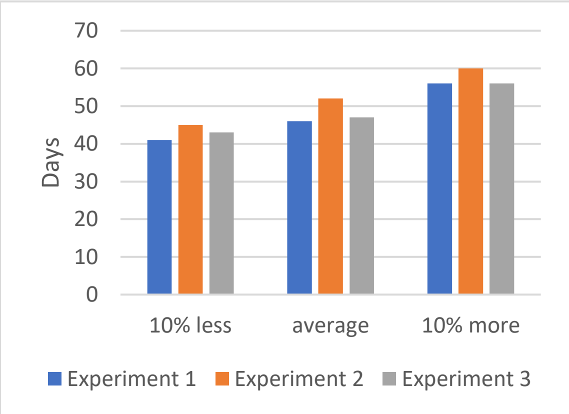

Figure 30. Sensitivity analysis on KPI overtime count for DBL location

Both experiment 2 and 3 manages the access time better than experiments of the current situation and bridging phase. Experiment 3 keeps the rise in access time to a minimum by opening more OR-slots when needed instead of having structurally more slots as in experiment 2. Working that way also results in a minimal increase of days worked in overtime compared to the baseline experiment. This sensitivity analysis shows that opening more OR-slots in peak periods results in lower access time, also when the arrival rate increases.

5.5 Conclusion

This chapter provided an analysis of various experiments on the simulation model of the current situation, the bridging phase, and the DBL location. For all experiments, multiple performance indicators are used to test the potential performance.

For the current situation, the need for more OR slots is high. This is shown by the performance indicators access time and the extra number of OR-slots that need to be used. With the use of the current scheduling rule, the access time drops by 25% if every time an OR-day is assigned to the brachytherapy department would have been two half days instead. Besides the access time, the number of extra OR-slots that are used from the gynecology department is decreased by 63%. With adjusting the current scheduling rule, the access time still drops by 13.8%, and the use of extra OR-slots decreases even with 77.3%.

The simulation model makes clear that the bottleneck is not necessarily the waiting time for an MRI slot because on average the use of flexible MRI slots will gain 17 minutes per patient on a lead time of 6:15h. The patients wait on average 8% of the total waiting time for the MRI slot, whereas the other 92% comes from the treatment planning. Improving the treatment planning techniques through auto contouring, auto planning, and training of personnel, can gain 1:15h less lead time and directly also less waiting time for patients. Decreasing the treatment planning time will automatically result in less overtime for the employees. The number of days that need to be worked in overtime can be reduced by 72% and the average overtime by 62%.

For the bridging phase, it is important to gain understanding of the impact the changes can have on the brachytherapy department. The requested OR interventions will rise by 62.7%. The simulation model of the current situation made clear that in the current situation there are too few OR-slots available, this will only rise for the bridging phase, if not more slots can be opened. The simulation study shows that the use of 1.5 OR-day every week will provide enough OR-slots. Between the OR-days need to be a minimum of one day, because most of the treatments will take two days and will otherwise cause congestion. Depending on the scenario of OR-days, some adjustment regarding personnel roster and blueprint of the small interventions needs to be made.

The bridging phase will have a big impact on the employees by raising the number of days that will be worked in overtime from 40 to 94-100 depending on the scenario. The average overtime will be around 1:46h, which is 27 minutes more than in the current situation. The number of afterloaders and bunkers will change for the bridging phase. Therefore, the use also must change to only using them when a patient receives irradiation.

The DBL location is the ultimate location for the brachytherapy department. The OR room will not be a bottleneck anymore. The ideal use of OR-time is five slots per week divided among Monday, Tuesday, and Thursday and make use of extra OR-slots when patients' arrivals peak. This way the access time stays in control. Depending on the choice of OR-days, a decision can be made for the small intervention blueprint.

Chapter 6: Conclusion

This chapter finalizes this research. First, Section 6.1 presents the main conclusions of this research. Then, a discussion of the results is described in Section 6.2. Finally, Section 6.3 offers our recommendations for the Amsterdam UMC brachytherapy department.

6.1 Conclusion

In this research, the following main research question is addressed:

"How do we set up the brachytherapy treatment process at the new location so that timely treatment and an efficient and patient-friendly treatment process can be realized for all patients while guaranteeing high tumor control and a low risk of (late) toxicity?"

We have developed a discrete-event simulation model that includes a lot of the complexity of the actual system. Multiple scenarios were evaluated using the simulation model, to start with the current situation. The goal was to see what bottlenecks keep the brachytherapy treatment from improving and how the treatment process can be modeled at the new location. Analysis of the results shows that the MRI slots and amount of personnel are of less impact than expected. The biggest bottleneck for the access time not being under the norm is the amount of OR time. Yearly, the OR facilitates only 74% of the interventions. It is proven that four interventions do not fit on one OR day. Therefore, it is suggested to use two half OR-days, the mornings, instead. Two half OR-days can reduce the average access time by 14% and reduce the use of extra OR-slots by 77.3%. Daily, the bottleneck for a fast treatment process is that all steps are consecutive, and the treatment planning is where the patients wait for most. Many steps belong to the treatment planning, among others: contouring, reconstruction, making the treatment plan, and checks. Treatment planning can start after the MRI is taken as the imaging is used as input. There are ways to shorten the treatment planning time by using auto contouring, auto planning, and personnel training. Improving the treatment planning techniques can gain 1:15h less lead time, which is an improvement of 20%. Decreasing the treatment planning time automatically results in less overtime for the employees. The number of days worked in overtime can be reduced by 72% and the average overtime by 62%.

There are a few necessary changes when the brachytherapy department moves to the bridging phase. Only performing HDR treatments results in a high increase in OR interventions. The best way to deal with that is to use five OR-slots per week, divided over a full OR-day on Tuesday and a morning on Thursday. Patients do not arrive equally over the year, which results in peak demand and low demand. During peak demand, the department must use OR-time outside their own, which causes unused OR-time during low demand. It is inefficient to leave slots unused, but it is not avoidable due to peak and low demand. To better use the given OR-slots, it is possible to structurally get fewer slots than required, thus two half days a week. Peak demand of the gynecology patients is known two months in advance, which leaves the opportunity to ask for extra OR slots in time. The bridging phase will have a significant impact on the employees, as the number of days worked in overtime rises from 40 to 94-100 days a year, with on average 1:46h. Improving the treatment planning techniques results in less overtime, but for the best scenario that is still 78 days with on average 0:46h. Working with shifts is worth looking into. Not performing PDR treatments significantly influences the use of bunkers and afterloaders. The time a patient uses the bunker is short. It is possible to use one HDR-bunker and afterloader, but that means less flexibility as every patient needs to be transported back to the nursing department.

A new workflow can be realized when the department moves to the new location. The biggest improvement for the department is the MRI under anesthesia. This way, the recovery time can go simultaneously with the treatment planning, both very time-consuming activities. Besides that, a dedicated OR is always available, which allows optimizing the use of OR-time to a certain extent. The simulation model shows that using five slots, one on Monday and two on Tuesday and Thursday, and planning extra OR-slots in peak demand, results in the least access time. If this OR schedule will be used, it is advisable to adjust the small interventions schedule and plan those on Monday morning, Wednesday afternoon, Thursday morning, and Friday afternoon. This way, the patients that need the bunker are spread through the week, and the patients from the OR do not need to wait for the bunker to be available. There is enough personnel when not considering holidays and workload outside the treatment of brachytherapy patients. However, the first bottleneck for this phase would be the amount of personnel because the small interventions are simultaneous with the OR interventions to reduce waiting time at the bunker.

For all scenarios, there is no immediate need for extra personnel. However, there is a significant amount of overtime, especially for the bridging phase and DBL location, caused by the rise in OR interventions. Even the fastest treatment planning scenario cannot eliminate overtime. Working in shifts might be a solution. Besides that, the current situation and bridging phase are not equipped for growth thus are not future-proof. The biggest bottleneck is the OR capacity restraining the throughput and raising the access time. This bottleneck is eliminated in the DBL location, but personnel becomes a restriction to the possible throughput.

6.2 Discussion

The discussion section is divided into three subsections. Section 6.2.1 addresses the limitations of this research, Section 6.2.2 explains the theoretical contributions, and Section 6.2.3 describes the practical contributions of this research.

6.2.1 Limitations

The simulation study can embody the complexity of the brachytherapy treatment trajectory and can evaluate various scenarios, but it is not an optimization tool. It can give great insight into predetermined scenarios but cannot optimize to provide the best scenario.

Four care plans are used in the simulation model, but not all patients fit in one of those four care plans. For the small patient groups with specific care plans we chose per patient group the care plan that works best. This means that the number of patients in the simulation model corresponds to the real number of patients, but the workflow is different, which can lead to a slightly different outcome. In addition, specific planning rules regarding patients' personal circumstances are not considered, for example, diabetic patients that need the first OR slot.

Input data of the times of the process steps is primarily based on professional judgment rather than actual data due to the lack of this data. The treatment planning speeds scenarios are also based on professional judgment and literature regarding automatic contouring and automatic planning. It might result differently in reality. For future projects, it can be helpful to log more data.

The simulation model does not plan volume measurements, which results in a higher availability for small interventions. That can cause a faster access time than in reality.

The simulation model does not provide insights on the personnel level. The amount of available personnel is used, but tasks or patients are not assigned to specific radiation oncologists or radiation therapists. This may cause the actual situation to turn out differently. However, less value is attached to this, since in the current situation another radiation oncologist will also step in if necessary. Besides that, the personal vacation of staff is not considered. The context analysis shows that the availability of radiation therapists can lead to understaffed OR days. This is not used in the simulation model. In addition, the number of radiation therapists changed during this project. During the context analysis, there was one less radiation therapist who is included in the simulation because this represents the normal situation. This may have influenced the context analysis.

6.2.2 Theoretical contributions

During the literature review, we have noticed that simulation studies are popular for healthcare processes. While existing studies have provided simulation studies for external radiotherapy, they did not address the brachytherapy at all or in detail. The brachytherapy department is a complex case because of the high dependency on other departments and the number of successive steps performed by various specialists before the treatment can start. This study shows that it is possible to simulate the treatment trajectory, considering the limitations. The simulation study can translate much complexity from the real situation and evaluate various scenarios.

Other brachytherapy departments in the Netherlands have also not yet looked in such detail, using a simulation, at the impact of various adjustments on the process and the lead time. MRI under anesthesia is a relatively new concept and will change the workflow a lot. Such a significant change cannot be tested in reality, where a simulation offers the opportunity to do this up to a certain level.

6.2.3 Practical contributions

For Amsterdam UMC, our research contributes to an increased understanding of the bottlenecks of the brachytherapy treatment process and the impact of changing the process on different parameters. The simulation model gives insights into data that is otherwise not available or being measured. This study can be used to form decisions about the current situation as well as the bridging phase that is starting soon and ultimately the DBL location. Results of the study only show implications for the brachytherapy department but can be helpful in consultation with other departments to improve the process, which is already put to practice with the OR planners. Amsterdam UMC verifies the value of the study. Based on the results of this study, an innovation request is filed and approved to extend this simulation study to hyperthermia and external radiotherapy.

6.3 Further research

The simulation model does not assign tasks and patients to specific personnel as in reality. Nevertheless, it can be interesting to know what impact certain rosters have on patients' access time and lead time. Optimizing detailed agendas of radiation oncologists and therapists can be done in future research. In addition, testing rosters for working in shifts is a recommendation. The simulation shows that every situation tested resulted in reasonable overtime caused by the OR interventions. Besides, optimizing the small interventions blueprint is also recommended for future research.

A large part of the input data is based on experts' opinions, thus might be biased. Improving the quality of input data by using actual measurements can increase the reliability of the results. If the department is interested in using such optimization processes more often, it can be helpful to log more data. More insight into the times a patient is received, in treatment, and ready at a specific step in the treatment is useful, for example at the MRI. Currently, the OR is working with a patient tracking system. That might be helpful throughout the whole hospital. Besides tracking the patients, logging times of the treatment planning process can gain better insights into the use of personnel and time for certain steps and care plans.

The current situation does not raise any questions about the availability of applicators. The department wants to treat more indications in the future, resulting in more patients. That, combined with the changing PDR to HDR treatments; thus more OR interventions might raise a question about the availability of applicators in the future. Therefore, we recommend evaluating future perspectives for the DBL situation and adding the availability of applicators.

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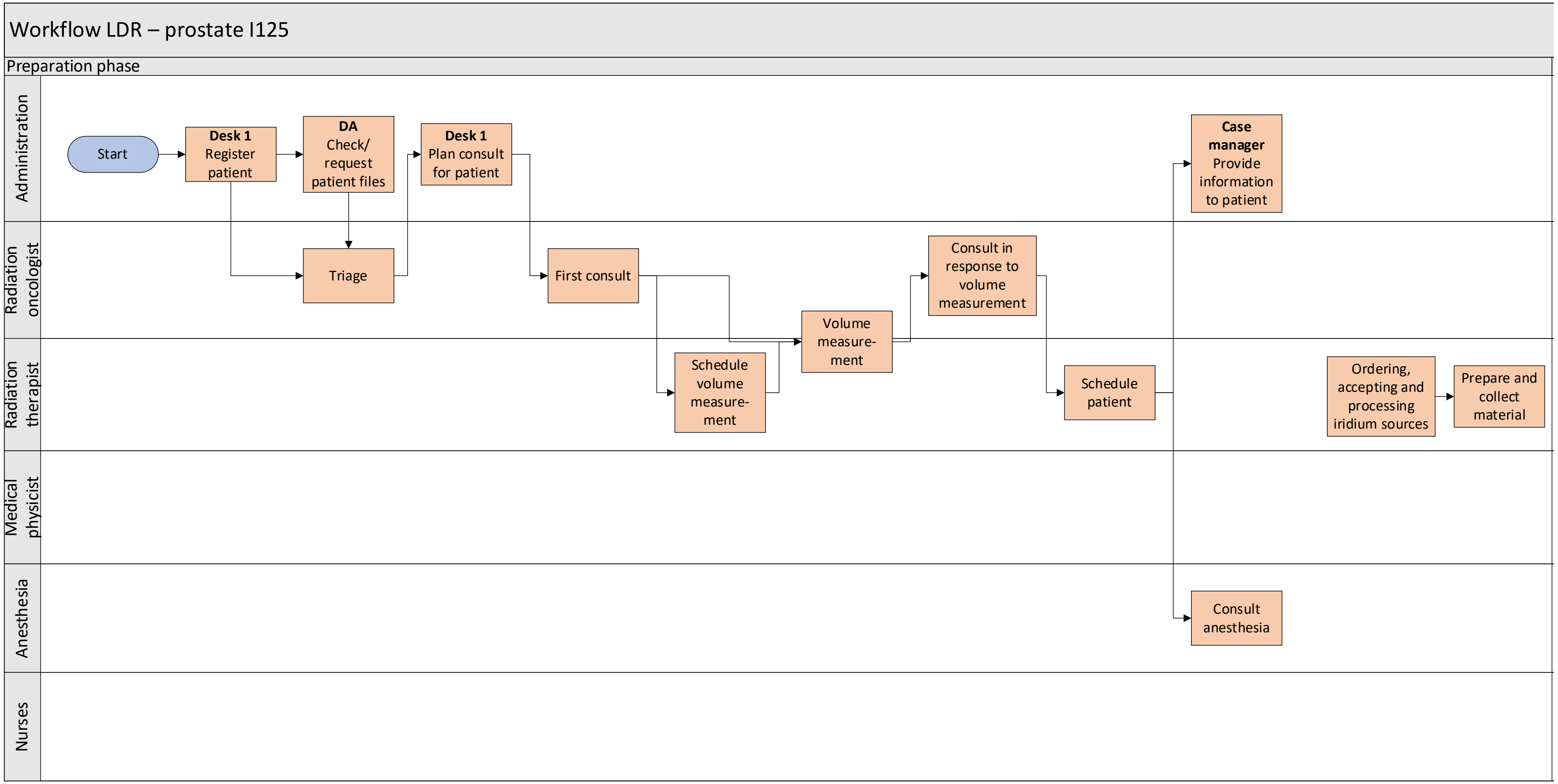
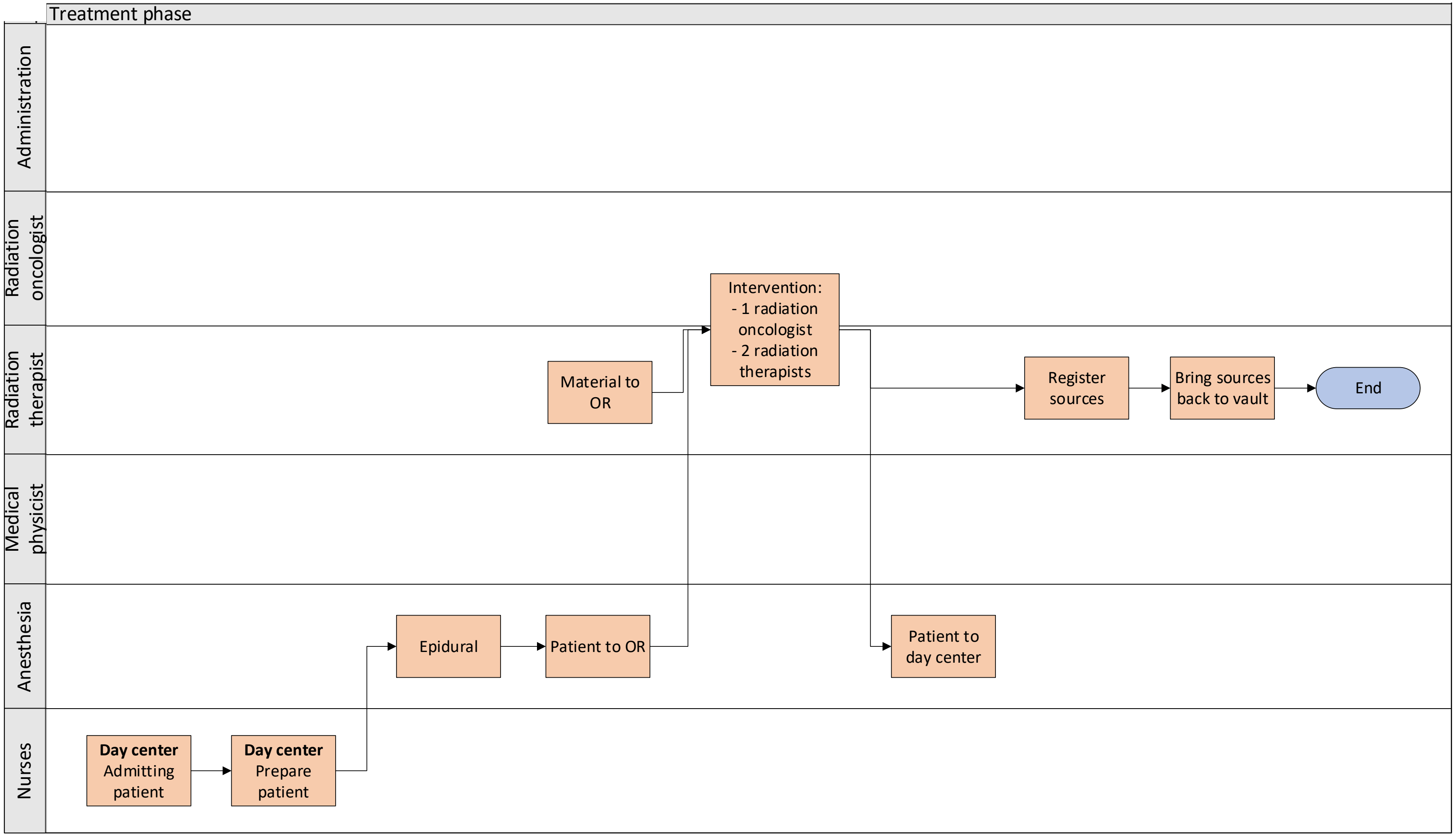
Appendix A: Work- and patient flows

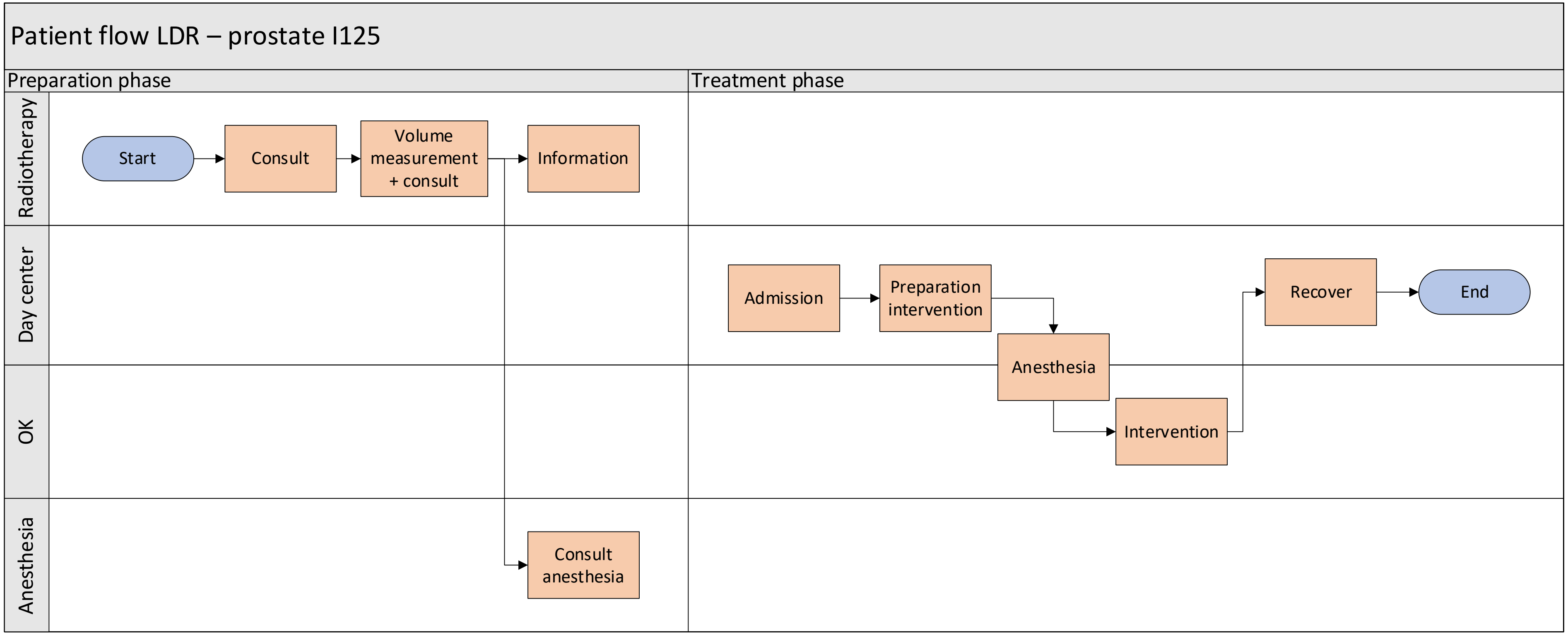
This appendix depicts all work- and patient flows.

Appendix A.1: Workflow LDR

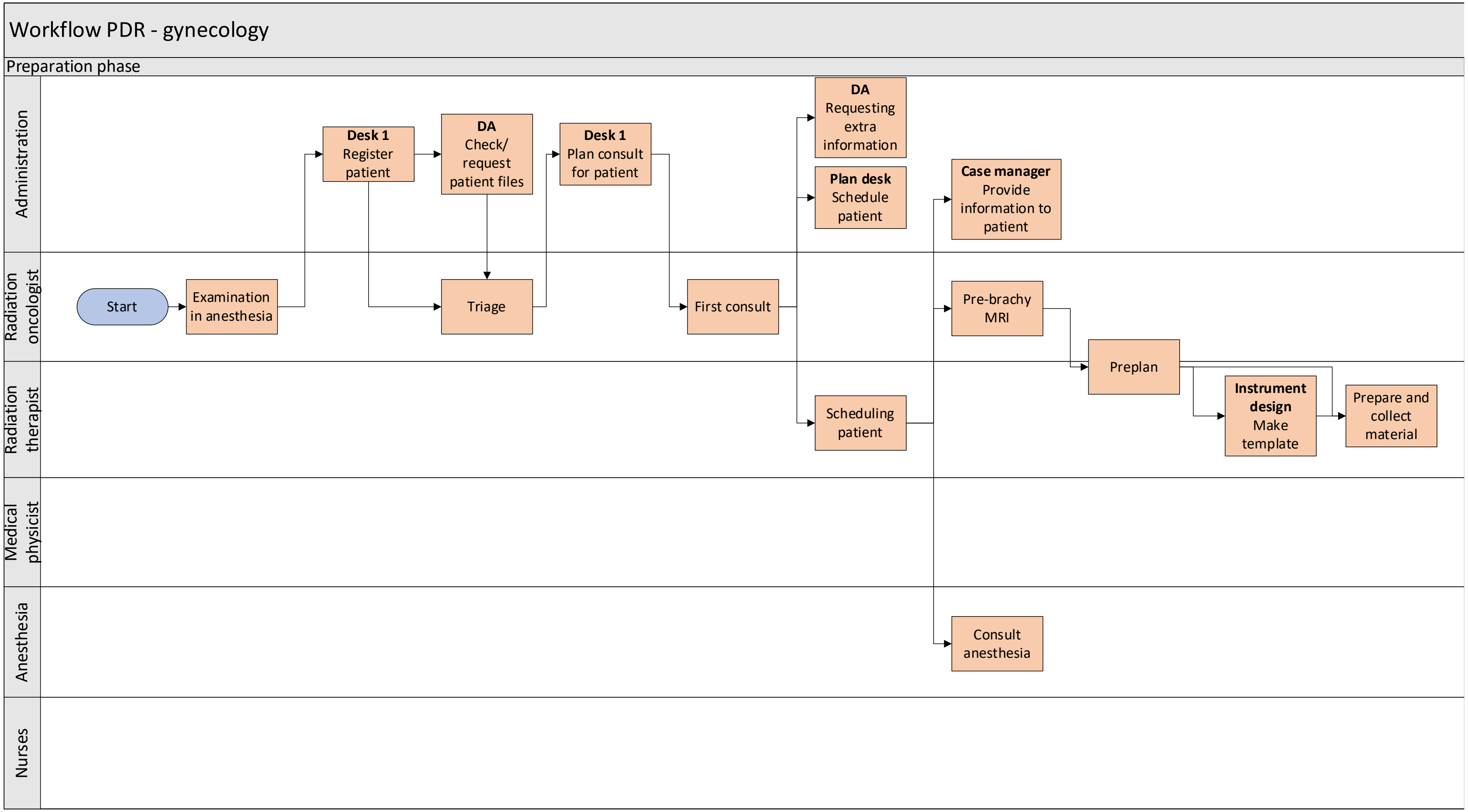


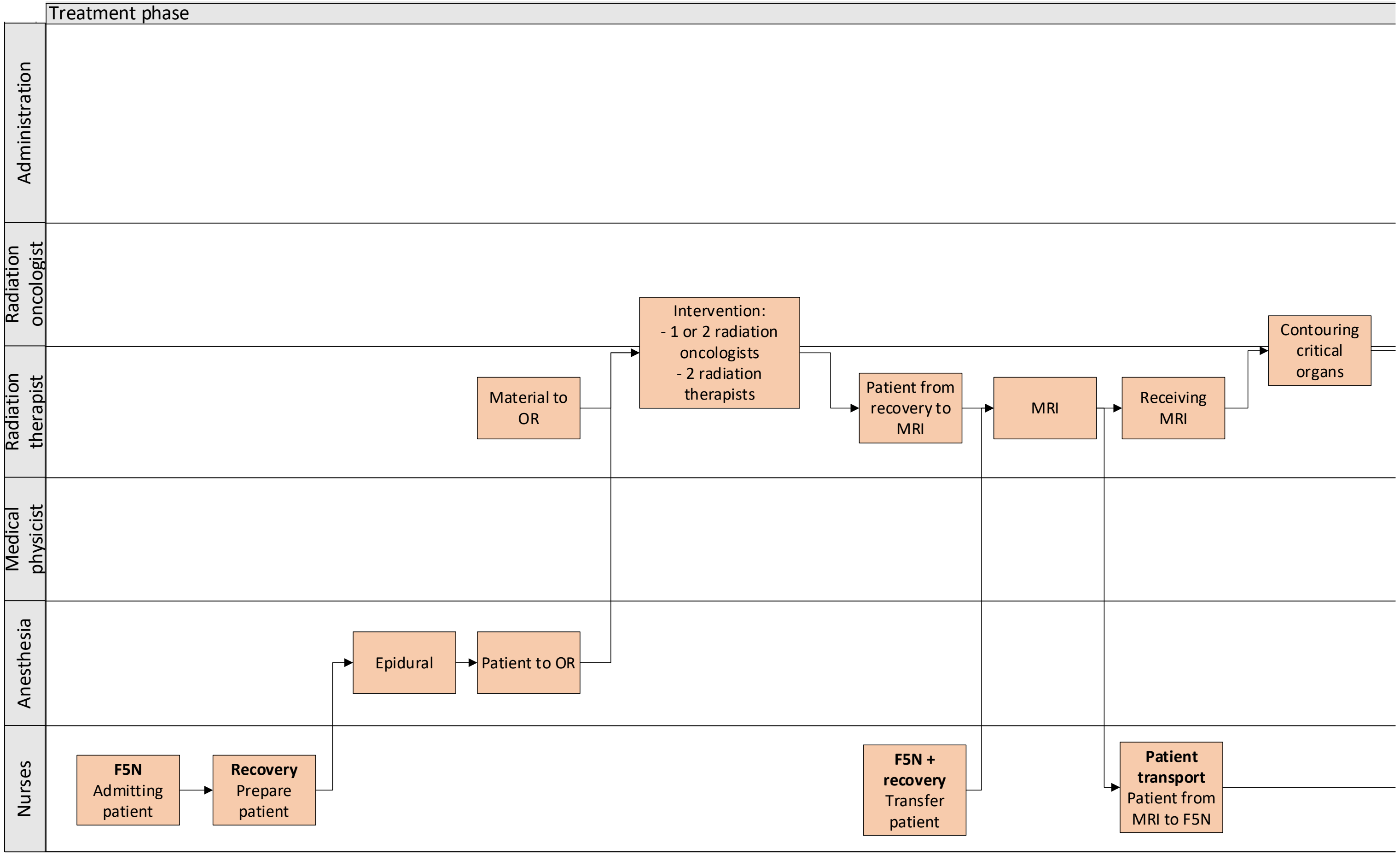

Treatment phase
Administration
Radiation oncologist
Radiation therapist
Medical physicist
Anesthesia
Nurses
Intervention:
- 1 radiation oncologist
- 2 radiation therapists
Material to OR
Register sources
Bring sources back to vault
End
Epidural
Patient to OR
Patient to day center
Day center Admitting patient
Day center Prepare patient

Appendix A.2: Patient flow LDR

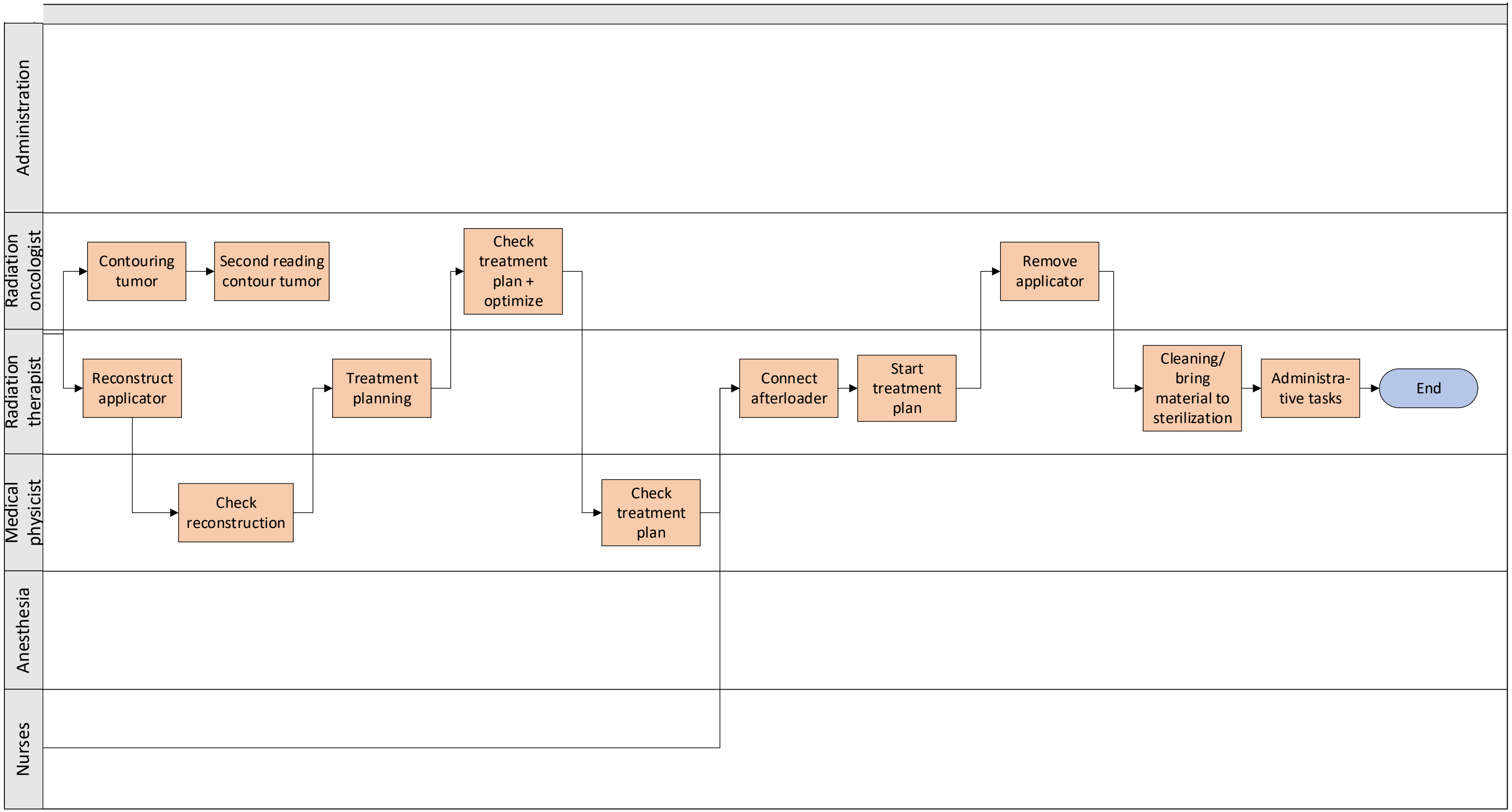


Appendix A.3: Workflow PDR

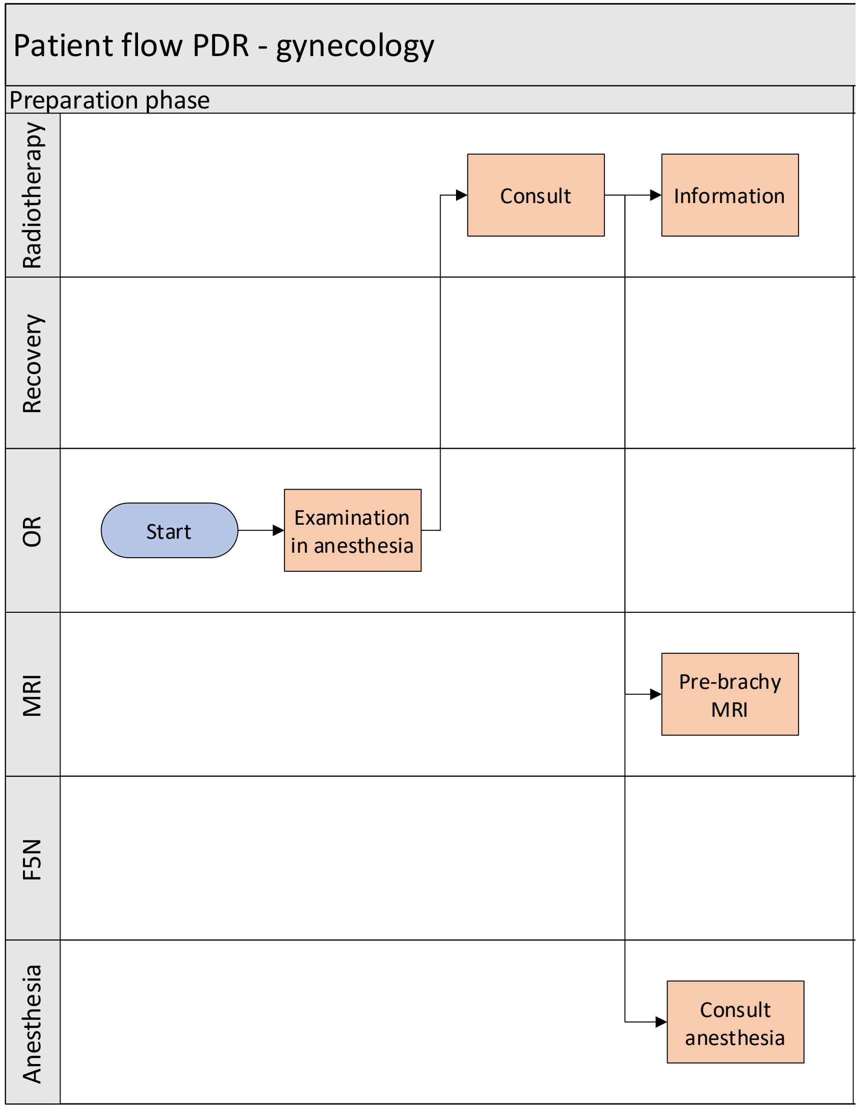


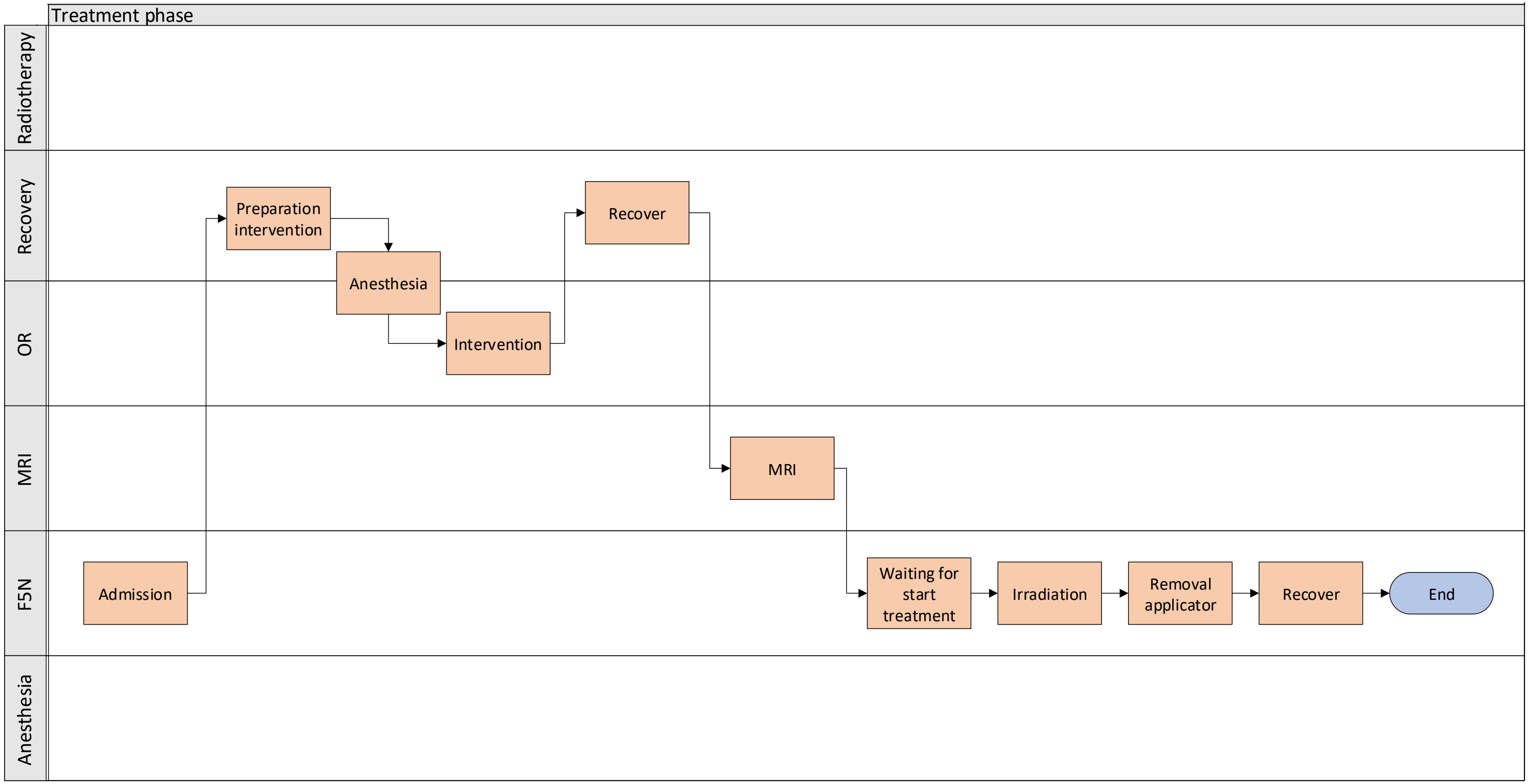


Treatment phase
Administration
Radiation oncologist
Radiation therapist
Medical physicist
Anesthesia
Nurses
F5N Admitting patient
Recovery Prepare patient
Epidural
Patient to OR
Material to OR
Intervention: - 1 or 2 radiation oncologists - 2 radiation therapists
Patient from recovery to MRI
MRI
Receiving MRI
Contouring critical organs
F5N + recovery Transfer patient
Patient transport Patient from MRI to F5N

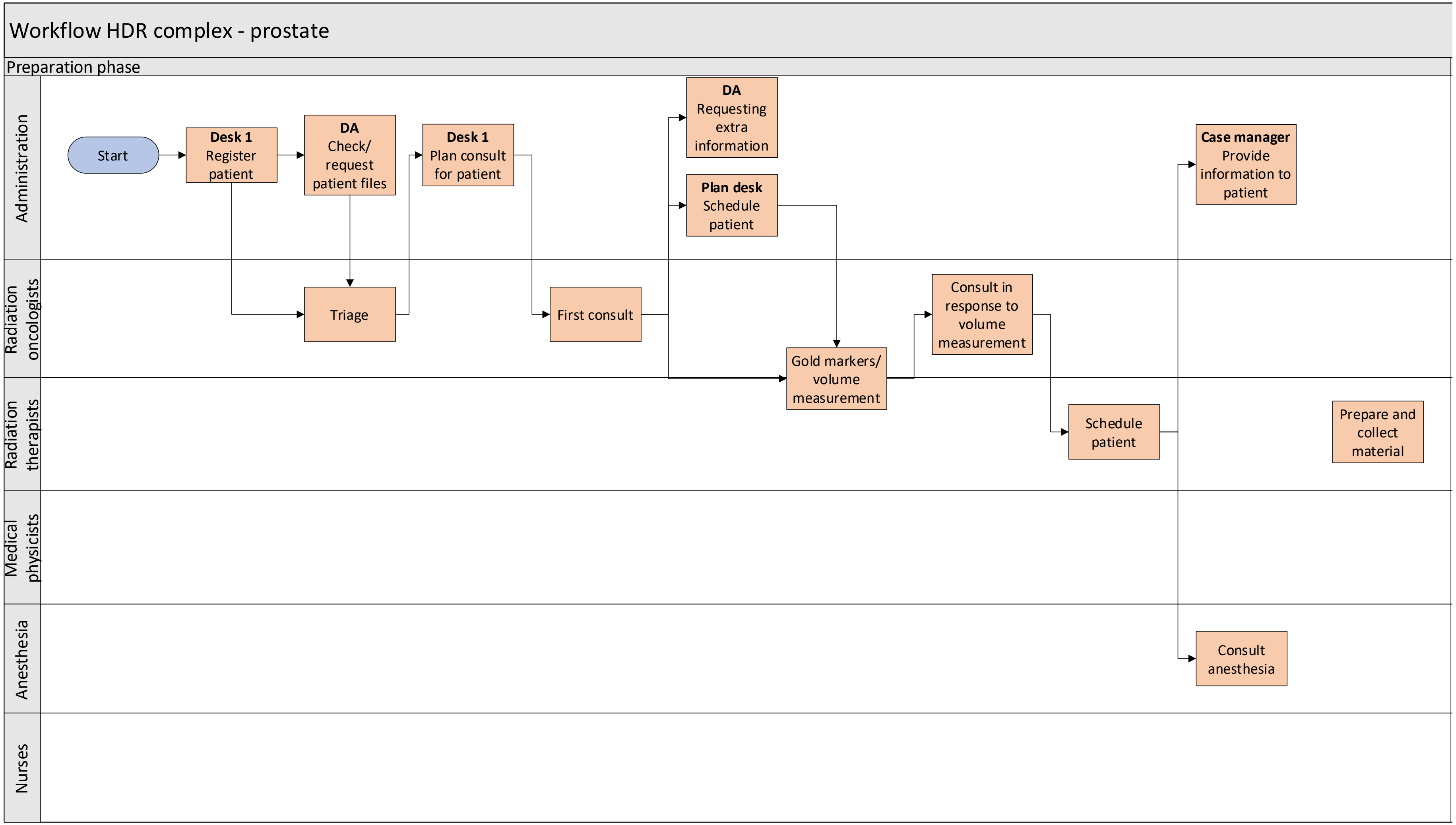

Administration
Radiation oncologist
Radiation therapist
Medical physicist
Anesthesia
Nurses
Contouring tumor
Second reading contour tumor
Check treatment plan + optimize
Remove applicator
Reconstruct applicator
Treatment planning
Connect afterloader
Start treatment plan
Cleaning/ bring material to sterilization
Administra-tive tasks
End
Check reconstruction
Check treatment plan

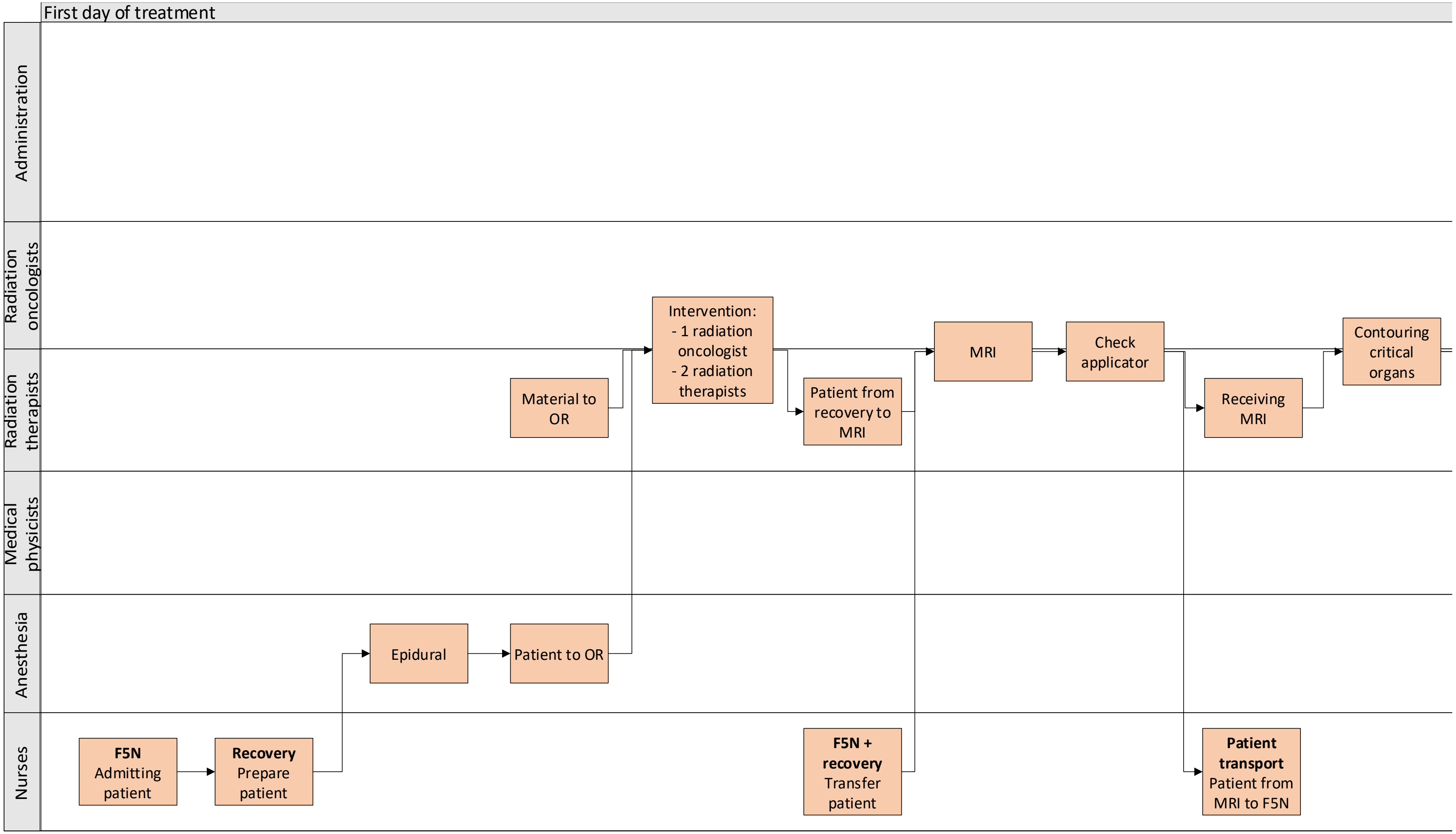
Appendix A.4: Patient flow PDR

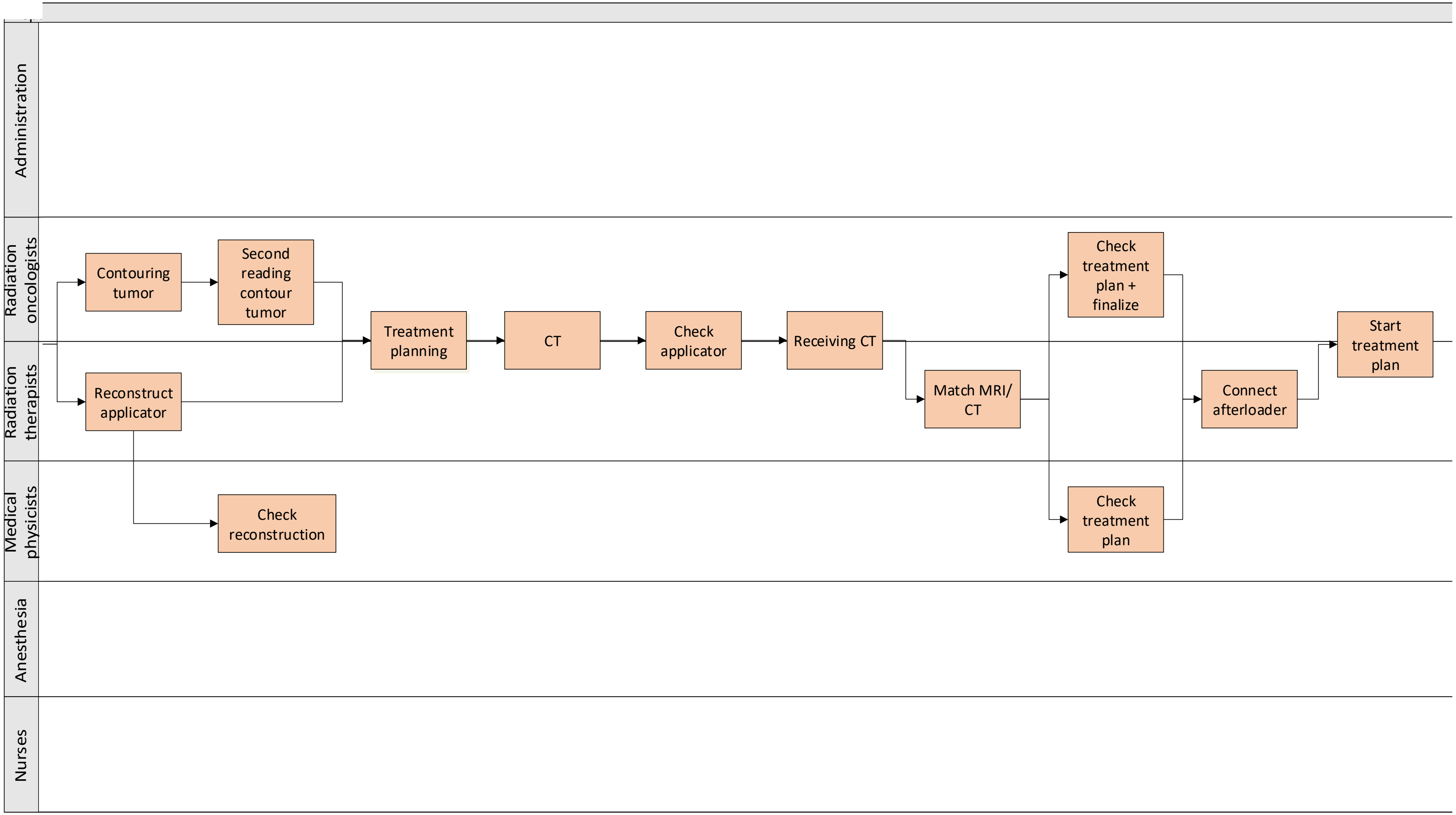



Treatment phase
Radiotherapy
Recovery
OR
MRI
F5N
Anesthesia
Preparation intervention
Anesthesia
Intervention
Recover
MRI
Admission
Waiting for start treatment
Irradiation
Removal applicator
Recover
End

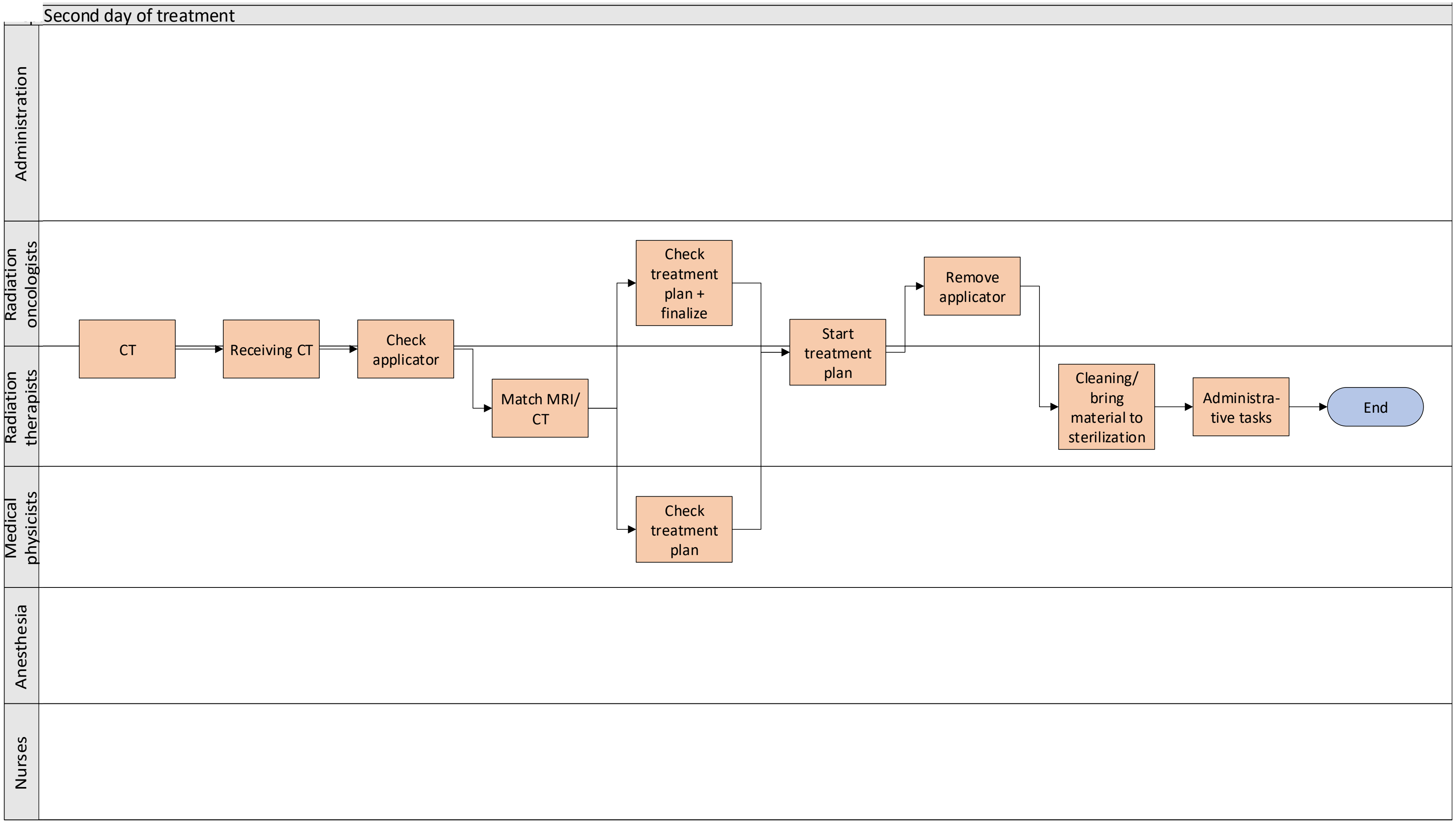
Appendix A.5: Workflow HDR-complex



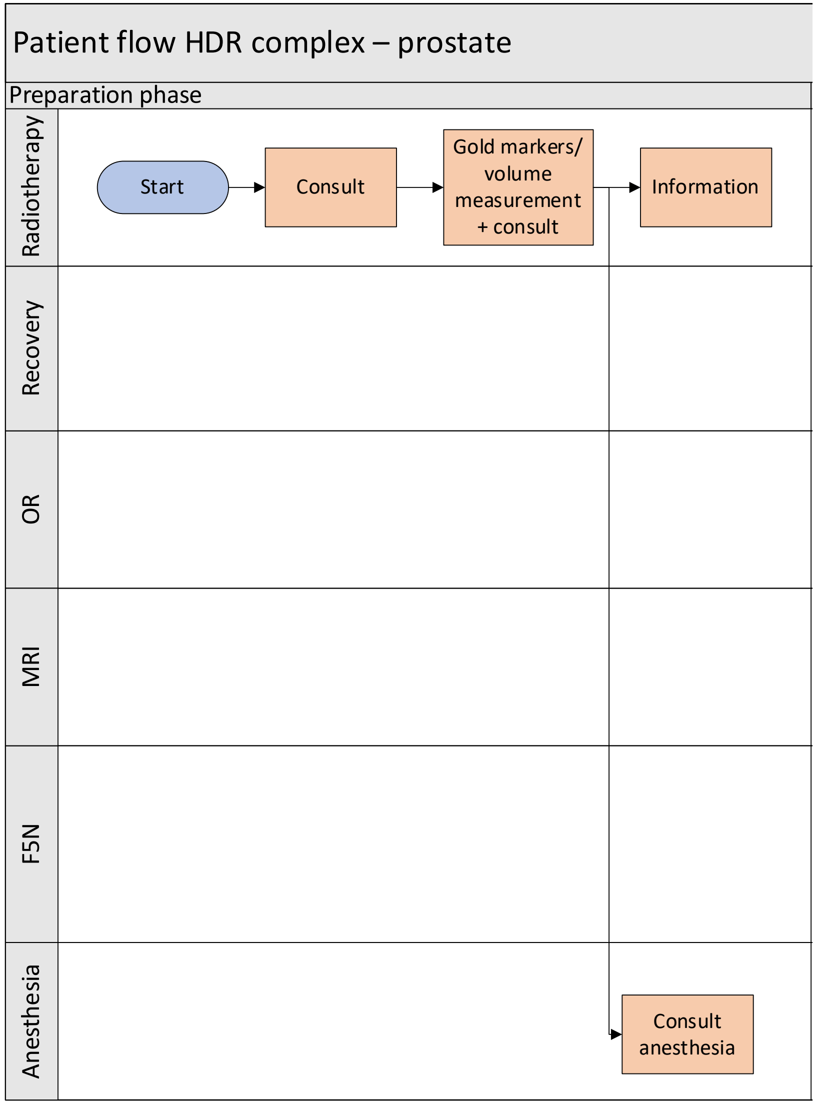

First day of treatment
Administration
Radiation oncologists
Radiation therapists
Medical physicists
Anesthesia
Nurses
F5N Admitting patient
Recovery Prepare patient
Epidural
Patient to OR
Material to OR
Intervention:
- 1 radiation oncologist
- 2 radiation therapists
Patient from recovery to MRI
F5N + recovery Transfer patient
MRI
Check applicator
Receiving MRI
Patient transport Patient from MRI to F5N
Contouring critical organs

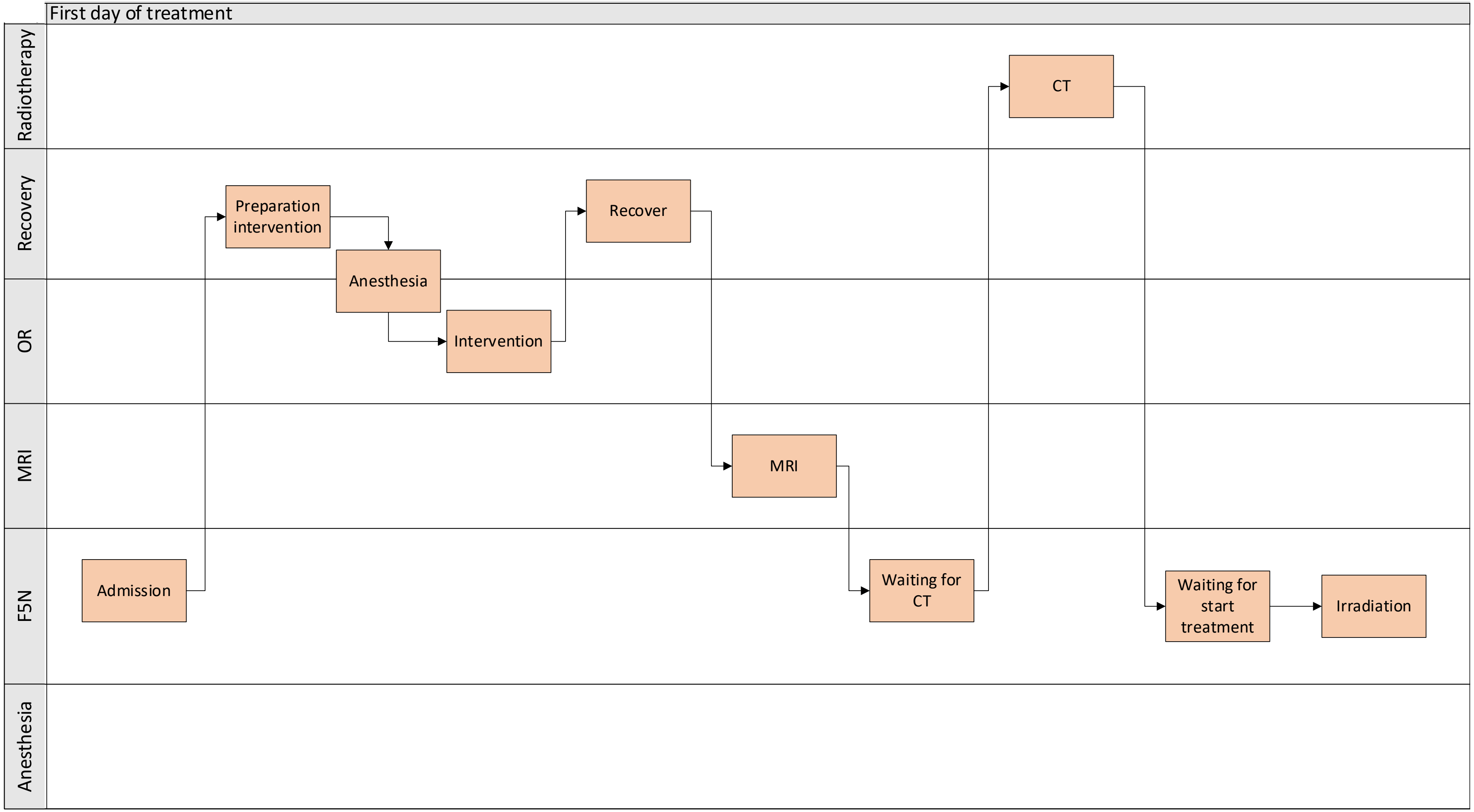


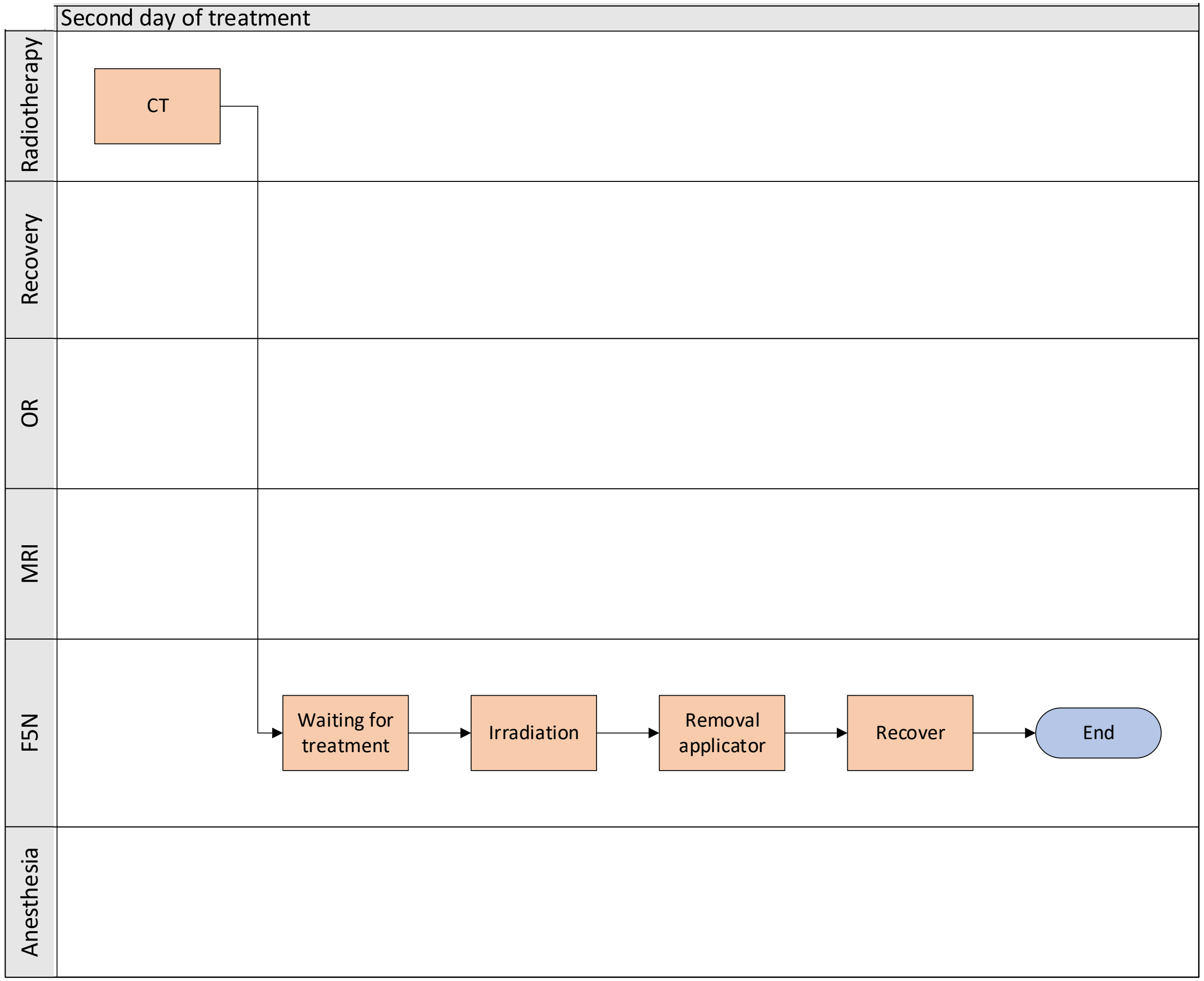
Administration
Radiation oncologists
Radiation therapists
Medical physicists
Anesthesia
Nurses
Contouring tumor
Second reading contour tumor
Reconstruct applicator
Check reconstruction
Treatment planning
CT
Check applicator
Receiving CT
Match MRI/ CT
Check treatment plan + finalize
Check treatment plan
Connect afterloader
Start treatment plan


Second day of treatment
Administration
Radiation oncologists
Radiation therapists
Medical physicists
Anesthesia
Nurses
CT
Receiving CT
Check applicator
Match MRI/ CT
Check treatment plan + finalize
Check treatment plan
Start treatment plan
Remove applicator
Cleaning/ bring material to sterilization
Administra-tive tasks
End

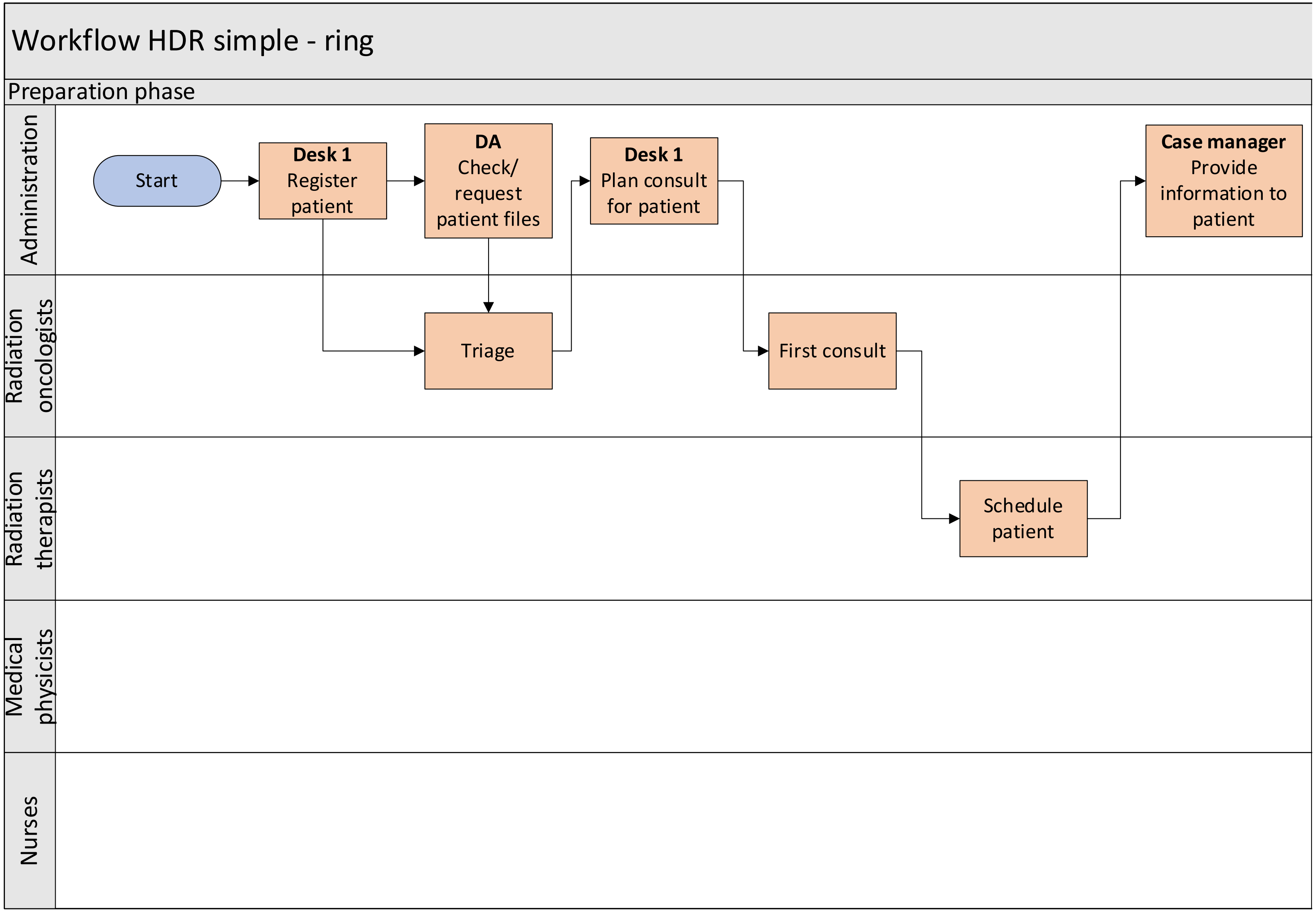
Appendix A.6: Patient flow HDR-complex

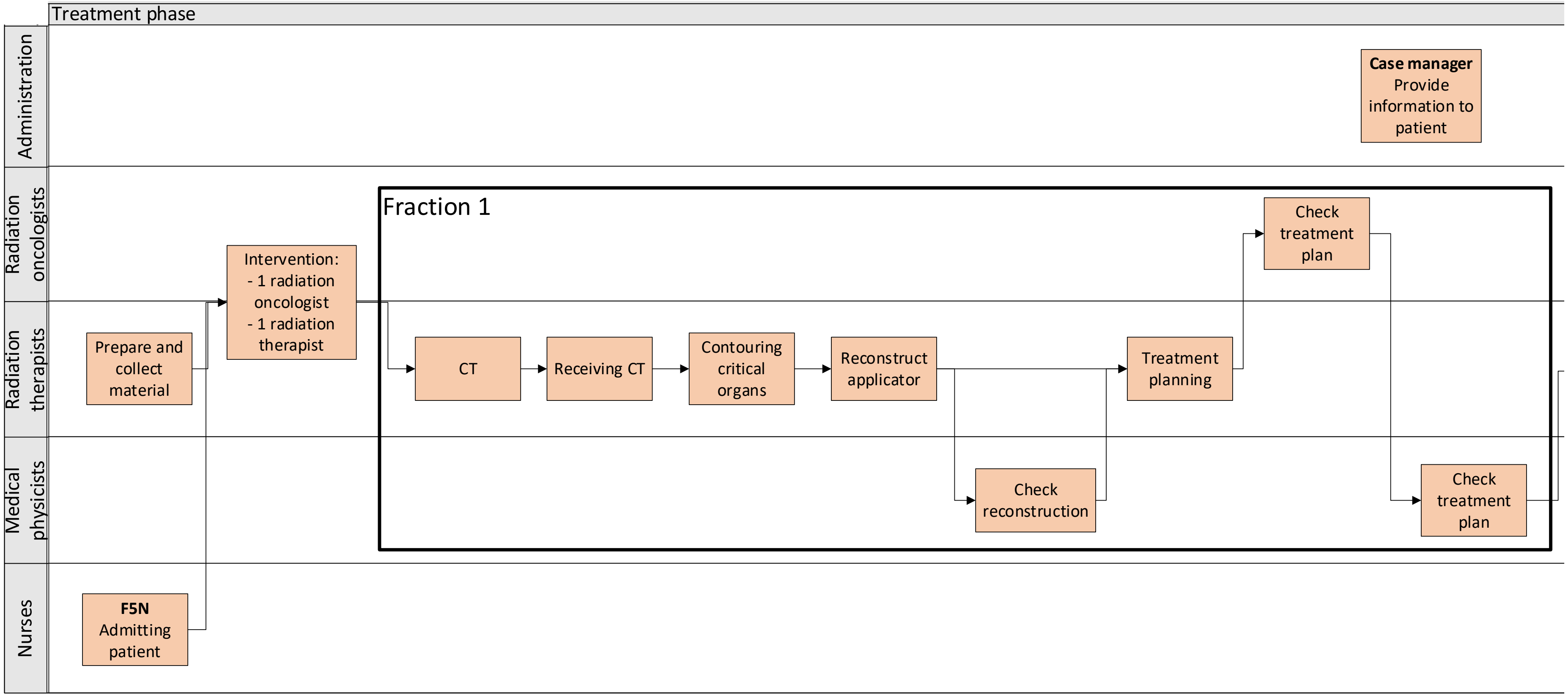


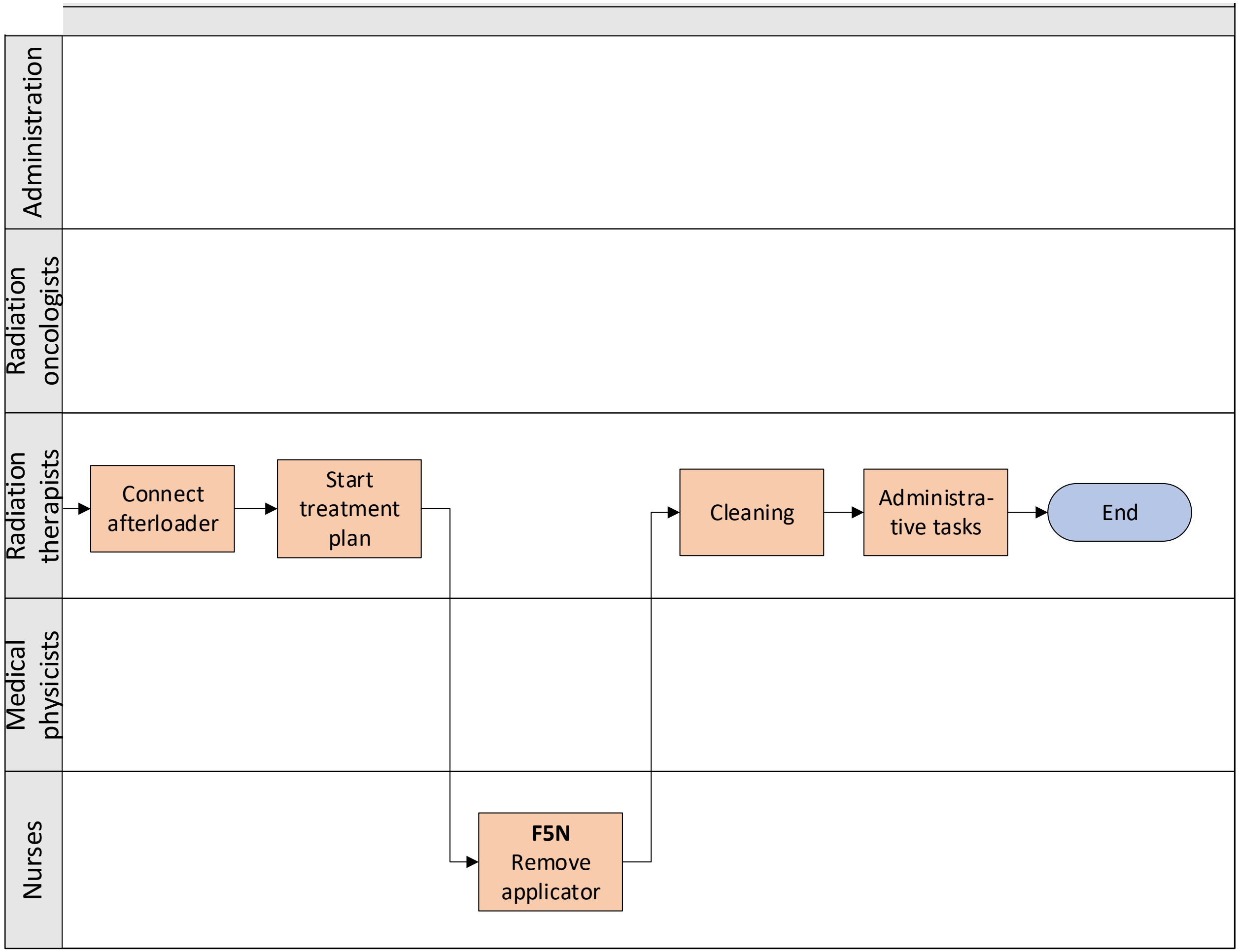

First day of treatment
Radiotherapy
Recovery
OR
MRI
F5N
Anesthesia
CT
Preparation intervention
Recover
Anesthesia
Intervention
MRI
Admission
Waiting for CT
Waiting for start treatment
Irradiation


Second day of treatment
Radiotherapy
Recovery
OR
MRI
F5N
Anesthesia
CT
Waiting for treatment
Irradiation
Removal applicator
Recover
End

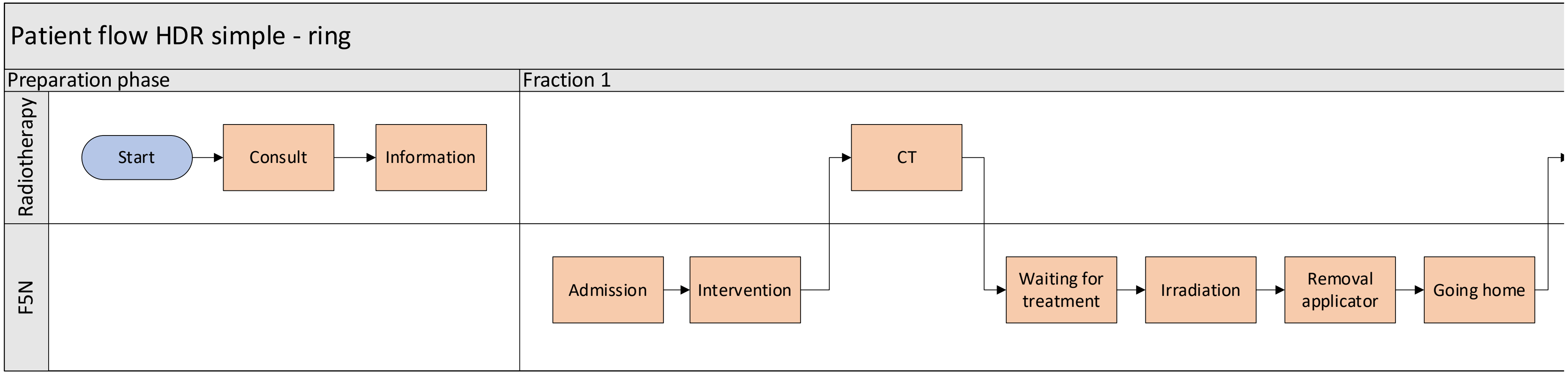
Appendix A.7: Workflow HDR-simple

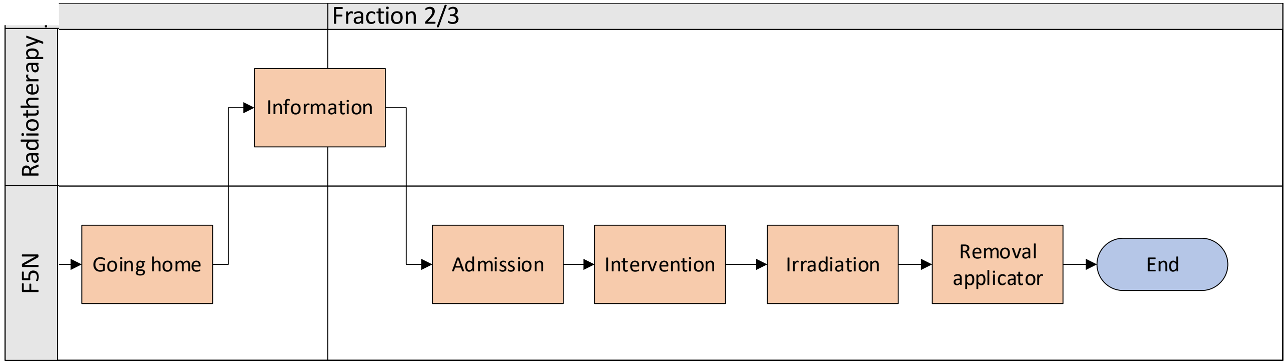



Treatment phase
Administration
Radiation oncologists
Radiation therapists
Medical physicists
Nurses
Case manager
Provide information to patient
Fraction 1
Intervention:
- 1 radiation oncologist
- 1 radiation therapist
Prepare and collect material
CT
Receiving CT
Contouring critical organs
Reconstruct applicator
Treatment planning
Check treatment plan
Check reconstruction
Check treatment plan
F5N
Admitting patient


Administration
Radiation oncologists
Radiation therapists
Medical physicists
Nurses
Connect afterloader
Start treatment plan
F5N
Remove applicator
Cleaning
Administra-tive tasks
End

Appendix A.8: Patient flow HDR-simple





Appendix B: Distribution patient ready for MRI

Figure 31 and Figure 32 depict the distribution of the time a patient is ready for the MRI. The data is extracted from 21 independent runs of one year of the simulation model from the current situation. The results are shown for one year; therefore, the number of patients is in decimals. Patients are divided into time bins of half an hour. MRI slot one is at 12h, and MRI slot two is at 13:30h. From both figures, we can read that the number of patients that need to wait long for their appointment does not occur often.

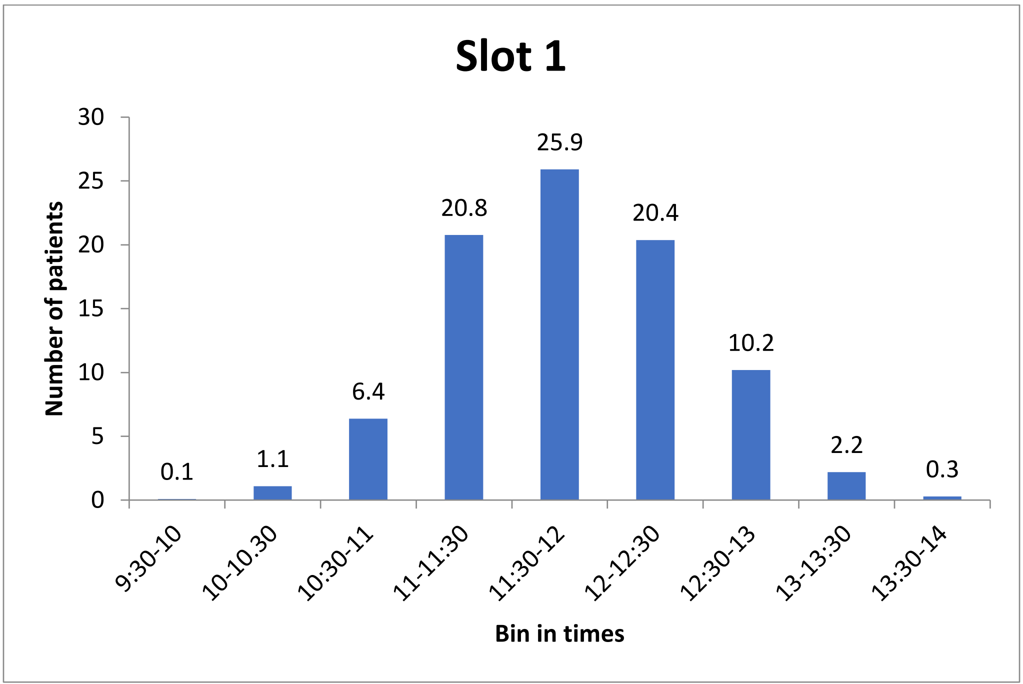


Figure 31. Time a patient is ready for MRI slot 1

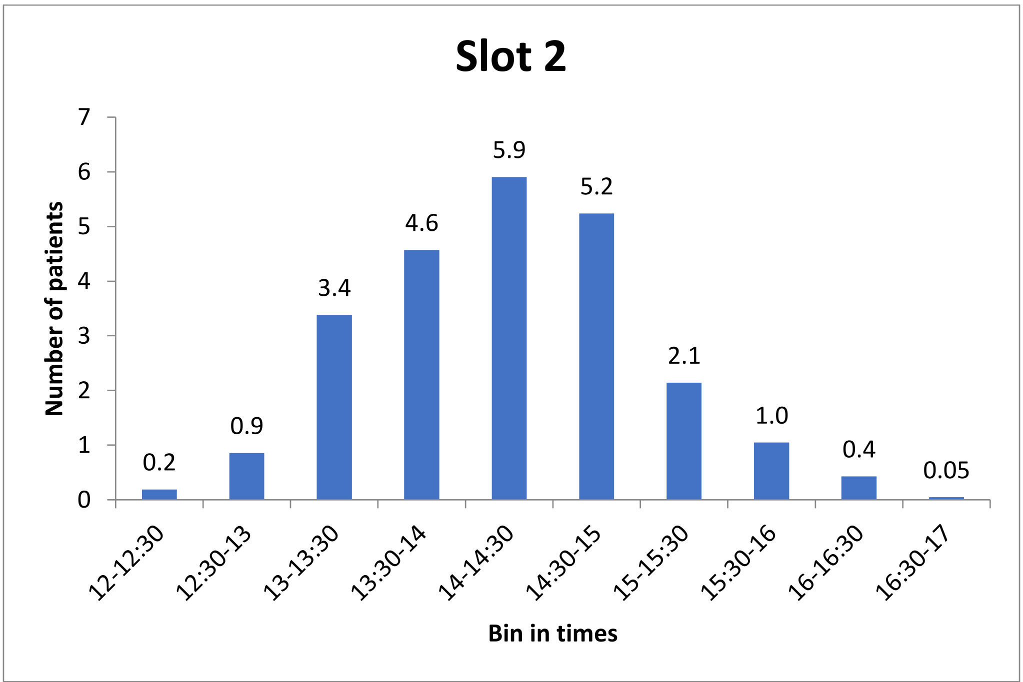


Figure 32. Time a patient is ready for MRI slot 2