Improving the patient order flow in the preparation process of a radiotherapy outpatient clinic

A case study performed at Amsterdam UMC - Location VUmc

by

Frans de Kok

in partial fulfillment of the requirements for the degree of

Master of Science
in Mechanical Engineering

at the Delft University of Technology,
to be defended publicly on Tuesday October 2, 2018 at 1:00 PM.

Report number:	2018.TEL.8275	
Student number:	4174100	
Project duration:	December 1, 2017 – October 2, 2018	
Thesis committee:	Dr. Ir. D. L. Schott,	TU Delft, Chair
	Dr. Ir. H. P. M. Veeke	TU Delft, Daily supervisor
	Dr. Ir. R. G. Hekkenberg	TU Delft
	J. M. van Angelen	Amsterdam UMC, Daily Supervisor

Delft University of Technology

Preface

A radiotherapy department is not the most common environment for the graduation of an mechanical engineer. Nevertheless it was the place where I did my graduation project. It was an encounter between two different backgrounds. And this 'encounter' was not without a result. This report presents the results of the search for improvements in patient order flow in the radiotherapy department of Amsterdam UMC - Location VUmc.

I would to thank the radiotherapy department to give me the possibility to graduate at the logistic processes in the department. It was great to join the the department for the period of my graduation project. I have much respect for all the people working in the department with patients suffering to such a severe disease. Most thanks to Judith van Angelen for introducing me in all relevant processes in the department. Thanks for all discussions on the possible improvements in the department. It was very helpful for my thinking process.

Apart from that I would like to thank Hans Veeke for the supervision from TU Delft. Thanks for all feedback, especially for the suggestion to look to the process from a broader perspective. Next to that I would like to thank Dingena Schott for being the chair of my graduation committee.

The execution of a graduation project is an intensive task. I want to thank my family and friends for supporting me. A special word of thanks to my mom and to Taco, Labrinus and Robbin for giving feedback on my report. Furthermore, I would like to thank my God for giving me the talents and the strength to perform this graduation project.

This graduation project marks the end of the period of my life as a student. During this period of seven years I learned a lot: Both in my study and beyond. I look back as a grateful person. I got to know my talents and my passion for optimizing. And next to that I could learn in several other aspects of life. I would like to thank everyone who was there for me during that period.

Frans de Kok
Delft, September 18, 2018

Abstract

Amsterdam UMC is an academic hospital where high level research is applied in practice. One of the outpatient clinics of location VUmc is the radiotherapy department. Radiotherapy utilises X-ray radiation to damage cancer cells. During their treatment period, cancer patients visit the department once a day to receive a radiotherapy treatment. Before the radiotherapy treatment can start an extended preparation process is executed. Improving the patient order flow in the radiotherapy preparation process is the subject of this research.

The preparation process is a complex process: Many different process steps are necessary to prepare the radiotherapy of a patient. Due to the presence of a waiting queue before each of the process steps, the flow is restricted and errors occur in the corresponding information flow. Often, the reason is the limited insight in the other process step. No overarching control is available to control the flow between the different sections. Interventions occur, but does not rely on organized control structure. The available control is only taking into account the own process step.

The fact that the radiotherapy department is too much functionally organised is the main reason for the existence of these problems. The functional design is a requirement for the radiotherapy system. However, within the outline of the functional design, improvements are possible. These improvements have to create an improved flow of patients with a transparent and coordinated execution.

The main solution for the problem is the design of control structure based on the matrix organisation theory. The functional control structure remains and a patient order control structure is designed. The functional control structure is elaborated by the measure of the length of the waiting queue of the previous process step. The patient order control structure controls the flow of the patient orders throughout the preparation process. This control is executed on the basis of the date of the start of the radiotherapy treatment. The start of the radiotherapy treatment is the end of the preparation process. This date is determined earlier in the process and the different process step due times will be adapted according to that date.

The solution is able to improve the transparency in the department. The patient order progress is monitored during the preparation process and the different process steps will have more insight in the upcoming flow. Especially the patient order control structure is able to coordinate the flow based on the determining of the date of the start of the treatment in an earlier phase.

For the examination of the effect of the proposed patient order control structure, a simulation model is built. The simulation model shows the positive effect on the flow of the patient orders through the department: The variation in the waiting queue length is reduced, the variation in the process time is reduced and the variation in the number of patients who will start their treatment on a certain day is reduced.

Samenvatting

Amsterdam UMC is een academisch ziekenhuis waar onderzoek op hoog niveau wordt toegepast in de praktijk. Een van de poliklinieken van locatie VUmc is de radiotherapie afdeling. Radiotherapie maakt gebruik van röntgenstraling om kankercellen te beschadigen. Tijdens hun behandelperiode bezoeken de patiënten de afdeling elke dag voor het krijgen van een bestraling. Voordat die bestralingen kunnen starten moet er een uitgebreid voorbereidingsproces worden uitgevoerd. Het verbeteren van de patiëntorderstroom in dit voorbereidingsproces is het onderwerp van dit onderzoek.

Het voorbereidingsproces is een complex proces: Veel verschillende processtappen worden uitgevoerd om de noodzakelijke voorbereidingen te treffen voor de radiotherapie van een patiënt. De doorstroming wordt gehinderd door de aanwezigheid van een wachtrij voor elke processtap en de bijbehorende informatiestroom bevat veel fouten. De reden ligt vaak in het feit dat er een beperkt inzicht is in de andere processtappen. Er is geen overkoepelende beheersing aanwezig voor de doorstroming. Interventies vinden plaats maar die hebben geen basis vanuit een goede beheersingsstructuur. De aanwezige beheersing is alleen gericht op de eigen processtap.

Het feit dat de radiotherapieafdeling teveel functioneel georganiseerd is, is de hoofdoorzaak van deze problemen. De functionele inrichting van de afdeling is een eis. Toch zijn er binnen de basis van de functionele organisatie verbeteringen mogelijk. Deze verbeteringen moeten een verbeterde doorstroming creëren waarbij de uitvoering transparant en gecoördineerd is.

De hoofdoplossing voor het probleem is het ontwerp van een beheersingsstructuur gebaseerd op de matrixorganisatietheorie. De functionele beheersingsstructuur blijft bestaan en een patiëntorder beheersingsstructuur is ontworpen. De functionele beheersingsstructuur is uitgebreid met de meting van de lengte van de wachtrij van de vorige processtap. De patiëntbeheersingsstructuur moet de stroom van patiëntorders door het voorbereidingsproces beheersen. De beheersing wordt uitgevoerd op basis van de datum van de start van de radiotherapie. Deze datum is tegelijkertijd het einde van het voorbereidingsproces. De datum van de start van de radiotherapie wordt eerder in het proces bepaald en de eindtijden van de verschillende processstappen zijn afhankelijk van deze datum.

Deze oplossing is geschikt om de transparantie in de afdeling te verbeteren. De voortgang van de patiëntorder wordt gemonitord tijdens het voorbereidingsproces en de verschillende processtappen hebben meer inzicht in de aankomende stroom. Vooral de patiëntbeheersingsstructuur heeft de mogelijkheid om de doorstroming te coördineren op basis van eerder bepaalde start van de behandeling.

Voor het onderzoeken van het effect van de voorgestelde patiëntbeheersingsstructuur is een simulatiemodel gemaakt. Dit simulatiemodel laat het positieve effect van de oplossing zien op de doorstroming van patiëntorders door het voorbereidingsproces: De variatie in de lengte van de wachtrij is kleiner, de variatie in de procestijd is kleiner en de variatie in het aantal patiënten dat hun behandeling start op een bepaalde dag is kleiner.

List of Figures

List of Tables

Abbreviations

AIOS	Medical doctor under training
CQi	Consumer Quality index
CT-scan	Computed Tomography scan
DBC	Diagnosis Treatment Combination
DIM	Decentralized Incident Reporting
IAT	Inter Arrival Time
MDO	Multi Disciplinary Meeting
NPS	Net Promotor Score
NVRO	Dutch Association for Radiation Oncology
OSS	One Stop Shop
PDL	Process Description Language
UMC	Universitary Medical Centres
VUmc	Vrije Universiteit Medical Centre

Technical terms radiotherapy

Care path - The combination of the several tasks that have to be executed for a specific patient order. The care path is visible in the software ARIA. Each of the tasks has a due time.

Linear accelerator - The treatment device for radiotherapy.

Metastasis - The appearing of cancer cells at different places than the original tumour.

Order process - Aspect process where all necessary background processes are executed in order to let function the main patient flow.

Patient order - Order connecting to a patient. The flowing element in the order/referral process.

Post-planning - The last preparations before the actual radiotherapy.

Pre-planning - The first general preparations on the CT-scan before the drawing of the tumour by the doctor.

Preparation process - All necessary process steps for making radiotherapy possible. The start point of the process is the referral reception. The end point of the process is the radiotherapy start. The tasks are mainly tasks of the domain of the order process.

Process path - The required process steps for a specific patient with the corresponding due times for each of the process paths. This can be initiated in the software ARIA.

Process step - Part of the total process that have to be executed. A process step executes a task for a patient order. Each of the process steps is executed by a specific section of the department. Examples of process steps are 'treatment planning' and 'appointment scheduling'.

Radiotherapy appointment - An appointment for the patient where the actual radiotherapy treatment is executed. The treatment is executed at the linear accelerator.

Radiotherapy Start - The point in time of the first received radiotherapy appointment by the patient. This is the end point of the preparation process.

Referral process - See order process.

Treatment Planning - The making of a treatment plan for each of the patients. The start point is the tumour drawn in the CT-scan. The end-point is the programming of the radiation trajectories.

Triage - The classification of the diagnosis. In the case of the radiotherapy department, the referral is placed in the triage-box. For all referrals, the necessary patient preparation steps are determined (A.o. consult, CT and moulage).

Contents

1 Introduction

When anyone receives the diagnosis 'cancer', your life can be suddenly turned upside down. Cancer is considered as a severe, life-threatening disease. That is not without a reason: Cancer is the number one cause of death in the Netherlands. 30% of the deaths in 2016 is due to cancer[4].

Although cancer is life-threatening, the treatment methods improve. Amsterdam UMC is a leading institute in the research to the improvement of treatment methods for cancer. One of the most important treatment methods is radiotherapy. Radiotherapy is the damaging of cancer cells by radiation. The radiotherapy department of Amsterdam UMC - location VUmc is a department where the highest level of research is applied in the fight against cancer.

Before the radiotherapy treatment of cancer patients an extended process takes place: The appointments need to be scheduled, a CT-scan need to be made and the radiotherapy need to be prepared. An appropriate and fast execution of these process steps is important for the best possible treatment for the patients. This preparation process needs to be improved. Too many errors are made and too many peaks are occurring in the process. This research is meant to improve the preparation process of the radiotherapy section. In order to achieve this, four research questions are formulated for the outline of the research:

1. What process is required in order to perform radiotherapy and how can that process be modelled?
2. What problems are ascending during the analysis and what is the root cause of these problems?
3. What solution directions can be applied to improve the radiotherapy process?
4. What are effective and implementable improvements for the radiotherapy process?

The radiotherapy preparation process will be analysed from the perspective of a logistic process. The different process steps are a set of tasks that have to be executed in order to execute the preparation of the radiotherapy. The research takes place on the intriguing balance between respect for the human values and the search for an efficient and optimal logistic process. The challenge for this research is not to disregard one of these sides in the final solution.

First the radiotherapy department and corresponding process will be described (Chapter 2) and modelled(Chapter 3). The modelling and further analysis has to show the actual problems of the department. The problems need to result in a root cause of the problems and a corresponding problem statement (Chapter 4). This problem statement is the start of the search for improvements (Chapter 5). The improvements have to be examined on both the qualitative and quantitative effect on the important parameters describing the radiotherapy preparation process (Chapter 6). After that, an implementation plan for the improvements is made (Chapter 7). Finally, the answers on the research questions and some recommendations are given (Chapter 8).

The radiotherapy preparation process is a complex process and several technical terms are used to describe the different elements of the process. This is the reason for the presence of a technical terms section in this report.

2
Process description

Radiotherapy is an effective treatment for cancer patients. It can contribute to the curing of the patient. For a certain period, the patient visits the radiotherapy department every working day to receive a radiotherapy treatment. In order to achieve these treatments several preparation process steps have to be executed. This chapter will describe the radiotherapy treatment and the corresponding preparation process steps. The process is described for the situation at Amsterdam UMC - Location VUmc.

2.1. Amsterdam UMC - location VUmc

Amsterdam UMC is the overarching name for two academic hospitals in Amsterdam: AMC and VUmc. AMC and VUmc are fused since June 2018. Location VUmc is the hospital of examination during this research. VUmc is a academic hospital in Amsterdam South. It is located next to the Vrije Universiteit Amsterdam (VU). VUmc exists since 1966 and has an annual turnover of €750 million. Every year, 22.900 admissions, 26.300 day treatments and 294.900 outpatient clinic visits take place at VUmc [5]. Therefore, 7.200 employees are connected to the hospital.

In VUmc, the hospital and the outpatient clinic are divided. The hospital and the outpatient clinic are located in a separated building. They are located on different sides of the Boelelaan and a closed bridge connects both buildings (See Figure 2.1). The hospital building can handle the admission of patients. In the outpatient clinic building, patients come to the hospital and went back home after the treatment. For some treatments, the patients are brought from the hospital building to the outpatient clinic.

VUmc works in cooperation with other hospitals. The result of one of the cooperatives is the cooperation with the Esparanz network. The Esparanz network is the cooperation of the hospitals in Zaandam, Purmerend en Hoorn in care for cancer patients. As part of the cooperation, the VUmc radiotherapy department has two different locations: One in VUmc and one in the Westfriesgasthuis in Hoorn. The patients can be radiated at both locations, dependent of diagnosis and domicile.

2.1.1. Cancer Centre Amsterdam

VUmc is an academic hospital. That results in an active cooperation between research and the implementation of the research in the hospital. It offers several study's and courses in the medical field on different levels: Varying from medicine degree to nursing studies and courses in leadership. In 2015, VUmc was responsible for 166 promotions, 2950 scientific publications and 429 specialist publications.

VUmc is pioneer in several medical fields like the brains (MS, Altzheimer) and the revalidation of children. The most well-known area of expertise is the research on cancer. The research on cancer is done by the Cancer Centre Amsterdam (CCA) as part of VUmc.

Figure 2.1: Plan VUmc containing the hospital (ziekenhuis), the outpatient clinic (polikliniek) and the CCA.[1]

Most of the researchers combine academic research with the practical work in the hospital. The Cancer Centre Amsterdam has 248 scientists. 183 full-time equivalents can be used for academic research. That results in 948 publications in 2016. For their work, they receive subsidy of the value of €18,8 million.

2.1.2. Cancer

The CCA is focused on cancer research. Cancer is a disease of the body cells[6]. Cancer cells duplicate unusual and uncontrolled. A group of those cells is called a 'tumour'. This can lead to several symptoms like the presence of a lump (due to the uncontrolled grow of cells) or chronic fatigue. In some cases, the tumour is benign: The grow of the cells is limited, the tumour doesn't disperse and doesn't penetrate other tissue. A benign tumour is not life-threatening. In the case of a benign tumour, the diagnosis cancer is not used.

Having cancer means the presence of malignant tumours. Malignant tumours have the tendency to grow fast and to penetrate adjacent tissues and/or organs. It can harm those affected areas. Tumours can extend to other parts of the body. Therefore the term 'metastasis' is used.

Due to the harming of other parts of the body and the metastasis, cancer is the number one cause of death in the Netherlands. 30,4% of the people that have died in 2016 is due to cancer[4]. Approximately half of the patients with the diagnosis cancer is cured[7]. The survival rate is dependent of the stadium of the cancer and the eventual metastasis.

The three most used treatment methods are operation, chemotherapy and radiotherapy. These treatment methods can be used in combination. In the case of an operation, tumours will be removed by a surgical procedure. Chemotherapy is used by the administration of medication to damage cancer cells. The third treatment method is radiotherapy. In radiotherapy, radiation is used to damage cancer cells.

2.1.3. Radiotherapy

The radiotherapy department focuses on the treatment of cancer patients by radiotherapy. X-ray radiation is used to damage the cancer cells. The goal of the treatment is to damage as many as possible cancer cells and to damage as low as possible healthy cells. The radiation uses a high dose of X-rays with a very high energy level. The radiation is more destructive for cancer cells compared to healthy cells. However, the healthy cells can be damaged too.

Table 2.1: Personnel Radiotherapy department (December 2017)

Specialism	**FTE**	**Persons**
Medical	26,7	30,0
Clinical Physicists	9,9	10
Technical support	9,2	10
Staff	5,8	7
Radiobiology	7	7
Radiotherapy lab Technicians (incl. team managers)	71,9	78
Administration, Reception and Logistics	16,4	20
Total	147	162

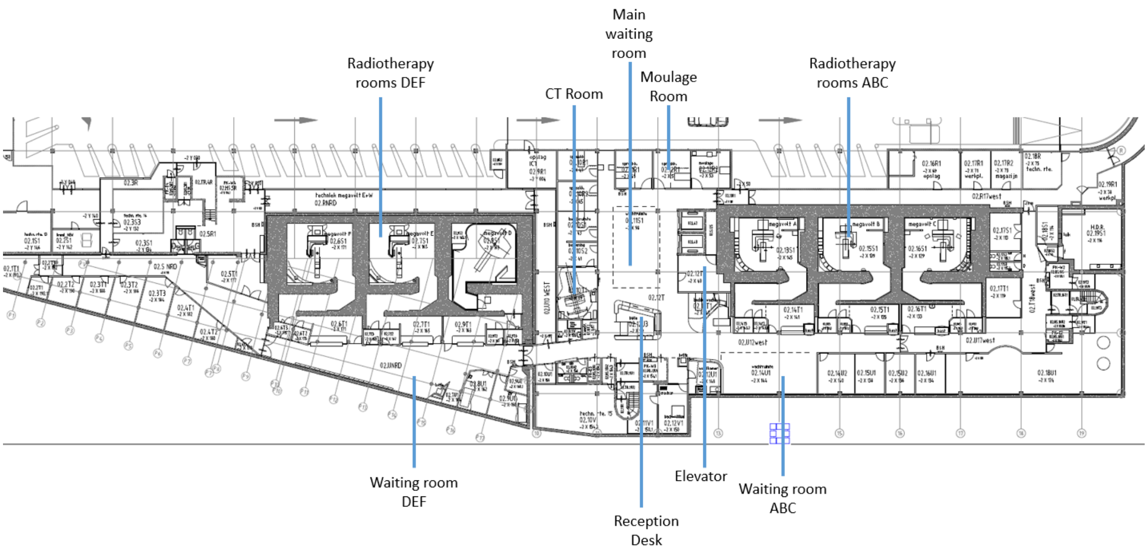


Figure 2.2: Plan of the radiotherapy department (Floor -2)

New techniques improve the balance in the reaching of those two types of cells. One of the techniques to limit the damage to the healthy cells is the rapid arc technology. During the radiotherapy, the radiation equipment turns around the patient. Due to this turning, the concentration radiation in healthy cells is limited.[8]

VU medical centre is one of the forerunners in the radiotherapy. The newest development is the MRIdian radiation equipment. The integrated MRI-scanner can visualize the tumour during the radiation. This can enhance the effectiveness of the radiotherapy. Since the spring of 2016, the device is operational: As the first hospital in Europe.

Radiotherapy can be both curative and palliative. Curative radiotherapy has the goal to cure from cancer. However, in some cases radiotherapy and other treatment methods cannot result in healing anymore. In those cases, the patient can suffer to the pain caused by the tumours. Radiotherapy can be used for the reduction of pain and other symptoms (palliative treatment).

Radiotherapy is one of the specializations in the field of oncology. The treatment in the radiotherapy department has to be done in cooperation with the other specialisms in the oncology field.

2.1.4. Outpatient clinic Radiotherapy

The radiotherapy department is functioning as an outpatient clinic: Every workday, the department is open for patients. The patients arrive for the treatment and will leave when they are finished. Every year, approximately 3000 new patients enter the department. Most of these new registered patients

(a) The open area [9]

(b) The reception desk [9]

Figure 2.3: The main waiting room

will receive radiotherapy. The number of patients receiving radiotherapy is lower than the number of registrations. That is due to the fact that the doctor or patient can decide that radiotherapy is not the best possible treatment. In the year 2017, 3006 new patients were registered and 2752 patients have started their actual radiotherapy. The department in Hoorn treates around 40% of the patients. The other patients are treated in Amsterdam.

For the daily operation of the radiotherapy department 162 employees are involved. These employees are responsible for the filling of 147 full time equivalents. The employees are divided over the different specialisms as shown in Table 2.1. The different groups of personnel together form the structure of the department. Each of the different groups has two or three management layers above it. The department is led by the Head of the Department. The second management layer is the head of the specific sections. For larger groups, a team manager is available as third layer. This is visible in the Organisation Chart in Appendix B.

The radiotherapy department contains a lot of important equipment. The most important equipment are the linear accelerators. The linear accelerators generate X-ray radiation to do the actual radiotherapy. In the department in Hoorn, three linear accelerators are present. In Amsterdam six linear accelerators are present. There are differences in the linear accelerators: not all equipment is interchangeable. Some diagnosis ask for specific treatment on a specific linear accelerator. Apart from that on both locations a CT-scanner and a branchytherapy afterloader (for internal radiation) are present.

The radiotherapy department revenue is originated from the health insurance company's. By the use of a DBC (Diagnosis Treatment Combination), the costs are declared depending of the outline of the treatment. This is the source of revenues. A total of 21 million Euro is earned by the DBC's. The main costs are the personnel costs (11 million), the depreciation of the equipment (2 million) and the use of VUmc buildings and overhead (3 million euro).

At VUmc, the outpatient clinic radiotherapy is located in the outpatient clinic building. The radiotherapy department is located at floor -2. The floor plan is shown in Figure 2.2. When patients take the elevator, they arrive in a big open area (See Figure 2.3(a)). In that area several sofa's and stairs are present to function as a waiting room. In one of the sides of the waiting room, a reception desk is

(a) Waiting room before radiation equipment [9] (b) Scan for bar code

Figure 2.4: The main waiting room

present (See Figure 2.3(b)). At the reception desk nurses are present to give information and answer questions. They also are responsible for aftercare and other medical care.

At the borders of the open area several rooms are located. In one of the rooms, the CT-scanner is present. Another room is destined for moulage (the making of masks). The other rooms are consultation rooms. The people in the waiting rooms can be called for the relevant appointment.

Behind the reception you can go the right or to the left. In those two wings of the building, the irradiation equipment is present. In both wings three rooms are equipped with irradiation equipment. The corridors are wide and contain seats before the radiotherapy rooms (see Figure 2.4(a)). When patients come for a radiotherapy treatment they go immediately to the right location. There they can sign up oneself with the received barcode. Therefore the equipment shown in Figure 2.4(b) is meant.

The described locations are relevant for the patients. However, the department is more than the patient-related environment. Several rooms are for other personnel (scheduling, ICT, administration, clinical physicists). Several rooms are destined for meetings with (medical) staff. Furthermore a room is destined for the making of radiation plans (planning).

2.2. Radiotherapy process

In the radiotherapy section, the patients are receiving a radiotherapy treatment. The radiotherapy process consists of the preparation of the radiotherapy and the execution of the several radiotherapy appointments.

However, before looking to the radiotherapy process itself, it is important to zoom out. The radiotherapy process is a part of a bigger process: The process of a cancer patient. That process starts with noticing the symptoms. The process ends with the eventual follow-up appointments after the treatment.

The overview of the different processes is shown in Figure 2.5. This overview only holds for patients receiving the diagnosis cancer and receiving a referral to the radiotherapy department. The figure shows the different processes over time. The green part is concerning the radiotherapy department. It considers the preparation process and the radiotherapy itself. Before the discussion of the processes of the radiotherapy department, the other processes will be discussed.

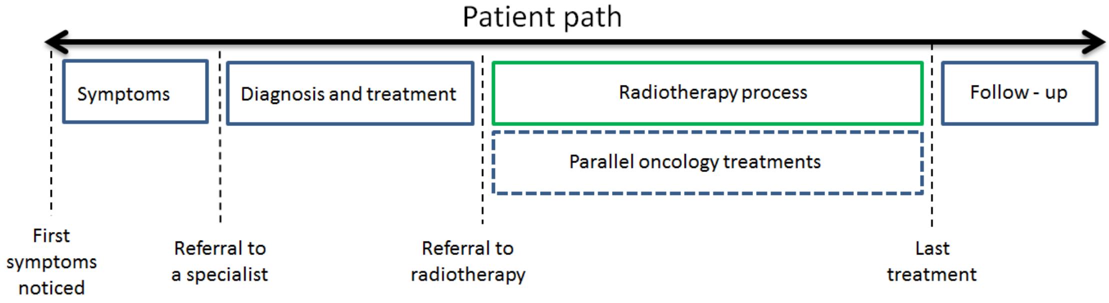


Figure 2.5: Processes required for treatment cancer patient that needs radiotherapy

2.2.1. Patient process in a broader context

The process starts with the symptoms. These symptoms can be noticed by a patient themselves, by a government population study, by a general practitioner or a specialist in the hospital. When the possibility for a cancer diagnosis is open, the patient is sent to the specialist (in a hospital). This specialist can make the diagnosis cancer.

Once or twice a week (dependent from the specialism) a MDO is organized for each of the disciplines. A MDO is a multidisciplinary meeting where relevant specialists are present. Radiotherapists will join these MDO's. During the MDO a specialist can discuss a patient having cancer. A discussion of a patient takes around five minutes. During the MDO the treatment outline is determined. If the decision is made that radiotherapy is a proper treatment method, the patient is referred to the radiotherapy department.

In some cases, the process is different. That is the case for some forms of head and neck cancer. The general practitioner can refer patients to the special surgery hours. During the surgery hours a specialist (in this case a head and neck-specialist) and a radiotherapist-oncologist (connected to the radiotherapy department). During the surgery hours, the specialists can refer the patients to the radiotherapy department. This patient-path will skip the MDO.

In Figure 2.6, the different locations of the referral are given. The origin of the referral is the current practitioner of the patient. In many cases it is from a specialist of the section that is responsible for the place where the tumour is located. Another option is the referral from the oncology department: Then the patient is already treated by an oncologist and when the decision is made that radiotherapy is necessary, the patient is referred to the radiotherapy department. The practitioner that refers the patient to the radiotherapy department is named 'referring specialist'. The specialists of the of the radiotherapy department is named 'Radiotherapist' of Radiotherapist-Oncologist'.

Apart from the referrals from other departments within VUmc, the referrals can come in from other hospitals. The most external referrals are originated from the Westfriesgasthuis in Hoorn. That is due to the fact that the VUmc radiotherapy department is located in Hoorn too. Furthermore, quite a lot of patients are coming from other hospitals. These hospitals don't have their own radiation facilities. In those hospitals, it is determined (by oncologists and specialists in the field of the tumour location) that radiotherapy is necessary.

When a patient is referred to the radiotherapy department, a consult is planned for the patient. The patient is planned for one of the radiotherapist having the matching focus area. This can be a doctor or a AIOS (Medical doctor under training). The specialist will investigate the medical information and will see the patient to come to a proper treatment. In most cases, the treatment is radiotherapy. However, it can be that the specialist decides to deviate from the treatment determined in the previous step (MDO, surgery hour or other hospital). In that case, the patient is referred to another department or is discussed again at the next MDO.

During the radiotherapy process, the radiotherapist-oncologist is the specialist most directly con-

Verwijzer	2015		2016	
VUmc	**Aantal**	**%**	**Aantal**	**%**
KNO	522	14%	424	11%
Oncologie	334	9%	435	11%
Longziekten	257	7%	317	8%
Hematologie	162	4%	132	3%
Neurochirurgie	154	4%	108	3%
Chirurgie	115	3%	89	2%
Urologie	76	2%	95	2%
Neurologie	54	1%	59	2%
Dermatologie	42	1%	48	1%
Plastische Chirurgie	50	1%	24	1%
Interne geneeskunde	7	0%	43	1%
Gastro-enterologie	20	1%	22	1%
Gynaecologie	6	0%	4	0%
Overige	6	0%	9	0%
Extern				
Westfriesgasthuis	761	21%	757	20%
Zaans MC	386	10%	319	8%
Waterland zkhs	259	7%	332	9%
Amstelland	218	6%	268	7%
OLVG	34	1%	37	1%
Leids UMC	29	1%	38	1%
St Antonius zkhs	24	1%	41	1%
AMC	22	1%	26	1%
AvL	19	1%	21	1%
Overige	153	4%	208	5%

Figure 2.6: The different referrals (dutch). Above: Departments VUmc, Below: Other hospitals [2]

nected to the patient. That is mainly due to the intensity of the radiotherapy process. The patients meet the specialist once a week and the patient is seen by the radiotherapy lab technician every working day. When the radiotherapy lab technicians observe a marked decline in condition or other particularities, the radiotherapist is called. When the radiotherapist notes other medical issues not in the field of the radiotherapy, the patient can be sent to another department.

Sometimes, other cancer treatments have to be done next to the radiotherapy. This can be decided in the MDO. The two main forms of processes next to radiotherapy are chemotherapy and an operation. Chemotherapy can be executed in parallel to radiotherapy. An operation is executed at a certain point in time. Radiotherapy can be used as preparation for the operation or as treatment step after the operation.

In principle these processes are take place without communication in between. Communication only takes place when one of the processes cannot be done as appointed. Some basic rules will help the cooperation. An example is the leading role of the schedule of chemotherapy above the schedule of the radiotherapy.

When the treatment is finished, some follow-up checks are required. These follow-up checks can be done by the radiotherapist-oncologist, the referring specialist or a general practitioner. In some cases, it is observed that the cancer is growing uncontrollable again. Sometimes, despite the treatments, metastasis is observed. In those cases, the follow-up consults can result in a new proposal of a radiotherapy treatment. Then the patient path starts again with the process.

Sometimes the treatments has to be considered as 'palliative'. In palliative treatment, the patient is incurable. The radiotherapy treatment can be necessary to reduce pain or other symptoms. Sadly enough, the cancer will be a cause of death for those patients. In some cases, the patient dies during the process. In that case the process must be stopped halfway.

2.2.2. Patient process radiotherapy

In Section 2.2.1, the different process steps are given that take place before the actual radiotherapy process. It is important to consider the process from the viewpoint of a patient. Therefore, the first description of the process only considers the elements that are 'seen' by the patient. In the description of the patient process, no distinction is made between the preparation process and the actual radiotherapy execution (see Figure 2.5); for a patient, this distinction has no relevance.

- The patient is called for an appointment for the first consultation and (if those are necessary) a CT-scan and/or an appointment for moulage. In an e-mail the other necessary information is sent to the patient: Date, time, location, doctor and a brochure containing the explanation of the treatment.
- When the patient is new in the hospital (that is especially the case for referrals from other hospitals), the patient has to check oneself in at the main reception desk. There the patient information is checked and the missing information is added. When everything is finished, the patient is sent to the radiotherapy section.
- The patient checks oneself in at the reception desk of the radiotherapy section. The patients, already treated by the VUmc can go directly to the reception of radiotherapy. There, the necessary information is checked and the person is requested to take place in the main waiting room.
- The patient can sit in the waiting room waiting for the first consult.
- The patient is called by the doctor for a consult of approximately half an hour. During the consult, the necessary questions are asked to the patient. When the doctor decides (mainly on basis of the delivered scans and other information on forehand) that radiotherapy is the best option, the patient is informed over the radiotherapy and the secondary effects of the radiotherapy.
- After the consult, the patient can wait in the waiting room for the next appointment.
- When the patient has an appointment for moulage, the patient has been called by a radiotherapy lab technician responsible for the moulage process. The moulage process takes around half an hour.
- After the eventual moulage process, the patient has to wait for the appointment for the CT-scan in the waiting room.
- The patient is called by a radiotherapy lab technician, responsible for the CT-scan. The CT-scan is executed and the necessary indications on the body are made.
- The patient can go home.

  For the patient, these steps are the preparatory steps for the treatment. After several days or weeks the next process steps will start. The difference in time is dependent of the severity of the disease and the processing of the patient information in the department. The process steps described in below will describe the actual radiotherapy steps:
- The patient is called for the appointment of the first radiation appointment.
- When the patient arrives at the dedicated time at the radiotherapy section, one of the nurses at the reception will guide the patient to the waiting room before the right irradiation room. The nurse explains the check-in process and gives a list of the coming radiation appointments. After that, the person can wait in the waiting room.
- The patient is called by a radiotherapy lab technician for the radiation appointment. The process of a radiation appointment is explained later on.
- After the radiotherapy appointments, the patient can go home.

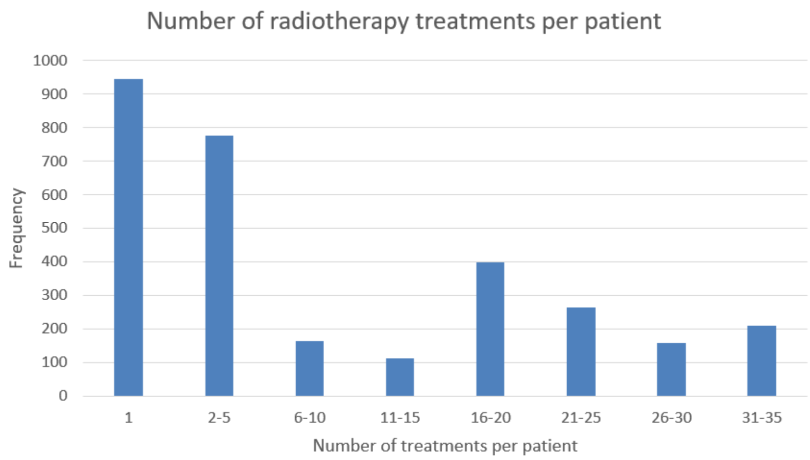


Figure 2.7: Number of radiotherapy treatments per patient

- Every day (in most of the cases), the patient returns to the hospital. The patient checks in at the check-in pillar before the correct radiation room. When the radiation room is available, the patient can start the radiation process.
- Once a week a consult with a doctor is planned. During the consult the medical condition and the secondary effects of the treatments will be discussed.
- Every Thursday, the patients can pick up at the reception their appointments for the next week.
- At the end of the radiation program, the patient has a consult at the treating doctor.

The radiation program can consist of several radiotherapy treatments. Every workday, one radiotherapy treatment is executed. The number of radiotherapy treatments can vary from 1 to 35 times. This is equal to a maximum treatment time of 7 weeks. In Figure 2.7, the frequency of the number of radiotherapy treatments is given for 2017.

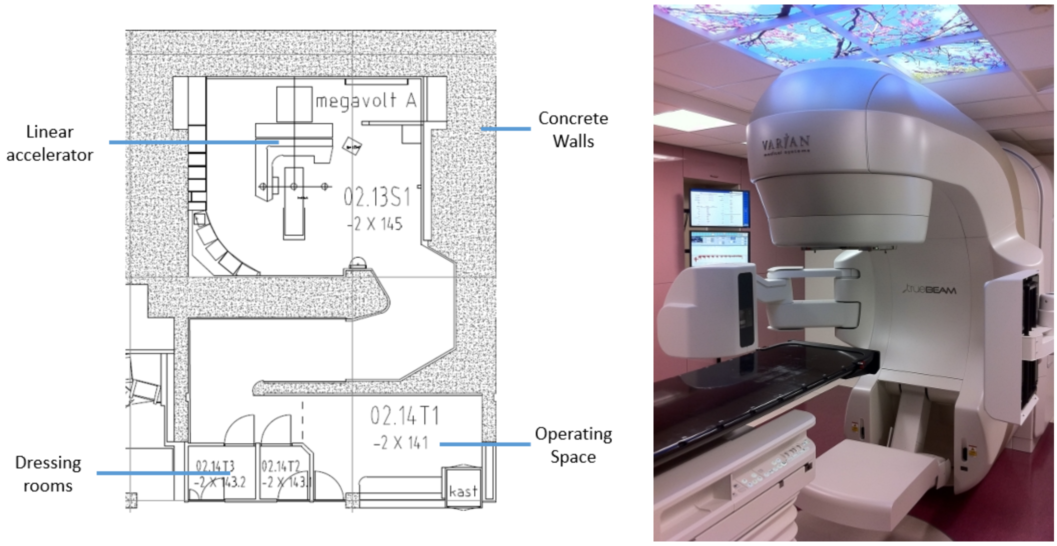
The process can be affected by many aspects. Medical conditions can change the radiotherapy program. In many times, the appointment times are changed. Then the patient receives an adaptation of the schedule at the daily appointment in the radiation room. In some cases, the patient is hospitalized. Then the patient is brought to the radiotherapy outpatient clinic. This can be in a wheel chair or in a bed.

In the list above, some processes are just mentioned. For 'the moulage process', 'the CT-scan' and 'the radiotherapy' the process is explained in more detail below:

Moulage process

Moulage is the making of a mask to fixate the position of certain parts of the body. It is often required for the radiation in the head-neck region. During the radiation, the position of the body may not change. The mask made in the moulage process will be used during all following radiotherapy appointments and during the CT-scan.

In the moulage process, first all necessary information is given to the patient. Then the patient has to lay down on a table. A correct head support is placed under the head and neck of the patient. The basis of the mask is located in a water bath of 70° Celsius. When the patient is laying in the correct position (the position has to be the same during all radiation appointment), the mask is placed upon the head of the patient. The two radiotherapy lab technicians form the mask in a way that it follows the skin at any place. Then the patient has to avoid all movements to let harden the mask in 7 minutes. After that, the mask is removed from the head and the mask will be prepared for further use by cutting some holes at the places of the mouth and the eyes.



(a) Plan radiotherapy room A (b) Linear accelerator [10]

Figure 2.8: Radiotherapy room and linear accelerator

CT-scan

When the patient is called for the execution of the CT-scan, the person is first brought to the corresponding dressing room. There, the person has to undress that part of the body where the tumour is located. After that, the patient is asked to lay down on the CT-scanner. The scanner shows some visible lines on the body. When the person lays in the correct position, markers are used to draw the same lines on the body. On the intersection between the lines, some small (definitive) tattoo points are applied. When the marker lines are worn from the body, the tattoo points can be used to reconstruct the lines.

When the positioning process is finished, the CT-scan can be made. Therefore, the two radiotherapy lab technicians will go to the next room and operate the CT-scanner from a distance. The scan can be 3D or 4D. In the case of a 4D scan, the position of the tumour is measured over the full cycle of the breathing. This scan can be useful for the special breath-hold radiotherapy. When the scan is finished, the patient can dress again and can go home. During the process, the different steps are explained to the patient.

Radiotherapy

The radiotherapy is executed in one of the radiotherapy rooms. The floor plan of one of the radiotherapy rooms is visible in Figure 2.8(a). A radiotherapy lab technician calls the patient and asks the patient to undress the part of the body that has to be radiated in one of the dressing rooms. When the patient is finished, the patient can leave the dressing room via a door in the back. The patient is brought by two of the radiotherapy lab technicians to the linear accelerator. The linear accelerator is visible in Figure 2.8(b). The linear accelerator is located between thick concrete walls.

The patient has to take place upon the table of the linear accelerator. The table is the object having a black colour. The radiation equipment displayed in Figure 2.8(b) has rapid arc technology. The radiation equipment can turn around the patient.

When the patient is placed upon the table, the patient is positioned correctly by the two radiotherapy lab technicians. Next, the necessary supports and straps are placed for the support of the patient. This is done in the same way as determined during the CT-scan. The equipment shows lines on the body (the same lines as the CT-scanner). These lines have to match with the lines marked on the body. When the positioning is finished, the two radiotherapy lab technicians go to the separated front room where a third radiotherapy lab technician is present.

The third radiotherapy lab technician is responsible for the operation of the machine. First a photo of the positioning is made. That photo can help in positioning the patient. The positioning can be adapted by a change of the position of the table. If that is not enough, a radiotherapy lab technician goes to the radiation room again and improves the position of the patient itself. The accuracy of the patient's position is really important to have effective radiotherapy. The lab technicians can have contact with the patient via the intercom.

If it is necessary, a scan is made to inform the treating doctor. Otherwise, the radiation is started directly. The radiation equipment turns around the patient twice. The radiation program takes only a few minutes. If the radiation cycle is finished, the patient is picked up by the radiotherapy lab technicians. The patient can go back to the dressing room and can leave the hospital. In the meanwhile, the next patient can be called to undress in the other dressing room.

Resources

The different processes experienced by a patient are discussed. To make that process possible, a full radiotherapy department is present. Several resources are present that make the processes possible. The linear accelerators are important resources for the department. Next to that the employees and the software are important resources that make it it possible to radiate the patients.

The following groups of employees are important for the patient process. Some of them more on the background; other more directly connected to the patients.

- **Doctors:** Responsible for all medical decisions. Doctors will do the triage process (explained later on) and the actual consults with patients. The doctors can be specialists or specialists in training.
- **Medical physicist:** Responsible for the technical (advanced) systems. In most cases necessary for approving radiotherapy plan.
- **Radiotherapy lab technicians:** Are responsible for the preparation and execution of the radiotherapy. They make a radiation plan and operate the CT-scan, the moulage room and the radiotherapy equipment itself.
- **Front-office:** The nurses connecting to the reception desk. Responsible for the communication with the patients during their attendance in the hospital.
- **Back-office:** Information communication with the patient outside the hospital. Their main mean of communication to the client is the telephone. The back-office handles the post for the doctors too.
- **Logistic office:** Is responsible for all scheduling and rescheduling tasks for both patients and personnel. One exception: The scheduling of the doctors is done by one of the doctors itself.
- **The Central Enrollment:** Processes all information for new patients in the outpatient clinic and makes an order to start the process. The Central Enrollment is no part of the radiotherapy department.

To make the radiotherapy possible, several computer programs will play an important role:

- **EPIC:** EPIC is the electronic patient dossier software of VUmc. There all relevant information of the patients is stored. The electronic patient dossier is build up from the history of a patient. The doctor can use the information of a patient in EPIC. Apart from the information, orders can be made in EPIC. When a patient is referred to the radiotherapy department, the order shows up in the order box of EPIC for the radiotherapy department. In that order box, the triage process takes place.

[redacted]

[redacted]

- **ARIA:** ARIA is the main software used for the radiotherapy process. This program is used for the making of the radiotherapy plans and the for scheduling. Furthermore, the program has an important role in connecting the process. At two points in the process (Scheduling the preparation steps and scheduling the radiotherapy appointments), a path is created. In that path the different tasks for the different sections of the departments are given. In Figure 2.9, an example of a patient path is given. In the left, the section of the department, responsible for the operation of the specific task is given. In the top, the due date is shown. In this example it is measured from day 0. When it is connected to a patient, this will be the day of the creation of the patient path. Apart from the due date, the due time is shown in the task box. Whenever, the path is created, the different tasks will appear in the task box of the relevant section. Whenever the due date is passed, the task will become red. The schedulers can choose from a long list of possible patient paths, depending of the medical patient path.

- **Pentaho**: is the information program for the department. After specific steps, questionnaires have to be filled in. These questionnaires contain important treatment information use full for other process steps.

2.2.3. Preparation process

The consult, the moulage and the CT-scan are part of the preparation process of the radiotherapy. Apart from these directly patient-related process steps, more process steps are necessary in order to make the radiotherapy possible. Below the preparation process is described. The directly patient-related steps will not be elaborated in detail. These process steps are discussed in Section 2.2.2.

The preparation process contains the following steps:

- The process start at the back-office. The back-office receives the referral of a patient. External referrals can come via the mail, the fax or via a letter. These referrals (including the letter of referral) have to be sent to the Central Enrollment for administration (mainly for assurance issues). Internal referrals will be placed as order in EPIC directly.
- For the external referred patients, the Central Enrollment will document the necessary information. The patient is added to EPIC by filling in the basic information. For the patient a specific patient number is made. Furthermore, the correct assurance company is added to EPIC. When all information is correctly added to the system an order is made.
- When the order is placed in EPIC it appears in the triage box (part of EPIC). Then the doctors have a task to do the triage process. The triage process is the determination of the possible next steps in the process. This contains the choice for a CT-scan and a moulage. During the consult, the doctor can deviate from the determined process steps. Also extra demands are documented by the doctor. The triage box is visible for all doctors. However, the doctors will only do the triage of the patients of their own focus area. For palliative patients, speed is important. Therefore all doctors will do the triage of palliative patients. For the breast-cancer patients another procedure hold: Due to the standardized approach, the logistic office can do the triage process. In case of doubt, the patients are triaged by a doctor.
- The logistic office will create a corresponding patient path in ARIA.
- According to the demands determined by the doctor, the logistic office will schedule the consult and eventual other preparations.
- The back-office calls patient for the appointment for the consult and the eventual preparations. In principle, the date and time is an announcement.
- The patient arrives for the first consult and eventual preparations. That process is described in Section 2.2.2.
- The radiotherapy lab technicians responsible for the execution of the CT-scan have to upload the results of the CT-scan having standardized names. Apart from that, a questionnaire with information have to be filled in.
- The next step is the pre-planning, executed by a radiotherapy lab technician. There other scans will be imported in ARIA. Furthermore the first elements are drawn in the CT-scan. An example is the designating of an artificial hip.
- The doctor has to draw the boundaries for the radiation in the processed CT-scan. They must designate the tumour and the eventual important area's where radiation is dangerous. Furthermore, the necessary questionnaires have to be filled in by the doctor.
- The radiotherapy lab technicians have to do the 'planning'. That includes the determination of the radiation field. The required lines are drawn in the software program. On that basis, the computer calculates the amount of radiation that has to be given to the patient over all degrees of the two turns around the patient.
- When the plan is finished, the plan is sent to the doctors again. The doctor responsible for the doctor has to approve the plan.
- The plan is discussed with all doctors during the morning meeting of the doctors. The morning meeting is executed every day.

- Parallel to the previous two steps, the logistic office makes a new path in ARIA for the actual radiotherapy preparation. In Figure 2.10

- The logistic office can schedule the different radiotherapy appointments. This can be together with the scheduling of a weekly consult at the doctor, appointments with the dietician and the dental hygienist.

- When the scheduling is finished, the back-office calls the patient for the first appointment for radiotherapy.

- The plan is checked again by the radiotherapy lab technicians. The different choices and settings are checked. If necessary, the plan is adapted to what is required.

- When certain more difficult radiation techniques are used, the radiation plan has to be checked by a medical physicist. This step is required for among others the most-used rapid-arc technique. That results in the fact that most of the plans have to be checked by the physicists. The check is done from a technical point of view: Is the right amount of radiation given to the right part of the body? By the mean of mutual agreements, the different check-tasks are divided. Each of the different checks is responsible for its own field of expertise.

- The next step for the physicists is the execution of a parallel computation. In the program 'FRAME' a simplified computation of the radiation dose is executed. When the results is within the acceptable margins, it is correct. When that is not the case, a measurement is done on the linear accelerator itself. That results of the measurements are checked again.

- The post planning is executed. Some necessary administration is done and the mask is brought to the right location.

- The post planning is checked by another radiotherapy lab technician.

- The patient comes every day to the radiotherapy department for a radiotherapy appointment.

Logistic Office

One of the important links in the chain is the logistic office. The logistic office is located in the process twice: The scheduling of the preparation and the scheduling of the radiotherapy appointments itself. For the planning they will use a basic schedule. In that schedule, different reservations are made for breaks, for maintenance and for use by physicist. In urgent cases, these reservations can be used for patients after discussion with the relevant persons.

Apart from that, reservations are made for new patients. These new patient places are reserved for patients that start their radiotherapy that day. A special stereo start place is reserved too. This planning strategy is named the 'Carve-out' strategy[11]. Around the reserved slots, the different repetitive radiotherapy appointments are scheduled.

Process quantification

The preparation process consists of several process steps that have to be executed before the patient can start its radiotherapy. The time of the preparation process is important due to the possible growth and metastasis of the cancer.

The average time between the start point of the preparation process (the reception of the referral) and the end point of the preparation process (start of the radiotherapy) is measured. In Table 2.2, the average results are given for the duration of the preparation process and the duration of the par before and after the consult.

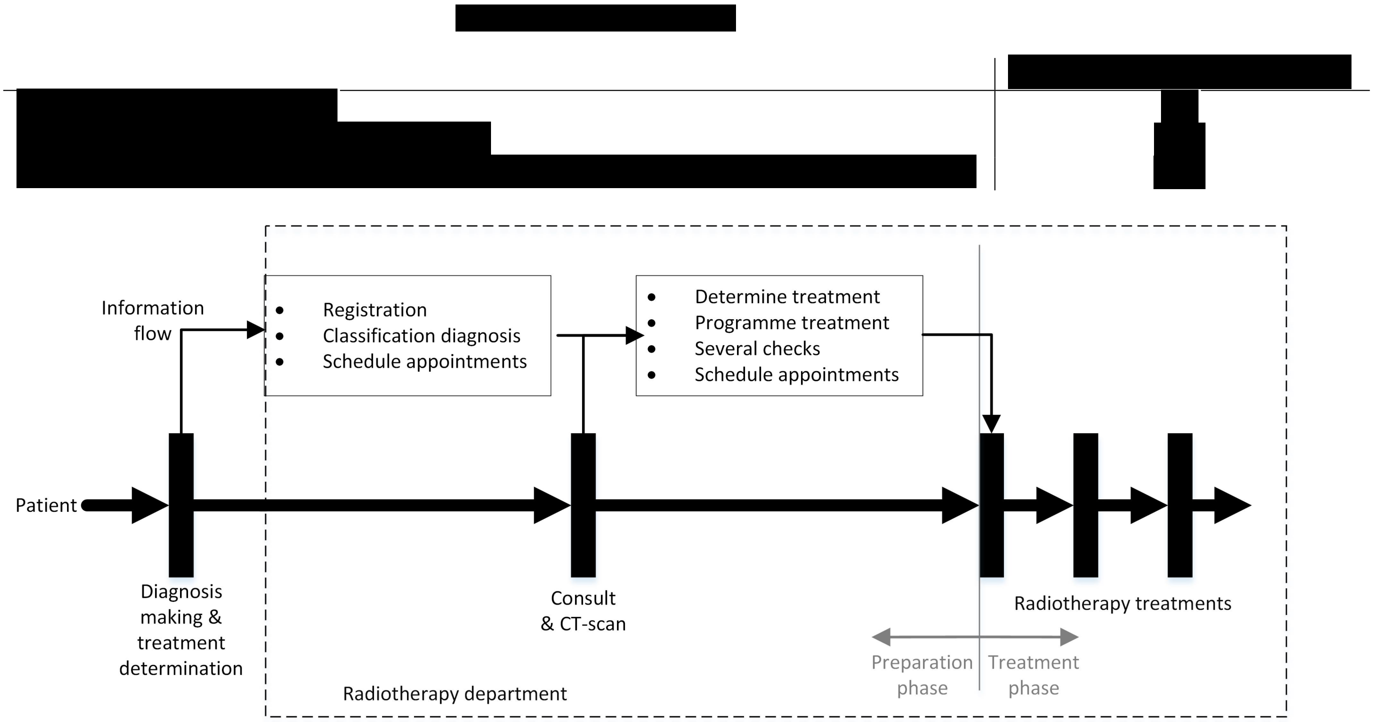


Figure 2.11: Radiotherapy process overview)

2.3. Process overview

Figure 2.11 shows the summary of the radiotherapy process. The dotted lines show the boundaries of the radiotherapy department. The radiotherapy process is divided in a preparation process and a treatment process. The patient flow and the points where the patient has to visit the department are illustrated. Next to that an information flow is depicted.

For the patient, the process starts outside the radiotherapy department, where the diagnosis is made and the treatment is determined. If the diagnosis is cancer and the treatment is radiotherapy, the patient is referred to the radiotherapy department. During the preparation process, the patient visits the department once. During this visit, the patient meets the doctor at a consult and a CT-scan is made. When the preparation process is finished, the patient can start its treatment period. The radiotherapy can consist of 1 to 35 radiotherapy treatments. The patient visits the department every working day for one radiotherapy treatment.

During the preparation phase, several process steps are executed without the physical attendance of the patient. The different process steps are summarized in Figure 2.11 and are divided into two different section: Before and after the consult and the making of the CT-scan.

3

System analysis

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

- [redacted]
- [redacted]
- [redacted]
- [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

- [redacted]
- [redacted]
- [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

- [redacted]
- [redacted]
- [redacted]
- [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

- [redacted]
- [redacted]
- [redacted]
- [redacted]

[redacted]

[redacted]

[redacted]

- [redacted]
- [redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

4

Research goal

In Chapter 3, the system-analysis is executed. From the analysis several problems are observed. Before a proposal of improvements it is important to search to the origin of the problems. Therefore it is important to search for the origin of the problems.

In Chapter 3, the functional design of the radiotherapy system is discussed. The functional design is a reason for the presence of the transitions between the different sections. In the radiotherapy department, the transitions contribute to the fact that the different functional sections operate as separated 'islands'. The errors in the information flow are often due to the fact that the different sections think from their own point of view.

The presence of buffers between the different process steps in the preparation process is another aspect of the functional organisational structure. The buffers represent the waiting queue of patient orders before the different process steps. In the radiotherapy department, no control is available for the flow of patient orders throughout the different process steps and corresponding buffers. The result is a restricted flow of patient orders throughout the preparation process.

Consequently, the origin of the problems can be found in the fact that the radiotherapy department is too much functional organised. The problems occur mainly in the preparation process, where most of the order flow process steps are executed. For this process, improvements have to be proposed. These improvements have to contribute to more transparency, better coordination and in the end to an improved flow. More transparency is required to get more insight in other sections and to smooth the transition between the different sections. Better coordination is required to be able to observe and act on the section overlapping flow of patient (orders). The final goal is to improve the flow of patient orders throughout the preparation process.

For the search for improvements, the following research goal is formulated:

Redesign the preparation process to create an improved flow of patients with a transparent and coordinated execution.

The preparation process is the process where improvements need to be suggested. Therefore, the system boundaries are redefined as visible in Figure 4.1. Most of the preparation process steps are executed in the domain of the order flow. As a basis for the second part of the preparation process step, the patient has to visit the department for at least a consult with a doctor and the making of a CT-scan. This part of the patient flow is taken into account too during the search for improvements. The resources flow is considered not to be part of the system.

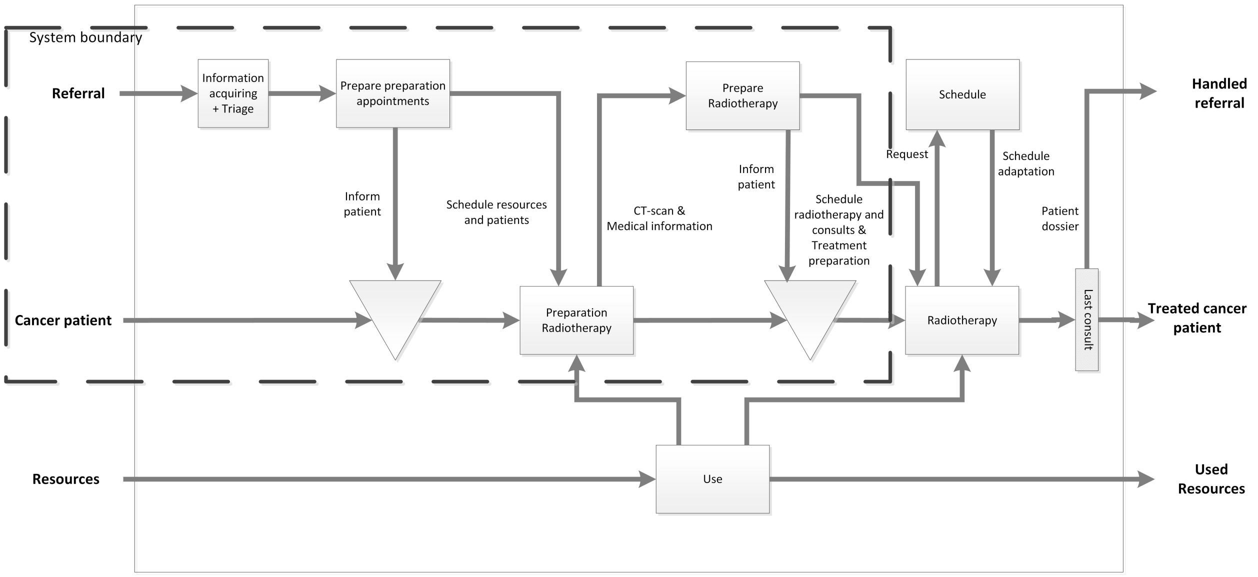


Figure 4.1: Redefining of the system boundary

5
Solutions

In the previous chapter, the research goal is determined. According to the problem statement, solutions need to be proposed to improve the flow of patients, which has to be done by redesigning the preparation process. In the redesign process it is important to end up in a situation with the following three requirements:

- The proposed situation must have more transparency than the current situation. More insight in the flow throughout the different functional sections is required.
- The proposed situation must contain better coordination. The redesign must be able to control the patient orders in the desired flow pattern.
- The flow must be improved. The solution must be able to smooth the peaks in the process.

This chapter describes the different solutions. Section 5.1 describes solutions regarding the design of the organisational structure of the department and section 5.2 describes solutions regarding the design of a control structure for the flow of patient orders through the department. The solutions have to satisfy the three requirements above.

5.1. Organisational structure solutions

In Chapter 3, it is concluded that the functional design of the department is a restriction for the flow of patients. An alternative for the functional structure is the product flow oriented design. In a product flow oriented design the system is organized according to the different products: All actions combined to a certain product are located in one institution[20]. A product flow oriented design can improve the flow of patient orders. Although it is rarely used in hospital organisational structures, examples of successful use of product flow oriented organisational structures are available. An example is the production line for hernia operations in the Shouldice Hospital [21].

However, the division of the department according to qualifications of employees is a requirement for the radiotherapy system. This is the reason, the preparation process cannot be organized according to a product flow oriented organisational structure. However, several mixed forms between the product flow oriented design and the functional design are possible[20]. Some of the mixed forms are discussed below in order to search for improvements of the flow of patient orders. The order of discussion is from more functional to a more product flow oriented perspective.

5.1.1. Multiple machine operation

Multiple machine operation is the first step in the direction of product flow oriented design. It can be explained according to a shop floor with several machines like lathes and milling machines. In a strictly functional divided organisation, the product 'visits' the required machines with corresponding workers. The process time of a product is the set-up time and the process time. In the case of multiple machine operation, the process time can be used to set up another product in another machine. This is only possible if the processing does not request human effort (automatic operation). [20]

When transferring this situation to the radiotherapy department it becomes clear that the fact of a process without human effort (like the processing in a milling machine) does not exist in the radiotherapy processes. However, multiple-machine operation can improve the efficiency of the processes.

This is the case for the different preparation process steps: The making of the CT-scan, the moulage, the upload of the CT and the preplanning. These functions are currently executed by three different employees (only CT and CT upload are combined). Especially the personnel of the CT-scanner has much time left apart from executing their tasks. If personnel is qualified for all preparation tasks, the personnel can be used more efficient. The tasks can be executed earlier. This can result in a faster flow of the patient orders throughout the department.

It is stated that more efficient use of employees can result in faster execution of patient order tasks. However, can these functions be combined in one institution? And can this lead to an improved flow of patients through these process steps? This is the next step in the search for improvement in the direction of a flow oriented process.

5.1.2. Defunctionalize

Before each of the different process steps in a functional structure, a waiting time is present. Defunctionalizing is the reducing of the number of departments. As a consequence, the number of buffers will decrease. Furthermore, the overall control will cover less departments, what can lead to a simpler control structure. [20] By doing this, the employees in the different sections must broaden their expertise for being able to execute the different tasks of the other section. Apart from that, the manager of the specific section has to control a bigger functional group. If these two points are not a restriction for defunctionalization, this could be realized.

Especially in the radiotherapy department, many information is transferred between the different sections (both feedforward and feedback). The communication is a source of errors. Especially due to the different functional background of the different sections, the communication is hampered. This is another reason for investigating the possibility to reduce the number of functional sections.

Within the radiotherapy department, the following functions can be combined:

- All patient-preparation steps executed by the radiotherapy lab technicians: The execution of the moulage, The execution of the CT-scan to the patient and corresponding import and the pre-planning. This is a further elaboration on the option mentioned under the multiple-machine-operation. These steps are all subsequently positioned in the process. The CT- and moulage-operation are bounded to the schedule. The import of the CT and the pre-planning are more flexible. This action removes the buffer between the import and the pre-planning and removes the double coding function (See Figure 3.7). All actions are executed by the radiotherapy lab technicians. However, the internal qualifications can differ. It is required to investigate in broader qualifications of the lab technicians when this option is coming true.[1]

- The scheduling and calling of the appointments of a patient by combining these process steps, the feedback of the patient can be processed directly and one of the buffers could be removed. Disadvantages are the required expansion of the skills of both sections and increasing noise in the scheduling room.

By combining some process steps, the transparency within the combination of sections is increased. Furthermore, the coordination of the full system becomes simpler due to the reduced number of sections. The patients flow through the preparation process will be faster.

[1] This idea is based on ideas/plans suggested by the department itself.

5.1.3. Other options

Apart from the multiple-machine operation and defunctionalization, more mixed forms are possible[20]. One of the options is the dock-system. In the dock-system a worker is executing all tasks for one specific product. Another option is the use of cells. Cells are mini-factories where a certain types of products are processed. However, both of these functions will contradict the external requirement of the division of the department in sections with employees with similar qualifications.

As discussed above, multiple-machine operation and defunctionalization can improve the radiotherapy process. However, these improvements let sustain the functional design of the radiotherapy itself.

5.2. Control structure solutions

The conclusion can be drawn that the functional lay-out of the department must be sustained. Defunctionalization can reduce the number of functions. However, it cannot solve the problems in the transitions between the different process steps. To solve the restrictions at the transitions between the different process steps, a new control structure is proposed. This control structure must coordinate the flow of patients through these transitions. For the solution, the theory of matrix organisations is used.

5.2.1. Matrix organisation

In traditional project organization the management structure is typically functionally organized. The organisational structure is divided in engineering, operations, financial and other functional departments. As for the radiotherapy department, overall control for the project itself is missing.[3]

Pure product organizational structures are organized around the different projects. For each project, a project manager is responsible for the single project. Under the supervision of the project manager of that project, the different functions are executed. The disadvantage of this organizational structure is the missing of strong functional groups where people can help each other and learn proper methods. [3]

A third option in project management theory is the matrix organizational structure. In this structure, functional management is responsible for the different functionalities and project managers are responsible for each of the projects. This is illustrated in Figure 5.1. Matrix organizations can sustain the importance of the functional groups and coordinates the project progress.

The difficulty in the matrix organizational structures is the dual aspect of the management. This can result in potential conflicts. This is one of the points that have to be taken into account in matrix management organizations. However, a matrix organization gives a new solution for the control of functional organizations.

The functional lay-out of the radiotherapy system have to be sustained. One of the problems is the lack of patient coordination through the order process. A matrix organizational structure sustains the functional lay-out and adds the product/project/patient coordination. Therefore, the matrix organization is chosen as a base framework for designing of a control structure.

On the level of the hospital itself, examples of the application of the matrix organization theory are available. The first example is the existence of unit management programs: A system for the coordination and integration of functional department personnel. In this system, unit managers exist, coordinating the decisions where actors from multiple fields(for example nurses, technicians and social workers) are involved. The unit managers are responsible for decision making in several administrative and policy areas. [22]

The matrix organisation theory could also be used for cost control in a hospital environment. Therefore the products of a hospital are defined to make it possible to control this on the basis of the pa-

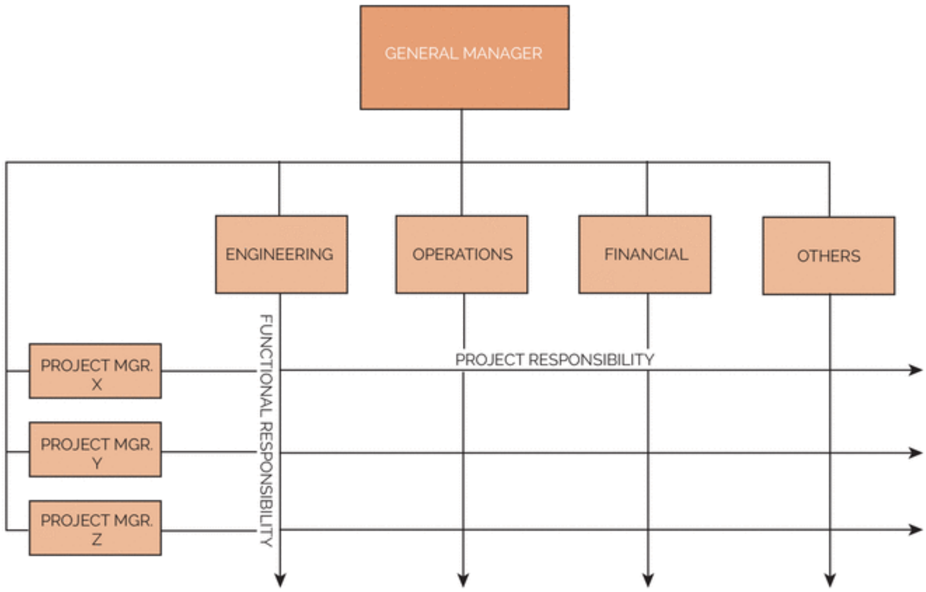


Figure 5.1: Matrix Organization [3]

tient group instead of the control of the costs on the use of the different functions on the hospital. [23] However, these examples differs from the radiotherapy system. The subject is different (policy/administration and costs) and the scope is wider in the mentioned examples.

When incorporating the matrix organization theory, each patient and corresponding patient order needs to be considered as one individual project. The modelling of a patient order as project is used for the incorporating of patient order control over all functional sections. Each project needs to be coordinated. Therefore a project leader has to be defined and the time span of 'project patient' need to be defined. The following steps are defined in project management theories[3]:

- Project initiation: This is the selection of the project. The project is selected when the project contains enough benefits. The first preparation of the process is done and a project manager is assigned to the project.
- Project planning: In the project planning phase, the requirements for the project are determined. Furthermore the required resources and the corresponding schedules are determined.
- Project execution: During the project execution, the work needs to be directed and managed and, if possible, improved.
- Project monitoring and control: The progress of the process needs to be tracked and evaluated. Eventual adjustments can be necessary to steer the project in the desired direction.
- Project closure. It has to be verified that the project has been accomplished. All necessary administrative issues needs to be finished.

For defining the time span of 'project patient', two different options can be chosen:

1. 'Project patient' starts when patient is referred to the radiotherapy department and ends when the last treatment is executed.
2. 'Project patient' starts when the patient is referred to the radiotherapy department and ends when all preparation steps are finished. In this case the project includes the preparation process.

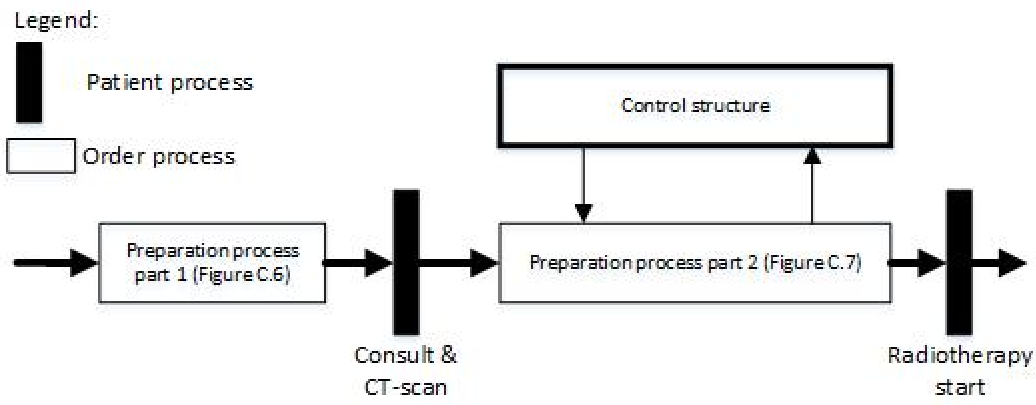


Figure 5.2: Place of the patient order control structure in the process

The first option copes ideal with the experience of the patient. The second option can be seen as the project initiation phase and the project planning phase of the first option. The system boundary as defined in Chapter 4 meets best with the second option. Therefore, the second option of 'project patient' is defined as the project. At the ending of the project, the patient still has to start the radiotherapy. The project is ended successfully when the preparation of the patient is finished correctly and in time.

Project initiation in the radiotherapy section is the process of the arrival of the referral. At the MDO, it is discussed if radiotherapy is the most appropriate therapy for each individual patient. This takes place outside the system boundary. In a later phase, a filter is present to check if radiotherapy is indeed a proper treatment method. The process of the reception of the referral is considered to be part of the project initiation phase.

The doctor determines the actual realization of the treatment method (project planning step). This realization determines the required process steps within the radiotherapy department. Some of the steps are done without the physical attendance of a patient (triage process), some are done with the physical attendance of the patient (consult with patient). Furthermore, the schedules for the consult, the CT and eventual the moulage are part of the project planning step. In the radiotherapy department, the project initiation phase and the project planning phase are not strictly divided.

Once the patient knows he or she has to receive radiotherapy treatment, the main steps for the project can be executed. The project starts with the CT-scan and ends when all preparation process steps are executed. The process is finished in the post planning step. This can be considered as the project closure step.

During the actual execution of the project, the work needs to be managed. This is currently executed by the functional team managers. The monitoring and control is not actively executed as determined in the analysis.

For the control of the process during the execution of the different process steps, a patient order control structure is developed. It is developed for the second part of the preparation process (Figure 5.2). The control structure is developed from the point when the consult is finished and the CT-scan is uploaded towards the end of the preparation process. The design of a patient order control structure for the first part of the preparation process is left out of the scope of this research. This requires a different approach due to the fact that the subsequent process steps cannot be estimated before the consult and the CT-scan.

The patient order control cannot influence the time that has passed before his assignment to the patient. However, it has to deal with this 'passed time'. The total time of the preparation for a treat-

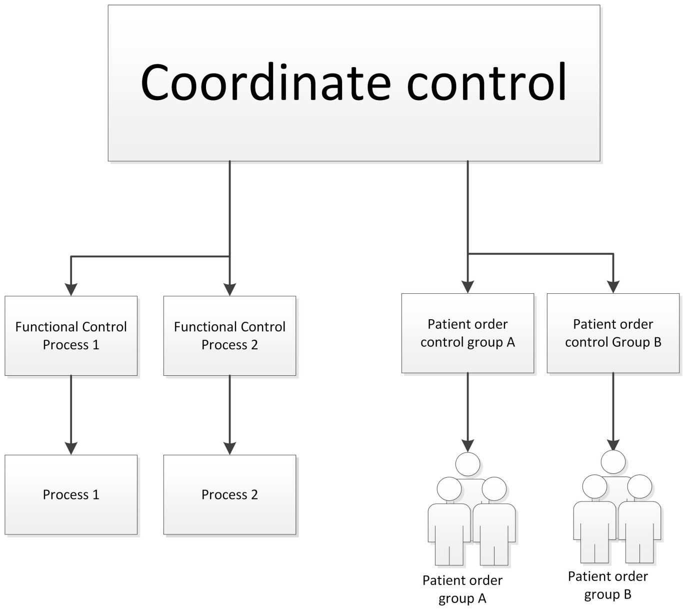


Figure 5.3: Control hierarchy

Functional control ≠ Function control

Figure 5.4: Difference in control names

ment is the time relevant for the patient. The 'passed time' is part of this total time.

5.2.2. Control structure

The patient order control structure is part of the total control structure based on the matrix organisation theory. The other part of the control structure is the functional control structure. Both functional control and patient order control have to be controlled by a control layer: The Coordinate control. The coordinate control controls the process over all functions and for all patient orders together. The control hierarchy is shown in Figure 5.3.

Below, the different elements are worked out in more detail. For both the functional control and the patient control, two types of control are available. The first type of control is the function control which is determined for the initiation, evaluation and update of the standards. Process control is the control of the daily fluctuations according to these standards. The difference between functional control and function control must be mentioned: Functional control is the control of the different functional sections and function control is the control of the correct execution of the function of the controlled part (Figure 5.4). The parameters used during further modelling are explained in Table 5.1. The process time used in this research is the time of the execution of the tasks combined with the waiting time.

5.2.3. Coordinate control

The coordinate control is responsible for the connection between the two types of control: The functional control and the patient order control. Figure 5.3 shows schematically the role of the coordinate control in the full control structure. The coordinate control is responsible for the translation of external requirements into process-related standards. As determined in the research goal, the flow of patients does have the attention during this research. Therefore, the control structure elaboration is only considering the aspect of flow. The quality aspect of the treatment is left out of the scope.

Table 5.1: Parameters for control structure

Parameter	Unity	Explanation
t_i	hours	Duration process i + Waiting time between process i - 1 and process i
t_{total}	days	Time between the reception of the referral and the start of the radiotherapy
L	days	Longest process path
Q_i		Length waiting queue process i
N	1/hour	Flow of patients

Table 5.2: Requirements for time between referral reception and start radiotherapy

Patient group	Requirement
Acute patients	100% within 24 hours
Sub acute patients	80% within 7 days 100% within 10 days
Other patients	80% within 21 days 100% within 28 days

Regarding the flow, the only external requirement is the time between the referral reception and the start of the radiotherapy. This is equal to the duration of the preparation process. The requirement is different for three groups of patients as noticed in Table 5.2. These requirements are the input of the coordinate control. The coordinate control structure is given in Figure 5.5. In the initiate function of the control structure, these different parameters are translated to relevant process parameters and patient parameters.

The coordinate control is responsible for the defining the standards for the duration of the different process steps t_i, max. The different process times are relevant for the functional control structure. The process times t_i, max are bound to Equation 5.1, where L is the longest process path. The maximum process time $t_{total,max}$ is an external requirement. This maximum process time is the input for the patient order control. If necessary, the coordinate control can decide to initiate a lower value for the total process time to the patient order control structure.

$$\sum_{i \in L} t_i \leqslant t_{total,max} \tag{5.1}$$

The coordinate control coordinates both functional control and patient order control. Both control structures are worked out in more detail.

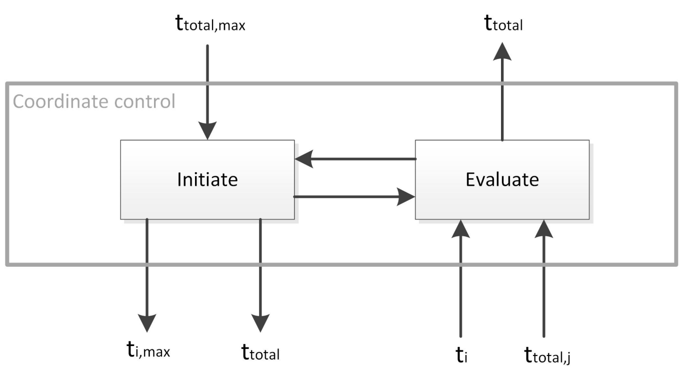


Figure 5.5: Proposed coordinate control structure

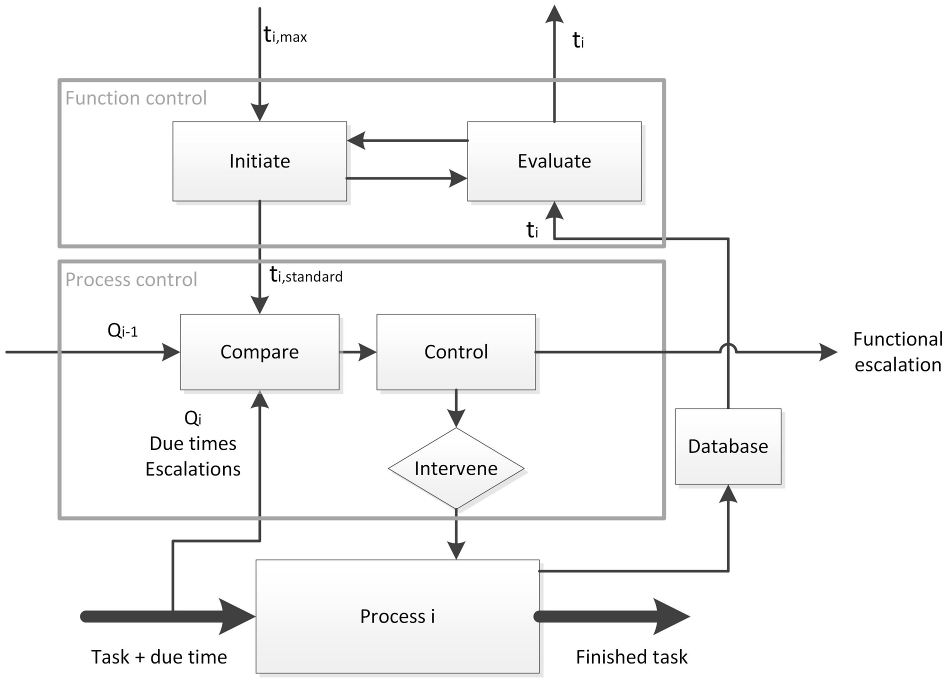


Figure 5.6: Proposed functional control structure

5.2.4. Functional control

Functional control is required for the control of the execution of the different processes in the process. In the current situation, functional control is present but not made explicitly. Therefore, a control structure is proposed in Figure 5.6 that can be used for every process step.

The function control of the functional control domain is defining the actual process time to steer on. The process time is the sum of the waiting time and the actual time for the execution of the task. The functional requirement is a maximum value for the process time. This value cannot be exceeded. The initiate function will feed the process control with the process time to steer on ($t_{i,standard}$). This standard needs to be evaluated by the current realized process times t_i. This can result in an update of the value $t_{i,standard}$.

The standard for the process time (including waiting time) is the input for the process control. However, the relevant and visible parameter for each of the functional section is the length of the waiting queue: The number of patient orders that waits for the process step of the current section. The length of the waiting queue is the control parameter for the functional process control. The standard for the waiting queue length can be calculated by Equation 5.2. It has to be noticed that the task is leaving the queue when the task is finished completely.

$$Q_{i,standard} = t_{i,standard} \times N \tag{5.2}$$

In the current situation in the department, the different processes do not communicate to each other regarding the peaks or dips in the patient order flow. The different sections in the process cannot anticipate on the coming demand. Therefore, this control structure adds the communication of the previous waiting queue length to the process control. The estimation of the waiting queue length for the short future is expressed in Equation 5.3. This equation holds also for the current situation (Δt = 0).

$$Q_i(T = T_{now} + \Delta t) = Q_i - \Delta t(-\frac{Q_i}{t_i} + \frac{Q_{i-1}}{t_{i-1}}) \tag{5.3}$$

The difference between Q_i and $Q_i, standard$ will determine eventual control actions. It is possible to estimate the length of the waiting queue at time $T = T_{now} + \Delta t$. This can be the basis for the control

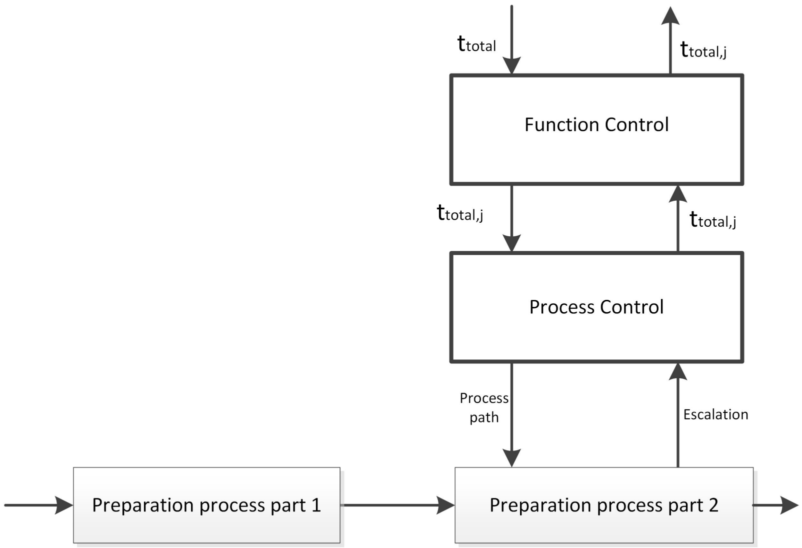


Figure 5.7: Overview patient order control structure

actions for the (short) future. Whenever it is possible, the time employees are scheduled for primary process tasks can be varied. Another option is eventual overtime for the employees.

These decisions will be dependent of another parameter: The due time of the different tasks. These due times have to be coordinated by the functional process control. The due times are the basis for the order of processing. Whenever a due time is passed, the task is becoming red. This can be a signal for the process control to intervene.

When the process control is not able to control the process in a way that the section can execute the required tasks within the determined time, the process control can ask for a change in the start time of the radiotherapy for one or more patients (functional escalation). This will create more process time. This request has to be done in the direction of the patient order control. Therefore it is important to determine the patient order control structure.

The proposed functional control extension is meant to improve the transparency. The insight in the upcoming flow will be increased. Next to that, more insight in the upcoming peaks will increase the possibility to smooth the peaks in the process.

5.2.5. Patient order control

Patient order control is the control of the patient order throughout the full process. This way of control is similar to the project-oriented control in the matrix organisations for project management. The main task of the patient order control is to coordinate the flow throughout the different process steps. In Figure 5.7, the patient order control structure is depicted. The control structure consists of both function control and process control. As stated earlier, the patient order control structure is designed for the second part of the preparation process. It starts from the point when the treatment of the patient (and the corresponding preparation steps) can be determined. It ends at the point where all preparation steps are finished and the patient can start their radiotherapy treatment.

The control structure is designed in more detail. The different aspects will be discussed below.

Function control

The coordinate control has determined the maximum total process time for the preparation process, which can be equal to the external requirement. The function control has to translate the department-wide standards for the maximum total process time in specific diagnosis group standards. The function control structure of the patient order control is responsible for the initiating and evaluation of these

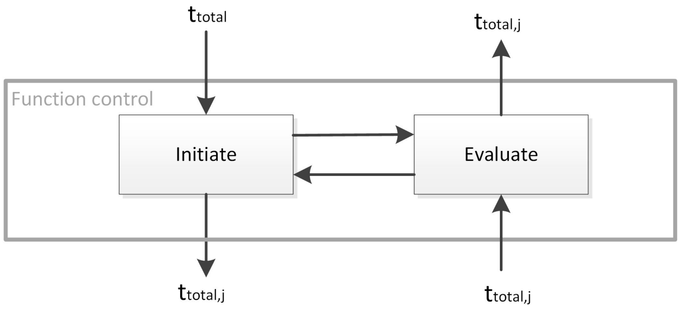


Figure 5.8: Function control of the patient order control

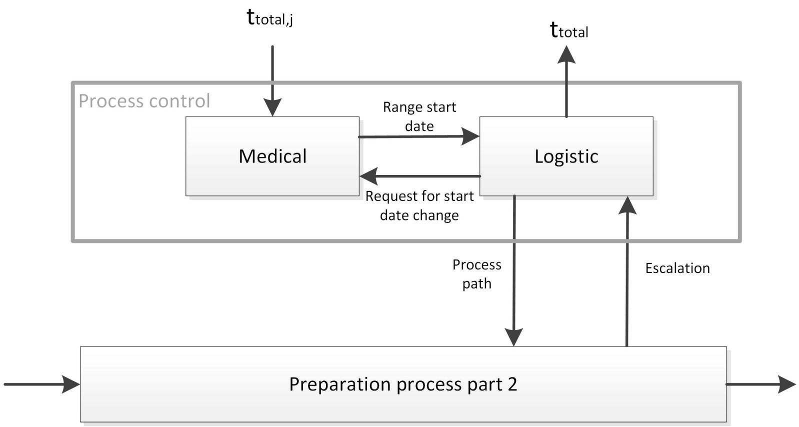


Figure 5.9: Process control of the patient order control (overview)

standards for the patient order control.

The patient order control structure is divided in the control for several groups as shown in Figure 5.3. The groups of patients are based on the diagnosis. For the different tumour groups (like lung cancer and breast cancer) specific standards need to be defined. These standards are standards for the maximum duration of the preparation process and the outline of the process (the process steps required for this group of patients). Within the diagnosis group, distinction in process path and process time can be made, for example for urgent patients. The overview is shown in Figure 5.8. In this overview, j is an annotation for the diagnosis group.

The most important standard for the patient order control is the duration of the preparation process itself ($t_{standard}$). The shorter the total preparation time, the earlier the patient can start his treatment. The patient control structure is only designed for the second part of the preparation process. However, the duration of the first part of the process is part of the total preparation process time too. This cannot be influenced by the designed patient order control structure. The patient order control structure can only influence the second part of the preparation process. By this, the total preparation process time can be influenced.

Process control

The standards defined in the function control domain has to be used for the daily control of the patient orders. The process control is responsible for initiating a process path for every patient. The standard for the duration of the preparation process is the most important parameter for the determination of this process path. Furthermore, the process control has to act on disturbances in the flow of patient orders.

In Figure 5.12, the overview of the process control part of the patient order control structure is

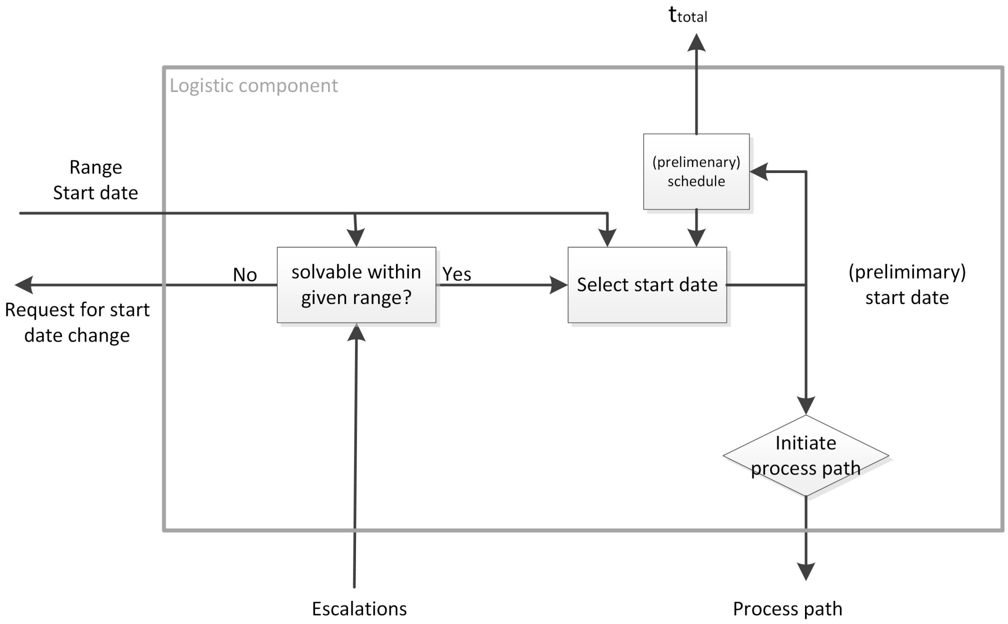


Figure 5.10: Patient order control structure (Logistic component)

given. It is visible that the patient order control consists of two different components: A medical and logistic component. The medical component can determine a minimum and maximum boundary for the end point of the process. The minimum boundary can represent the time required for the different process steps and the maximum boundary is patient-specific depending on the diagnosis.

The patient order control structure has to be able to smooth the peaks in the process. That is the reason for the adding of a logistic component to the control structure. The logistic component can choose a preliminary start date bounded by the given boundaries by the medical component. Based on the preliminary start date, a process path can be initiated. The process path contains the required process steps for a specific patient with the corresponding due times for each individual process step.

Below, the medical and logistic component will be explained in more detail.

Logistic Component

The task of the logistic component is to determine the radiotherapy start and the corresponding process path. Furthermore, the logistic component has to take care of situations where the preparation process cannot be finished before the radiotherapy start of the patient. The logistic component is visible in Figure 5.10.

For the initiating of the start date of a patient, a range is received for the date of the radiotherapy start from the medical component. Between these boundaries, the logistic component has to determine a start date of the patient. According to this start date a process path for the different process steps is determined. This process path contains all required process steps. Each of the process steps has a due time: At that time, the task of the specific patient order has to be finished.

The making of a process path is currently done during the scheduling steps (see Figure C.7) The individual process step due times are calculated from the base point of the time of the generation of the process outline. The process outline is made in ARIA (the radiotherapy software that guides the radiotherapy process). An example is visible in Figure 5.11.

In the proposed situation, this process outline can still have the same function. It contains due times for the individual process steps. However, the due times will be calculated from the base point of the preliminary start date instead of the date of patient outline generation. Due to this change, the

Figure 5.11: Example of a patient path

patient orders having an earlier start date will be executed earlier. This will contribute to the fact that the preparation process is finished when the patient start is planned.

The execution of the processes based on this known end point of the preparation process will give more insight in the process compared to the current situation. In Chapter 3 it is concluded that the red sign of due date passing has lost its signal function. In the proposed situation clear insight in priority and the fact that being too late will result in a change of the already determined start can probably result in a revaluation of the signal of the due time passing.

The logistic component has to choose the preliminary start date. The choice is made to optimize on the number of starters per day. The most ideal situation is where the number of starters is equal every day. This situation is assumed to be ideal because it can optimize the flow of patient orders. This has two reasons:

1. This situation can equalize the number of patient orders present at each of the process steps. The due times of the individual tasks are based on the start date of a patient. If the output in the last process step is constant (due to a constant number of starters), the connected previous steps can have a (approximately) constant flow too.
2. This situation can lead to a homogeneous schedule for the linear accelerators. It is assumed that if the number of first radiotherapy appointments is equal for each day, the number of repetitive appointments is equal too.

Apart from initiating the start of radiotherapy and the corresponding outline, the logistic component is able to control the disturbances. One of the main causes of disturbance is the fact when the preparation process cannot be finished before the radiotherapy start of a patient. This can be observed by the functional control and can lead to a functional escalation (see the description of the functional control).

Figure 5.10 shows the behaviour in case of a functional escalation, which asks for a change of the start date. If the start date can be changed within the given range, the start date can be changed. Otherwise, the medical component has to approve a delay of the start date. If that is possible, the control part can look for a new start date for the patient. This start date and the corresponding process path will be initiated to the process.

The start date is preliminary during the time when it is determined. The patient is informed a few days before the start of the treatment. After informing the patient it is not desirable to change the start of the radiotherapy. Before informing the patient, the start date can be changed more easily than

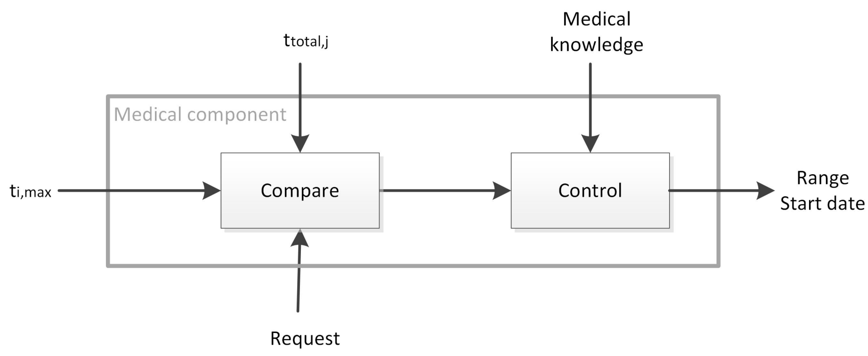


Figure 5.12: Patient order control structure (Medical component)

afterwards. It is important to make reservations in the schedule for urgent patients. Urgent patients have a process time lower than the time between the informing of a patient and the radiotherapy treatment.

In most cases it is possible to find a start date for the patient. The equal division of the starts over the days is desired but not obligatory. However, in case a start date cannot be found, for instance if a more than average number of urgent patients has to be placed in the schedule of one day and the schedule has no empty slots left. If that is the case, the start date of other patients has to be changed.

Medical Component

The task of the medical component of the process control of the patient order control structure is to define boundaries for the radiotherapy start of the patient and to decide on eventual disturbances.

The medical component can use standards for determining the boundaries for the start date. For the minimum boundary it is necessary to determine the process steps required for the specific patient. The minimum boundary is a representation of the time required for the execution of these process steps. This minimum time is a summation of the functional standards for the different process steps. In some cases, the medical component has to deviate from the standards. For example, the treatment planning of an urgent patient is executed in a shorter time: The treatment plan is less complex.

For the maximum process time, standards are developed in the function control domain. In principle, the medical component of the patient order control has to use this standards to denote the maximum boundary for the start of the radiotherapy. In the calculation of the maximum boundary the medical component has to incorporate the already passed time since the patient order referral. For example, if the maximum standard is 21 days and the referral is received 10 days ago, the maximum boundary is 11 days.

Next to the initiating of the standards, the medical component has to decide on eventual disturbances. It can receive a request on the adaptation of the range. The medical component has to decide on the medical consequences: Is it possible to delay the patient start. If it is not possible, the medical component has to give that as a feedback. For example, overtime can be used to finish the different process times before the radiotherapy start.

Improved scheduling strategy

The scheduling strategy is the carve-out strategy. The carve-out strategy reserves slots for all first radiotherapy appointments in the schedule. This is required due to the fact that all radiotherapy treatment appointments are scheduled at the same time. The first treatment appointment (the start) is scheduled a few days ahead. The scheduling of the repetitive appointments can be done for several weeks ahead. To keep space for the radiotherapy starts of new patients, slots are reserved. Chapter

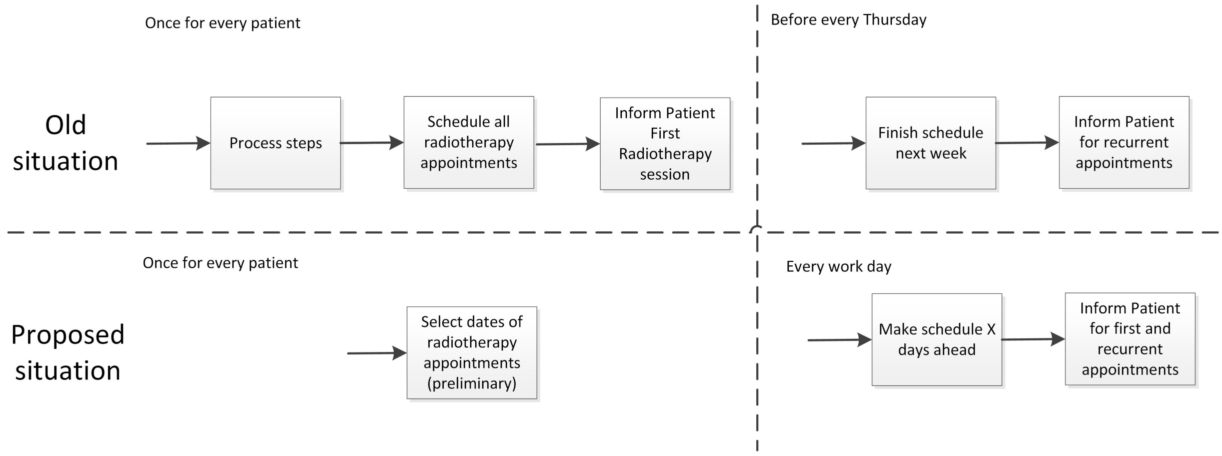


Figure 5.13: Scheduling strategy improvement

3 concludes that the carve-out strategy results in an inefficient schedule.

Another observed problem in Chapter 3 is the weekly informing of the patients for their repetitive appointments. Every Thursday a list of appointments for the entire next week is given to the patients. The period between informing and the treatment itself can vary between 4 days (for treatments on Monday) and 8 days (for treatments on Friday). The longer the period, the more chance on the adaptation of the schedule. Furthermore the work flow for the logistic office contains peaks: Before every Thursday, the schedule needs to be finished and handed over to the patients.

The determining of the start date in an early phase made it possible to change the scheduling strategy and to improve the flow as a result. The start date of a patient is determined in an early phase. If the start date is determined in that phase of the process, the number of rescheduling actions will probably increase. To cover that problem (and to solve the problems sketched above), a changed scheduling strategy will be proposed.

The old situation and the proposed situation are illustrated in Figure 5.13. In that situation, the weekly flow is transformed into a daily flow. For every patient, the preliminary start date is determined early in the process. The first appointment and the corresponding recurrent appointments are preliminary consuming scheduling capacity. This capacity is made definitive by the scheduling of the appointments. The definitive schedule will be made X days ahead (for both start appointments and recurrent appointments). X can be for example three days. After the making of the definitive schedule for X days ahead, the appointments are communicated to the patient.

This change requires a different way of informing the patients. For creating a daily flow of information to the patient, the handing over of appointment papers is probably not efficient. However, different ways of patient informing are possible: Website, mail or sms notifications are effective ways of communicating the recurrent appointments. In Amsterdam UMC sms notifications are used for appointments of other departments. The communication of the first appointment can still be executed via the telephone.

By incorporation of this scheduling strategy, the work flow could be optimized. Each day the scheduling tasks of one specific day (X days ahead) is executed. A short scheduling time horizon is beneficial regarding waiting time till the first appointment and efficiency of the schedule [11] [14]. The need for the carve-out strategy and its reservations is limited to the need for one or two slots for urgent patients, having a time horizon of less than three days (see Table 5.2). The translation to a scheduling strategy where the actual scheduling is done in a short time horizon before the actual appointment has some similarities with the advanced access strategy [11]. The advanced access strategy is a proven scheduling strategy for outpatients clinics where requests for appointments (Both urgent and non-urgent) are handled within the same day.

5.3. Conclusion

The preparation process of the radiotherapy department is too much functionally organized. The different process steps function as 'islands' in the full process. This was a reason to define the following research goal:

Redesign the preparation process to create an improved flow of patients with a transparent and coordinated execution.

This chapter proposes solutions that will meet this research goal. It is a prerequisite to maintain the functional sections in the department. Nevertheless, it is possible to combine some of the process steps. The combination can result in a quicker flow of patient orders through the department and it can increase the transparency for the processes that are combined.

The main solution for the problem is the design of control structure based on the matrix organisation theory. The functional structure remains and a patient order control structure is designed. The patient order control structure controls the flow of the patient orders throughout the preparation process. The functional control structure is elaborated by the measure of the length of the waiting queue of the previous process step.

This new control structure is able to improve the preparation process. It can meet the research goal. The adding of the length of the previous waiting queue results in more transparency for the different functional sections. The patient order control structure is another mean to increase the transparency. The patient order is now controlled during the full process. The coordination is improved by the selection of the start date earlier in the process. This makes it possible to coordinate the order of the patients and the time when the patients orders finish the preparation process. Proper coordination can result in an improved flow of patients: Less variation in the process time, less peaks in the waiting queue lengths of the different process steps and a more equalized schedule for the linear accelerators. All three aspects of the research goal.

The conclusion is that the solution is able to meet the research goal at all three aspects (More transparency, better coordination and an improved flow). The next chapter will examine these effects quantitatively.

6

Simulation model

The goal of this research is to improve the flow of the orders in the radiotherapy system. This improvement has to be done with a transparent and coordinated execution. The improvements are proposed in Chapter 5. The main solution is a new control structure based on the matrix organization theory.

In this chapter, the new proposed control structure is compared to the current situation. In the current situation, the control is pure functional and not made explicit. This control is made more explicit and transparent. Patient order control is designed to control the project of a patient order through the full cycle of the radiotherapy. Next to the design of the patient order control structure, the functional control is made explicit and some of the functions are combined.

The solution must meet the research goal as defined in Chapter 4:

Redesign the preparation process to create an improved flow of patients with a transparent and coordinated execution.

In order to examine the effect of the proposed solution on the research goal it is important to define the parameters that will judge the possible improvements (Section 6.1). For the examination, a simulation model is built (Section 6.2). The model is described first for the current situation. After that, the implementation of the different solutions is discussed. The simulation model is used for the examination of the effects of the solutions. Therefore the solution is tested on the main improvement parameters. The experimental plans and the results are available in Section 6.3, 6.4 and 6.5.

6.1. Definition of improvement parameters

During the answering-process of the research goal in Chapter 5, the improvements are chosen on the basis of the three main elements in the research goal. It is stated that the solution has to improve the flow of the patient orders while the execution need to be transparent and coordinated. This chapter will examine the effect of the solution on these three different aspects: Flow, transparency and coordination. For each of these three parameters it is defined when the solution improves the current situation.

The **flow** is improved if the improvements are able to reduce the variation in the process. The flow hindrance has to be minimized. This can be described by the following three aspects:

- The variation in the process time can be reduced
- The variation in the number of starters each day can be reduced.
- The total process time is kept equal or is reduced by the improvements.

The **transparency** of the radiotherapy will be improved if the process can give insight in the relevant information necessary to control the department. The necessary information is at least the progress of the patient orders during the process and information regarding the upcoming patient orders for each of the sections.

The **coordination** is improved if the control is able to steer the system in the desired direction. The patient order control must be able to coordinate the flow of the patient orders in the desired flow pattern based on the preliminary start date of the patient. The functional control must be able to reduce peaks in the process by incorporating previous waiting queue control.

6.2. Model outline

Before implementation, the solution needs to be tested. The test environment must give insight in the effect of the improvements regarding the defined improvement parameters.

A simulation model is chosen as test environment due to its ability to model complex systems. Next, a simulation model presents more than the outcome; it can give insight in the actual behaviour of the system. It can incorporate a useful visualization. Last but not least, simulation models can handle stochastic input. This is the case for several variables in the radiotherapy department. Therefore, a simulation model is a suitable test environment for the flow in the radiotherapy department. [24]

For the simulation, discrete event simulation is used. Discrete event simulation is the simulation of the reality as a discrete series of events. The radiotherapy department can be properly modelled by this type of simulation. The change of a status of a patient order can be seen as an event. Lazarus software[25] and a corresponding Tomas simulation package[26] is used for this simulation.

The goal of this simulation is to show the effect of the solution proposed in Chapter 5. The simulation model is meant to show the effect of the improvements regarding flow, transparency and coordination. The utility of the model is bounded to this use. The model has to represent the reality simplified but correct. The (quantitative) results cannot be compared with quantitative measurements in the real system. It has to represent the difference between the current situation and the proposed situation. For the translation from reality to the model, several assumptions have to be made which have to be represented in this report.

6.2.1. Components

The radiotherapy department is modelled in Lazarus. The model has to use the same elements as the radiotherapy itself. Therefore, the different elements will be discussed below. The main elements of the process are the elements in **bold**.

The main element of attention is the **patient order** itself. The patient order is received by the department. From the point of referral reception, the actions can be executed. When all process steps are executed, the patient can start its radiotherapy treatment. This is the end of the preparation process.

The different process steps can be modelled as different **tasks**. For most of the patient orders, the list of tasks is quite similar. Therefore, for each of the different patient orders a fixed list of tasks is modelled. Each task has to be executed by a unique **section**. These sections have **employees** executing the different tasks. These employees will work for a certain time on a day on the tasks required for the patient orders. This time will be smaller than the number of work hours on a day.

A **generator** is necessary that generates the different patient orders and the corresponding tasks. Furthermore a '**time-process**' is used that determines the time that the department is active and that generates the required output.

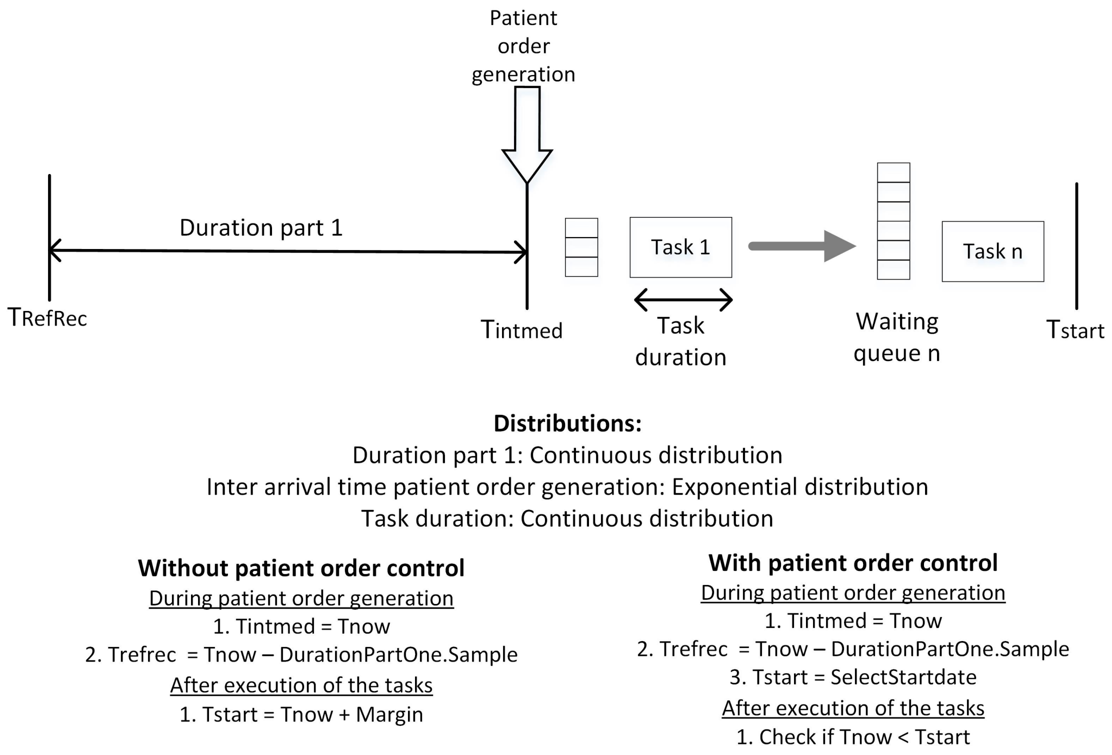


Figure 6.1: Simulation model structure

6.2.2. Model description

The different components of the model need to form the model. These components need to be connected to each other.As discussed earlier, the changes are proposed in the second part of the preparation process. Therefore the preparation process is divided in two different sections during the simulation. The first part of the process is modelled by a duration taken from an distribution. The second part is modelled by discrete event simulation (Figure 6.1)

This results in three important points in time that will be used throughout the model:

- **the point of referral reception.** This is the point where the preparation process starts.
- **The intermediate point.** This is the point denoting the difference between the two different sections of the preparation process. The part before the intermediate point is modelled by a duration. The part behind the preparation process is modelled by a series of discrete events.
- **The radiotherapy start.** This is the end of the process discussed in this research. For the patient, the actual treatment starts at this point.

These three points are the points of transition in the simulation model. The patient orders are generated at the intermediate point. The time of the referral reception is calculated at the point of the patient order generation.The points denote point in the preparation process as illustrated in Figure 6.2.

Simulation of preparation process part 1: Continuous distribution

The first part of the preparation process (till the intermediate point) is not influenced by the solution. Therefore, this part of the preparation process is modelled by a duration, sampled from a distribution. The duration of this part is a summation of the following elements:

- The processes depicted in Figure C.6.
- The time between the informing of the patient and the Consult and the CT-scan.

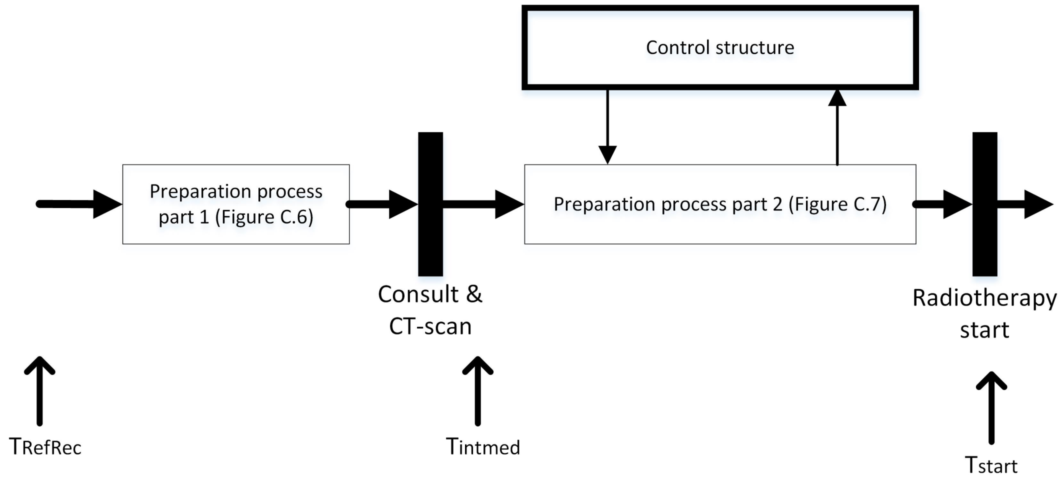


Figure 6.2: Place of the three points in the process

Table 6.1: Parameters chapter 6

Parameter	Unity	Explanation
$IAT_{average}$	s	Average inter arrival time for patient orders
WH	hours	Number of work hours per day
P_{input}		Number of patients arriving per day
W_i	s	Working time of process step i
A		Factor for determining working time
B		Factor for determining working time
L_i		Length of waiting queue of process step i
t_i	s	Process time process step i
n		Number of process steps
E		Number of employees
DF		Decision factor for boundary choice

- The duration of the consult, the CT-scan and the upload of the CT-scan.

The sum of the elements above can vary a lot. The path of the patient order varies for external and internal patients, several patient orders have to wait on information from other hospital and the time between informing and consult will vary a lot. As a consequence of these variations, an continuous distribution is assumed for the duration of the first part.

The intermediate point: Generation of patient orders

The patient orders are generated at the intermediate point. At the intermediate point, the 'arrival' of patient orders can be assumed independent. The intermediate point is located after the CT-scan and the corresponding tasks (upload CT and pre-planning). The different patients are scheduled at the CT-scan after each other for the whole day. Due to the variation in the duration of the upload of the CT and the preplanning the order of patients at the intermediate point can be changed. Therefore, the patient orders at the intermediate point can be assumed independent. Independent arrival can be modelled by an exponential distribution. The mean inter arrival time can be calculated by Equation 6.1. The different parameters are explained in Table 6.1.

$$IAT_{average} = \frac{WH * 3600}{P_{input}} \tag{6.1}$$

Due to choice for the generation of patient orders at the intermediate point, the first part of the process is modelled 'back in time'. The patient order is generated at current time of the simulation (Tnow). The time of the referral reception is calculated by the subtraction of a sample from the continuous distribution of preparation process part one from the value Tnow. The time of referral reception is smaller than the time of the order generation.

The patient order generator is responsible for the generation of patient orders. The generator is active during the working hours of the department. The time between the generation is calculated as a sample from an exponential distribution. The working hours of the department are from 8:00 AM til 5:30 PM from Monday till Friday. The active hours are determined by the time-process. Apart from keeping the time, the time process will calculate the required results and present those results in the output screen.

The duration of a task is already assigned during the patient order generation process. This is due to the fact that the duration is mainly dependent of the diagnosis of the patient connected to the patient order. The duration of a task represents the time, an employee is active in handling of the task for a patient order. The probability of occurrence of a task from a certain duration can be assumed equal over the full possible variation in duration. Therefore, a continuous distribution is chosen as type of distribution for the task variation.

Each of the patient orders have a fixed number of tasks. Each of the tasks have to be executed by a specific section. The average process time differs per section. Therefore, for the different tasks (for each of the sections one), a specific upper and lower boundary is assigned to the continuous distribution. As a result, each of the patient orders contains a fixed number of tasks having a duration derived from a continuous distribution of the corresponding section.

Preparation process part two: Series of discrete events

When the patient order is generated and the different tasks are assigned to that patient order, the patient order is placed in the waiting queue of the section of the first task. For each of the sections, a certain (fixed) number of employees is active in handling of the tasks. The variable in the employee capacity is the amount of working time used for primary process tasks. The primary process tasks are the tasks assigned to the patient order. The primary process tasks are only a part of their activities. Therefore it is assumed that the number of employees is constant and the working time can vary.

In a section, one or more employees can be active. This is dependent from the requested capacity. The section can determine the working time possible for primary process tasks. This can not be higher than the total working hours per day (as determined in the time-process). It is dependent of the number of patient orders present in the waiting queue. Whenever the waiting queue is longer than the average waiting queue, the amount of working time is more than average. For a short waiting queue, the situation is reversed. This is represented in Equation 6.2.

$$W_i = \begin{cases} B_{max} * W_{i,mean}, & \text{if } L_i \geq A_{max} * L_{i,mean} \\ B_{min} * W_{i,mean}, & \text{if } L_i < A_{min} * L_{i,mean} \\ W_{i,mean}, & \text{otherwise} \end{cases} \quad (6.2)$$

Whenever a task is finished, the patient order is placed in the waiting queue of the section belonging to the next task in the tasklist of the patient order. It the current situation, the the due time is dependent of the time of the making of the ARIA-path. Therefore, the patient orders are placed in the next waiting queue sorted on the time of the intermediate point: The startpoint of the discrete simulation

When the last task is finished, a specific 'Finish-procedure' will be used to finish the patient order. In that finish procedure, the start time of the patient is determined. This is determined according to the following algorithm:

- The patient starts two days later if the scheduling can take place before 12 o'clock
- The patient starts three days later if the scheduling is after 12 o'clock.

This determines the radiotherapy start of the patient. This can be represented as a schedule presenting for each day the number of starting patients. Within the remaining two or three days some tasks are executed too. These steps are not modelled. It is assumed that these steps will be finished in the remaining time.

6.2.3. Solution implementation

The implementation of the three different solutions will be discussed below.

Patient order control

The main solution is the adding of the patient order control as a part of the matrix organization theory. The process described in this research is finished when the patient can start their radiotherapy. As part of the solution, the start date is determined earlier. On the basis of the preliminary start date, a process path is determined. The processes in the process path are based on the preliminary start date.

The preliminary start date is determined by the logistic component of the patient order control structure. This is represented by a function 'SelectStartDate' in the simulation model. For the selection of a start date, an upper and a lower boundary have to be used. The upper boundary is a maximum time of the total process time, representing the external requirements (see Table 5.2). The lower boundary is a minimum value that is given to the model representing the required process time for the different tasks.

The preliminary start date is chosen between the two boundaries according to the following algorithm.

1. The patient will start at a day where the number of starters is less than the average number of starters. This algorithm is executed from lower boundary to upper boundary.
2. The patient will start at the date with the lowest number of starters. In the case of equal number of starters, the earliest date is chosen.

In the case the upper boundary calculation results in a value lower than the lower boundary, the upper boundary is set equal to the lower boundary. The placement in weekends is not possible. If this is the only possibility, the patient will start on Monday.

Whenever the start date is determined, the different process steps (modelled as tasks) can be executed. In the current situation start date need to be determined afterwards. This is not necessary anymore in the case of the patient order control. However, it has to be checked whether the different process steps are executed before the determined start date. If that is not the case, the start date has to changed into a later date. This represents the part of the patient order control handling the escalations.

As discussed in Chapter 5, the preliminary start date will result in a process path for the different process steps. This process path will contain for each of the process steps a due time based on the preliminary start date. This simulation model does not take into account the individual due times of the single tasks. A benefit of a process path based on the preliminary start date is the constant requested capacity for the different process steps (in case of a constant number of radiotherapy starts per day). These benefits will not be available in this simulation model due to the absence of due times of the individual process steps. However, the patient order control will control the process on the basis of the preliminary start date. This is the same in the simplified simulation model and the proposed solution in Chapter 5. The effect on the total process time and the time of the radiotherapy start of the patients will not be different.

The only difference in the output can be the number of patient orders that can not be finished before the preliminary start date due to (eventual) different functional control actions in the process. The value of the number of not possible starts is only used for the initiating of the input values. A different output of the number of not possible starts will not result in different conclusions.

In Figure 6.1, the situation is visualized for the situation with patient order control. This overview shows the comparison with the situation without patient order control.

Previous waiting queue control

Apart from the adding of the patient order control it is important to examine the effect of another sub solution: The incorporating of the previous waiting queue control in the functional control domain. For the examination of the effect of the previous waiting queue control the functional control behaviour has to be changed. This is done by the adaptation of Equation 6.2 into Equation 6.3.

$$W_i = \begin{cases} B_{max} * W_{i,mean}, & \text{if } L_i \geq L_{i,mean} \text{ and } L_{i-1} \geq A_{max} * L_{i-1,mean} \\ B_{min} * W_{i,mean}, & \text{if } L_i < L_{i,mean} \text{ and } L_{i-1} < A_{min} * L_{i-1,mean} \\ B_{max} * W_{i,mean}, & \text{if } L_i \geq A_{max} * L_{i,mean} \\ B_{min} * W_{i,mean}, & \text{if } L_i < A_{min} * L_{i,mean} \\ W_{i,mean}, & \text{otherwise} \end{cases} \tag{6.3}$$

Defunctionalization

In the defunctionalization, some tasks will be combined to one task. In the simulation it is examined as a variation in the number of tasks. The average total time for all the tasks is kept constant. Therefore, the duration per tasks is scaled according to Equation 6.4. In that equation n is equal to the number of process steps, t_i is equal to the process time and $t_{i,sample}$ is equal to the process time calculated from the distribution for the duration.

$$t_i = \frac{n_{average}}{n} * t_{i,sample} \tag{6.4}$$

The capacity of the different sections is scaled too, as denoted in equation 6.5. The capacity is the product of the number of employees (E) and the amount of working time (W).

$$E_i * W_i = \frac{n_{average}}{n} * E_{i,standard} * W_{i,standard} \tag{6.5}$$

6.2.4. PDL

The model description need to be translated to the Lazarus environment. Therefore, the description is translated into a basis outline for the code. This basis outline is called the Process Description Language (PDL). The PDL shows the most important building stones for the code in Lazarus.

Table 6.2: Elements and attributes for the current situation

Element class	Attributes
TPatientOrder	TaskList: TomasQueue TRefRec, TIntMed, TStart: Real
TTask	Duration: Real Section: Tsection
TPatientOrdergenerator	Process: Method MyPatientOrder: TPatientOrder Newtask: TTask FirstSection: TSection IATDist: TExponentialdistribution DurationPartOneDist: TUniformdistribution
TEmployee	Process: Method Finish: TProcedure MyPatientOrder: TPatientOrder MyTask, NextTask: TTask Mysection, NextSection: TSection
TSection	Process: Method NumberOfWorkingHours: Integer WaitingQ: TomasQueue DurationDist: TUniformdistribution
TTime	Process: Method
Global Sets	SectionsQ Startschedule

PatientOrderGenerator.Process
```
Repeat
   NewPatientOrder = TPatientOrder.create
   NewPatientOrder.TIntMed = Tnow
   MyPatientOrder.TRefRec = Tnow - DurationPartOneDist.Sample
   NewPatientOrder.Tasklist = TomasQueue.Create
   for i = 1 .. NumberOfSections
      NewTask = TTask.Create
      NewTask.Duration = Newtask.Section.DurationDist.Sample
      NewTask.Section = SectionsQ.Element(i-1)
      NewPatientOrder.Tasklist.AddToTail(Newtask)
   FirstSection = NewPatientOrder.Tasklist.FirstElement.Section
   FirstSection.WaitingQ.Addtotail(MyPatientOrder)
   If ProcessCoordination = False
      FirstSection.WaitingQ.Addtotail(MyPatientOrder)
   If ProcessCoordination = True
      SelectStartDate
      FirstSection.WaitingQ.AddSortedOn(MyPatientOrder, MyPatientOrder.Tstart)
   Hold(IATDist.Sample)
```

TPatientGenerator.SelectStartDate
```
SelectionPoint = f(StartSchedule)
MyPatientOrder.TStart = Selectionpoint
```

TSection.Process
```
Repeat
   If PreviousWaitingQueueControl = False
      NumberOfWorkingHours = f(WaitingQ.Length)
   If PreviousWaitingQueueControl = True
```

```
    NumberOfWorkingHours = f(WaitingQ.Length, PreviousWaitingQ.Length)
  Hold(24*3600)
```

TEmployee.Process

```
Repeat
  if (Workedtime >= Mysection.Workinghours)
    While workhours = True Do Standby
  While (workhours = false) Or (Mysection.WaitingQ.Length = 0) Do Standby
  MyPatientOrder = MySection.WaitingQ.FirstElement
  MyPatientOrder.LeaveQueue(Processtep.WaitingQ)
  MyTask = MyPatientOrder.Tasklist.FirstElement
  MyTask.LeaveQueue(MypatientOrder.Tasklist)
  Hold(MyTask.Duration)
  MyTask.Destroy
  If MyPatientOrder.Tasklist.Length > 0
    NextSection = MyPatientOrder.Tasklist.Firstelement.Section
    If ProcessCoordination = False
      NextSection.WaitingQ.AddSortedOn(MyPatientOrder, MyPatientOrder.TIntmed)
    If ProcessCoordination = True
      FirstSection.WaitingQ.AddSortedOn(MyPatientOrder, MyPatientOrder.Tstart)
  If MyPatientOrder.Tasklist.Length = 0
    If ProcessCoordination = False
      Finish
    MyPatientOrder.Destroy
```

TEmployee.Finish

```
If hour < 12
  Mypatientorder.Tstart = Tnow + 2*24*3600
If hour >= 12
  Mypatientorder.Tstart = Tnow + 3*24*3600
```

Time.Process

```
Repeat
  Week := f(Tnow)
  Day := f(Tnow)
  Hour := f(Tnow)
  If Day <= 5
    Hold(8*3600)
    Workhours = True
    Hold(9,5*3600)
    Workhours = False
    Hold(6,5*3600)
  If day > 5
    Hold(24*3600)
```

Initialization

```
PatientOrderGenerator = PatientOrderGenerator.Create
PatientOrderGenerator.IATDist = Texponentialdistribution.Create
PatientOrderGenerator.DurationPartOneDist = TUniformDistribution.Create
PatientOrderGenerator.Start
Time = Time.Create
Time.Start par for i = 1 to NumberOfSections
  Section = TSection.Create
  Section.WaitingQ = TomasQueue.Create
  Section.DurationDist - TUniformDistribution.Create
  for j = 1..NumberOfEmployees
```

```
{Name, Number of employees, min. process time, max process time, Qmean, Meanworkhours}

'P1'    6    60   300    18   6
'P2'    3    30   90     6    4
'P3'    8    40   120   12   2
'P4'    1    5    15     6    2
'P5'    4    40   120    12   4
```

Figure 6.3: Input file

```
    Employee = TEmployee.Create
    Employee.MySection = Section
    Employee.Start
Section.Start
```

6.2.5. Input

For the model, relevant input values need to be chosen. For these input values the necessary assumptions are required. This will be discussed in this Section.
The most important input is the number of patients. Around 12 patient orders arrive each working day in the radiotherapy department. This will be the input of the model too. According to Equation 6.1 and assuming 9.5 working hours on a day, the mean inter-arrival time is 2850 seconds.

For the continuous distribution representing the first part of the preparation process, a lower boundary and an upper boundary need to be selected.

In the fastest case, the reception referral, triage, scheduling and informing can be executed on the same day. The patient can visit the department two days later in this case. On the same day, the next preparation tasks can be executed. This gives a lower boundary of three days.

For the upper boundary, the maximum values for the standards need to be determined. The maximum standards are determined in Appendix D. Reception referral, triage, scheduling and informing can take six work days. For the time between the informing and the arriving of the patient a value of four work days are assumed. For the determining of the treatment and the process path, a value of three days is assumed. This leads to an upper boundary of thirteen days.

The capacity of the different sections is dependent of the number of tasks that have to be executed and the average time required for a task. As determined earlier, the duration of a task is calculated by a sample from a continuous distribution. For five different process steps, an upper and a lower boundary are chosen for the duration. This is visible in Figure 6.3 This reflects the variety in process times of the department visible in Appendix D. The required capacity can be calculated by Equation 6.6.

$$N_{Patients} * t_{i,average} = E_i * W_i \tag{6.6}$$

For the different process steps, the approach is different. For example, the doctors will do the tasks, connected to the first part of the process, only for a few hours per day. In contrary to that, the treatment planning executes its task for almost a full day. Therefore, for the five different process steps, a different input is chosen for both the number of employees and the average number of working hours. This will necessary hold Equation 6.6.

The average number of working hours is the input for the control actions of equation 6.2 and 6.3. In the description of this control behaviour the parameters A and B are given as input. Currently, the control is not executed in that way. Therefore, it is assumed that the change in the waiting queue length leads to an equal change in the capacity. The values for A and B or both determined at 0,75 for the minimum case and 1,25 for the maximum case.

Another required parameter is the average length of the waiting queue. The average standards for the time of presence in the waiting queue is given in Appendix D. The values of the average length of the waiting queue can be calculated by Equation 5.2. The average time of presence in the waiting queue is respectively, 0,5 day, 1 day or 2 days for the department. This time represents the combination of waiting and processing. With the value of 12 patients arriving per day and an expected task execution time of 0 - 0,5 days, the average length of the waiting queue is respectively 6, 12 and 18. This is presented in Figure 6.3.

Most of the parameters above are considered as constant. These parameters describe the situation of the department in the model. The proposed solution will not influence these parameters. In the case of the values of Figure 6.3, for each of the process steps, different values are chosen. This represents the variety in the department. It will test the stability of the model too; the results need to show stable behaviour or not.

Apart from the constant values for the input, some input values have to be varied throughout the model to test the effect of the solutions. These inputs will be visible on the output screen of the model as represented in Figure 6.4. The inputs will be described below:

- **The number of process steps** can be varied for the testing of the effect of the defunctionalization. The model can be simulated for five or ten process steps. The capacity of the process steps and the task duration are scaled with the number of process steps.
- **The patient order control and the previous waiting queue control** can be selected. When this is selected the alghorithm is chosen that belongs to that type of control algorithm.
- **The minimum process time of a patient** can be chosen in case of the patient order control option. This is the minimal time required till the radiotherapy start. It represents the time required for the different process steps.
- **The maximum total process time** can be chosen too in case of the presence of patient order control. This value determines the upper boundary for the preliminary start date. This is a representation of the maximum duration of the preparation process determined by external requirements.

6.2.6. Output

Apart from the input of the model it is important to select the output of the model. The output needs to represent the flow of the model. The output consists of multiple elements. The main part of the output screen shows two different graphs. The first graph shows the development of the patient order in three different measure points: The point of the referral reception, the intermediate point where the actual simulation starts and the point where the treatment of the patients can start. This graph can give insight in the progress of the patient order at the three points. The behaviour of both the referral reception point and the intermediate point are given as input in the model by the different distributions. The graph of the last point in time can show if the process is able to smooth out the process. The graph is mainly determined for the giving of the insight in the process.

The second graph shows the development of the waiting queues for the different process steps. This graph can show the effect of the functional control of the waiting queues. Is the control able to smooth out the waiting queues of the different sections. All lines in the graph must show stable behaviour. All sections need to solve the peaks in the waiting queues. This graph gives insight in the flow of the patient orders at each of the sections.

In the right column of the output screen, the necessary output values are given. During the simulation, the week-box and the day-box show the point in time of the simulation. The schedule box below shows the number of starters for the five different working days. Three weeks back in time and two

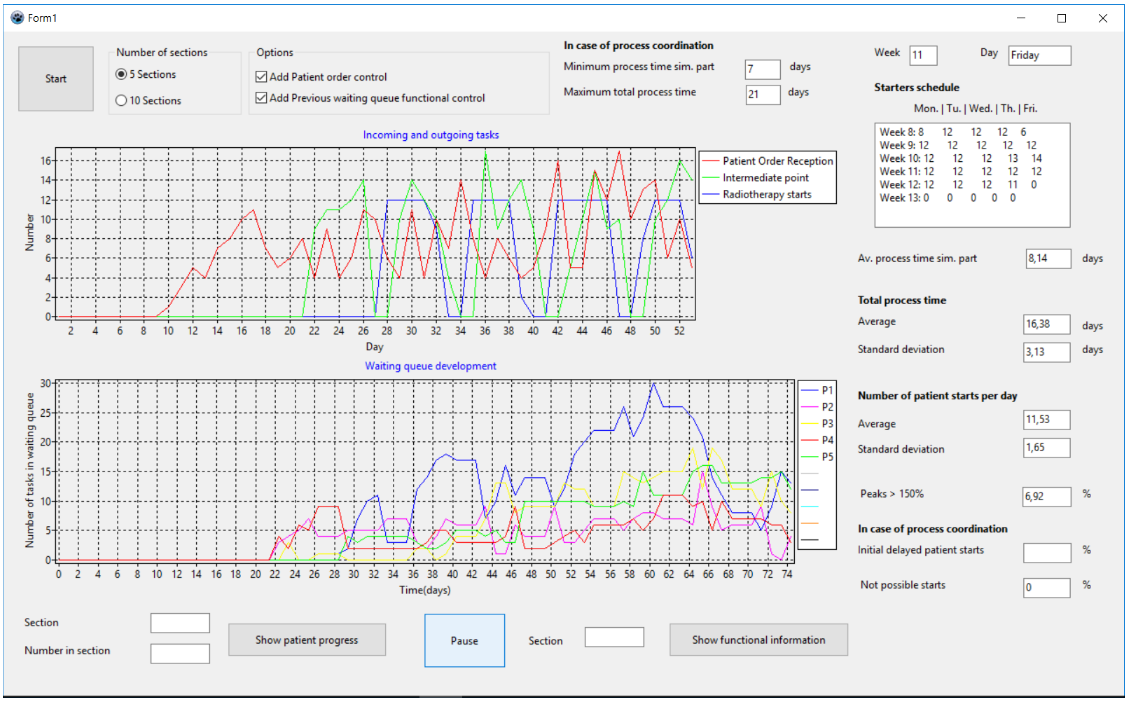


Figure 6.4: Lazarus output

weeks forward in time are made visible.

As discussed earlier and visible in Figure 5.2, the preparation process is divided in two sections. The second part is the part where a patient order control structure is designed. The first part is of the patient order path is simulated by a continuous distribution varying from three till thirteen days. In this part no changes are proposed. The variation in duration of the first part influences the second part. This explains the use of the process time output values. The average process time for the second part and the total process time are given.

The process time in the situation with patient order control and the situation without patient order control is different. In the situation without patient order control, the radiotherapy start is determined at two or three days after the last simulation process step. However, in this period some other tasks are executed. In the situation with patient order control, the radiotherapy start is determined in an earlier phase. Between the finishing of the last simulated step and the radiotherapy start, no tasks are executed.

In fact, the situation without patient order control executes more tasks during the process time measured in the simulation model. In the process path defined in ARIA, the last task is finished 0,5 day before the start of the radiotherapy. In the period between determination of the start and the start of the radiotherapy tasks for the duration of 1,5 days are scheduled (taking into account the minimum duration between determination of the start the start itself). For the comparison, 1,5 days are subtracted from the process time simulation results in the case without patient order control.

Apart from the process time itself, the standard deviation of the total process time is given. This value denotes the possibility to smooth the process due to the high variation in the first part of the process path.

The number of patient starts per day is visualized in the starters schedule. The average number of starters per day is calculated in the the 'average number of starts per day' box. This value needs to be equal to the value of incoming patients per day (12). The standard deviation shows the variation in the number of starts per day. This value has to be as low as possible. A low value shows the fact that the control can smooth out the process.

Especially for the testing of the previous waiting queue control, the percentage of the peaks that will exceed the 150 % of the average is measured. Each day, at midnight, the value of each of the waiting queues is measured. The percentage of the measures that exceeds the 150% of the average value (given in the input via the input file of Figure 6.3)

For adding of the patient order control, two different extra output values are required:

- **The initial delayed patient starts**. This value (as percentage of the total number of handled patients) is the number of patients that have to be scheduled later than the maximum total process time due to the fact that the maximum total process time is smaller than the minimum required time. To prevent the initial delayed patient starts, the value of the maximum total process time has to be set high enough. This value is set at a maximum of 5%.

- **The not possible starts.** This value measures the percentage of patients where the process cannot be finished before the predetermined radiotherapy start time. Increasing the minimum process time will reduce this percentage. This value is set at a maximum of 2%. This value is even smaller than the value for the initial delayed starts. A 'not possible start' is both the change of the process and a delay of the allready determined start.

6.2.7. Verification

Verification is required to show the correctness of the model. The behaviour of the simulation is modelled in the PDL. The PDL is translated to the Lazarus code with the required elaboration on the input and the output. For the verification it is required to show if the model is executed in the way it is programmed. Therefore, the first steps of the discrete simulation are followed in Appendix E. The program contains a 'trace' option. This option gives a description of the several steps executed. The verification in the appendix shows that the model is executed in the way it is programmed.

.

On average 12 patients are entering the system each day. The number of patients leaving the system has to be equal to the number of patients entering the system. The number of leaving patients is represented by the output value 'number of patient starts'. The results are varying between 11.9 and 12.1.

The next parameter result verification is for the process time. The total process time consists of the process time of the first part and the process time of the second part. The process time of the first part is determined by a uniform distribution with a minimum value of 3 days and a maximum value of 13 days. The average is equal to 8 days. The subtraction of the second part of the process time from the total process time results in values varying between 7.9 and 8.1 days. This can be assumed as verified too.

In Figure 6.3, the capacity is determined by the number of employees and the average number of working hours. The average number of working hours is an input for the control of the actual number of working hours. After a simulation run, the average process times are calculated. The process times pop-up in a message shown in Figure 6.5. The results are similar to the input given in Figure 6.3.

No actions are executed but the time is running during the weekends. Therefore, the schedule is verified for the Saturday and Sunday. A slight transformation of the output shows the result of the starting patients for all seven days of a week. This is visible in Figure 6.6. The two right columns represent the Saturday and the Sunday. For all weekend-days the required zero-result is achieved.

6.2.8. Simulation run determination

The model is described, the input and output parameters are determined and the model is verified. For the comparison it is required to execute some experiments. For the execution of these experiments it is necessary to determine the length of the simulation run and the number of runs per experiment.

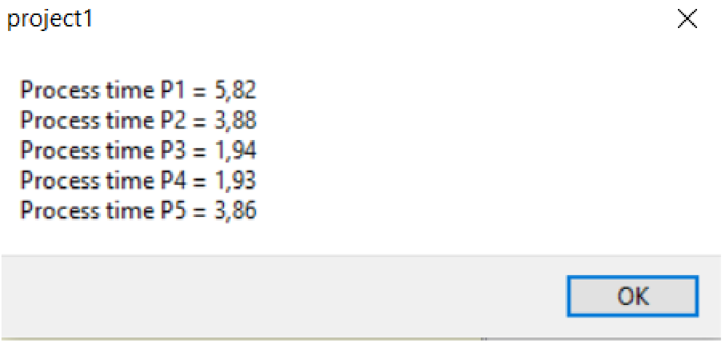


Figure 6.5: Process time results

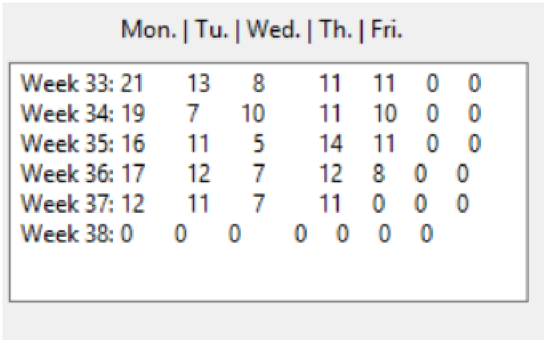


Figure 6.6: Weekend behaviour

The simulation program has some start-up behaviour. The actual simulation starts at Monday of week 4. For correct results, the measurements need to start when the start-up behaviour is not present anymore. Each of the waiting queues of the different section is empty in the beginning. This will result in the immediate execution of the first tasks.

After seven weeks (four weeks after the generation of the first patient order), the start-up behaviour can be assumed to be passed. This is made visible in Figure 6.7. The waiting queue of each of the sections has been at least once higher than the average value at that time. Apart from that, the number of radiotherapy starts shows steady-state behaviour at this point (the blue line in the upper graph). The measurements will start after the mentioned seven weeks.

The run time is selected at one year and 7 weeks. This is equal to one year of measurements and more than 3000 patients that have entered the system. For the selection of the number of simulation runs per measurement, the simulation is executed eight times with constant input values. The values are assumed to be part of a normal distribution. The standard deviation is calculated in Table 6.3. The standard deviation (σ) is calculated by Equation 6.7 for n values of x with average μ. [27].

$$\sigma = \sqrt{\frac{\sum (x-\mu)^2}{n-1}} \tag{6.7}$$

The relative high standard deviations will lead to the choice for more than one run for a selected scenario. When calculating the standard deviation of the average of five simulation run results, the standard deviation is reduced. This visible in Table 6.3. This standard deviation is accepted. The values can be used in the comparing of the results.

The values are measured after one year. It is important to check whether the behaviour of the different output values and the number of patient starts per year (representing the main input) will reach stable behaviour. Therefore, the results are measured for 1,2,3,5 and 10 years and normalized by the value reached after 10 years. The results in Figure 6.8 show stable behaviour.

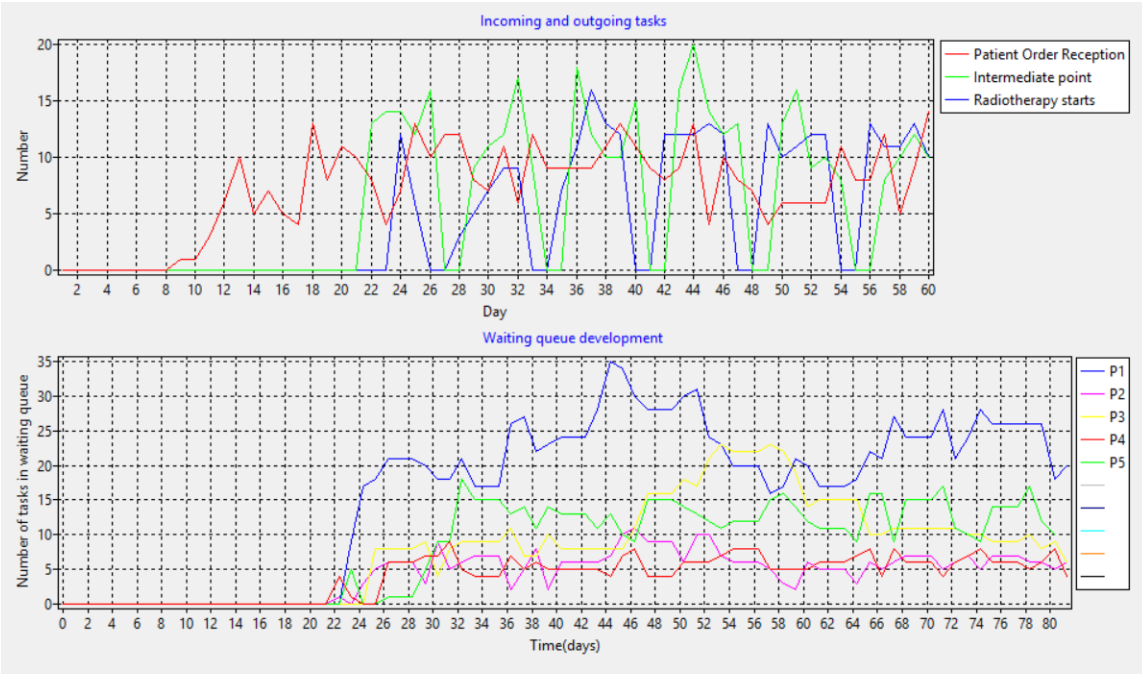


Figure 6.7: Start-up behaviour

Table 6.3: Standard deviation for the output variables (Input values: five sections, patient order control and previous waiting queue selected, minimum process time: 7 days, maximum total process time: 19 days)

	Av. process time second part (days)	**St. dev. process time (days)**	**St. dev. nr. of starters**	**peaks > 50%**	**% initial delayed patients**	**% not possible starts**
Average	7,59	2,86	2,27	6,90	5,49	2,28
Standard deviation 1 simulation run	0,08	0,02	0,13	1,89	0,29	0,61
Standard deviation average of 5 simulation runs	0,02	0,01	0,04	0,56	0,11	0,23

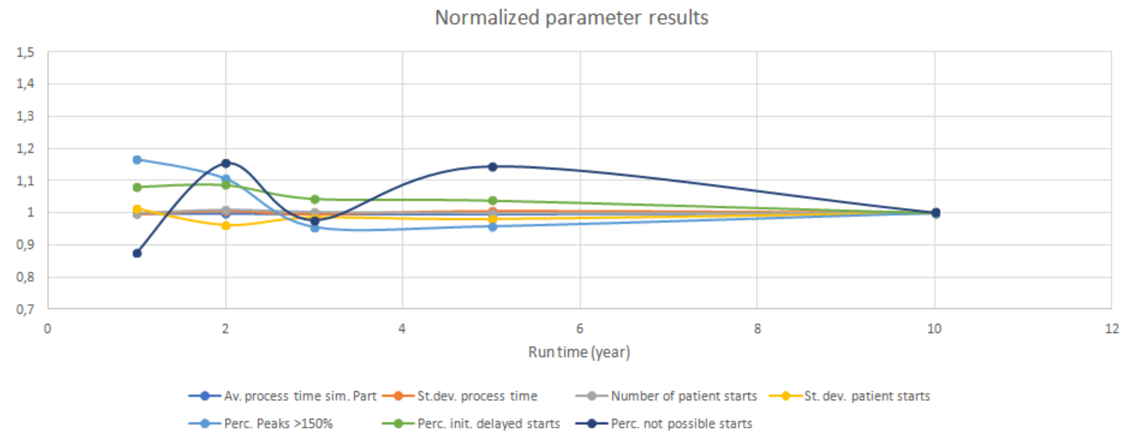


Figure 6.8: Stability check

The standard deviation of the percentage of peaks is relative high. However, the availability of peaks is an important value for eventual conclusions about the flow through the different process steps. A run time of one year will result in much variation in the output results. Therefore, a run time of 10 years is used for the specific situation of the effect of the previous waiting queue control on the availability of peaks in the process. This will make it possible to draw statistical significant conclusions. It is important to discuss first this statistical method.

Statistical significance

The simulation model has to test the effect of different proposed solutions. The effect can show an improvement of the value for a certain parameter. It is important to consider if it is possible to conclude if the solution is an improvement for the specific parameter. The statistical significance is calculated to confirm (or reject) the statement of improvement.

The simulation is executed five times. This results in an average value and the standard deviation of the different measured parameters. The standard error of a difference of a parameter for situation A and B is calculated by Equation 6.8. [28]

$$\sigma_{dif} = \sqrt{(\sigma_A^2 + \sigma_B^2)} \tag{6.8}$$

The average difference can be calculated by Equation 6.9.

$$\mu_{dif} = (\mu_A - \mu_B) \tag{6.9}$$

μ_{dif} and σ_{dif} are the basis for the confidence interval for the difference. A 95% confidence interval can be used for the determining of the statistical significance of the difference. In that case 95% of the cases will be in the confidence interval. 2,5% of the cases is larger than the interval and 2,5% of the cases is smaller than the interval. If the confidence interval does not contain the zero, the difference can be assumed statistical significant. A 95% confidence interval is defined by Equation 6.10. [28]

$$\text{Confidence interval:} \mu \pm 2\sigma \tag{6.10}$$

6.3. Transparency

The simulation model is a representation of reality. The model can give insight in the behaviour. For each of the three different aspects (transparency, coordination and flow), the behaviour is compared. Transparency and Coordination are prerequisites for the execution. In the end, the solution need to contribute to an improvement of the flow. The first aspect of examination is the transparency.

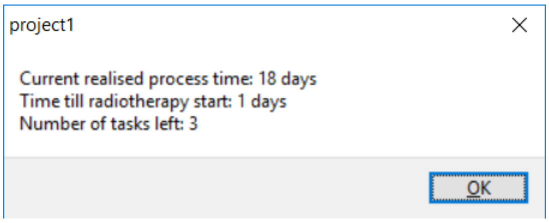


Figure 6.9: Patient progress visualisation

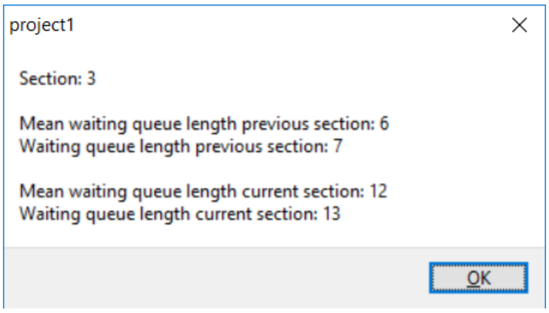


Figure 6.10: Functional control information

If the solution is more transparent than the current situation, the simulation model must be able to give more insight in the necessary parameters. The extra elements contributing to the transparency will be shown in the simulation model environment. The simulation model contains several options to show the relevant information. (See Figure 6.4)

The patient order control gives the possibility to track the patient order flow during the execution of the process steps. For the patient order control structure the progress of the patient order is important. The model has the ability to show this progress. To know the progress of the patient order, the information about the time the patient is already present in the department, the time till the predetermined start date and the current number of tasks left for the patient order are important.

The simulation model can show the information for all patients present in the department. The result is visible in Figure 6.9. The visualized result is a typical example of a situation where intervention is required. Three tasks cannot be executed in one day. In the simulation model, no control actions are executed during the execution of the process as discussed earlier. The intervention is simulated by the replacement of the radiotherapy start to a later time when the different process steps are finished.

Observing the progress of the patient is an important element of the patient order control. Apart from the patient order control, the other two solutions will contribute to more transparency. Adding the previous waiting queue control is important for the observing of the incoming flow of the patient orders.

The simulation model has the possibility to appeal the relevant screen for one of the sections. This screen is visible in Figure 6.10. The information shown can be used by the functional control domain. In the presented situation, the waiting queues are exceeding the average value. However, no control action is executed. This is only done if the length of the waiting queue is more than 125 % of the average waiting queue length.

6.4. Coordination

The coordination of the the radiotherapy preparation process needs to be improved too. The coordination is the ability to steer the system in the desired direction. Adding the patient order control can change the coordination at several points. First a preliminary start date is determined. After that the several processes are executed on the basis of this preliminary start date.

	Mon.	Tu.	Wed.	Th.	Fri.
Week 13:	21	8	14	6	16
Week 14:	13	13	18	7	7
Week 15:	3	10	20	14	4
Week 16:	11	18	14	4	0
Week 17:	0	0	0	0	0
Week 18:	0	0	0	0	0

(a) Starters schedule without PC

	Mon.	Tu.	Wed.	Th.	Fri.
Week 13:	15	12	13	12	12
Week 14:	12	12	12	12	7
Week 15:	13	12	12	12	12
Week 16:	14	13	12	12	12
Week 17:	12	8	0	0	0
Week 18:	0	0	0	0	0

(b) Starters schedule with PC

Figure 6.11: Difference in starters schedule due to patient order control

	Mon.	Tu.	Wed.	Th.	Fri.
Week 6:	16	15	13	12	10
Week 7:	13	12	12	11	11
Week 8:	11	11	17	14	18
Week 9:	15	16	15	15	7
Week 10:	15	13	9	0	0
Week 11:	0	0	0	0	0

Figure 6.12: Output schedule with low minimum boundary (5 days)

The results of the patient order control are visible in the schedule of the radiotherapy starters. The current situation is described by the situation in Figure 6.11(a). The situation with patient order control is visible in Figure 6.11(b). The situation shows the effect of the coordinating of the radiotherapy start date of the patients. The equal number of starters is realized with the use of the patient order control.

An equal number of starters for each of the days is beneficial due to two reasons:

- It can lead to a homogeneous schedule for the linear accelerators. It is assumed that if the number of first radiotherapy appointments is equal for each day, the number of repetitive appointments is equal too.
- It can equalize the number of patient orders present at each of the process steps due to the fact that the due times of the individual process steps can be determined on the basis of the preliminary start date. The control of the patient order based on the due time of the individual tasks is outside the scope of the simulation model as discussed in section 6.2.3.

The output schedule is determined before the execution of the process steps. However, the start date is changed whenever the task cannot be executed before the preliminary start date. Therefore, the minimum boundary has to be chosen in a way that not more than 2% of the patients have to change the start date. The effect of a boundary that is chosen to low is visible in Figure 6.12. Due to many rescheduling actions, the schedule of Figure 6.11(b) is changed into the schedule of Figure 6.12.

The upper boundary is another parameter that can be used by the coordination. For the upper boundary an optimal value need to be chosen too by the coordination. This coordination is required to let the treatment start as fast as possible. For this boundary, the external requirements are important (Table 5.2).

6.4.1. Experimental plan

For the examination of the optimal condition of the boundaries several experiments need to be executed. The optimal combination of these parameters will show the possibility to steer the system in the right direction. Furthermore, these parameters are required as input values for the examination of the patient order control regarding the flow. The boundary values are bounded to the standards determined in Section 6.2.6. The percentage of initial delayed patients has to be lower than 5 % and the value of the not possible starts need to be lower than 2 %.

The patient order control is meant to improve the flow of the patients throughout the department. The process time of the simulation part, the standard deviation of the total process time and the standard deviation of the starters schedule describe the flow of the department. The optimal combination of the boundaries have to be selected. In order to select the optimal boundaries a 'decision factor (DF)' is defined. This decision factor can be use to decide on the optimal boundary conditions.

The decision factor has to be build from the three factors describing the flow in the department: The total process time, the standard deviation of the process time and the standard deviation of the number of starters. The weight of the three different parameters is assumed respectively 1:2:2. The reason for the difference in weight is due to the limited variation in the result of the last two parameters. This parameter has no physical meaning and is only used for the selection of the parameters. As defined above, DF is calculated by Equation 6.11.

$$DF = \sum_{i \in Sim} t_i + 2 * \sigma(\sum_i t_i) + 2 * \sigma(\frac{N}{t}) \tag{6.11}$$

For the selection of the optimal boundaries, the following measuring scenario's have to be executed.

1. **To obtain the value of the minimum boundary: The variation of the minimum boundary with the maximum boundary equal to the sum of the minimum boundary plus 13 days.**
2. **To obtain the value of the maximum boundary: The variation of the maximum boundary with a constant minimum boundary equal to the optimal value selected in (1)**

In these scenario's, the number of process steps will be kept at 5 and the previous waiting queue control is off.

The first step assumes a similar behaviour for situation with a fixed difference between the boundaries. The minimum process time is reserved for the execution of the different simulated process steps. The maximum process time is reserved for both the execution of the simulated process steps and the time between the referral reception and the start of the simulation. The difference between the maximum and the minimum represents this difference in referral reception time and the simulation start. The maximum difference between the referral reception and the simulation start is 13 days. These experiments will be executed in the results section. However, first another measuring scenario is determined.

Previous waiting queue control

Apart from the examination of the effect of the patient order control, it is required to examine the effect of the functional control. The functional control is made explicit in Chapter 5. The main contribution is the adding of the previous waiting queue control.

The adding of the previous waiting queue control is meant to control the length of the waiting queue. For the examination of the effect of the previous waiting queue control the parameter that measures the peaks exceeding the 150% are important. The situation is compared again for the situation with 5 process steps and without patient order control.

For this coordination examination, the following measuring scenario is defined.

Table 6.4: Results scenario 1

Minimum process time (days)	Maximum process time	Av. process time sim. part	St. dev. process time	St. dev. number of starters	Not possible starts	Decision parameter
6	19	7,52	2,80	3,07	9,37	Not Possible
7	**20**	**7,94**	**2,93**	**1,67**	**1,01**	**17,12 (0,32)**
8	21	9,04	3,00	1,51	0	18,04 (0,29)
9	22	10,13	3,01	2,18	0	20,51 (0,27)

Table 6.5: Results scenario 2

Maximum process time (days)	Av. process time sim. part	St. dev. process time	St. dev. number of starters	Initial delayed starts	Not possible starts	Decision parameter
19	7,61	2,88	2,25	5,67	5,22	Not possible
20	7,88	2,92	1,76	0,00	1,43	17,26 (0,17)
21	**8,41**	**3,02**	**1,28**	**0,00**	**0,25**	**17,01 (0,35)**
22	8,74	3,10	1,18	0,00	0,22	17,29 (0,30)
23	9,32	3,18	1,27	0,00	0,01	18,22 (1,57)

3. **The comparison between the situation with and the situation without previous waiting queue control**

6.4.2. Results

Above three different scenarios are determined for the examination of the coordination possibilities. Each of the three scenario's is examined.

Scenario 1: Effect of variation of minimum boundary

The average results are given in Table 6.4. The parameter is tested for the values of 6,7, 8 and 9. The maximum boundary is set at respectively 19, 20, 21 and 22 as discussed in the experimental plan. The value of 6 is not possible due to the fact that the percentage of not possible starts is exceeding the 2%. For the other values the sum of the three flow parameters is calculated and the standard deviation is given between brackets. These standard deviations are the basis for statistical confidence calculations (Section 6.2.8). It can be concluded that the difference between the results for the decision factor is statistical significant. The conclusion can be that the situation of a minimum process time of 7 days is the optimal choice due to the lowest result for the decision factor.

Scenario 2: Effect of maximum boundary

The results are given in Table 6.5. For the chosen lower boundary of 7, the upper boundary is varied from 19 to 24. The maximum boundary of 19 results in a situation that does not satisfy the requirement of respectively 5% and 2%. It can be observed that the influence of the upper boundary on the flow is limited compared to the influence of the lower boundary variation. Increasing the upper boundary will result in more freedom for the smoothing of the starters schedule (low standard deviation of the starters schedule) but results in an increased process time.

The decision parameter results are given in Table 6.5 too. The standard deviation is given between brackets. By calculation of the standard error for difference it can be concluded that the difference in the decision parameter is not statistical significant. For further modelling, the value of 21 days is chosen as a maximum time.

Table 6.6: Results scenario 3

	Percentage of peaks >150%
Situation without previous waiting queue control	8,6 (0,65)
Situation with previous waiting queue control	6,4 (0,35)

Scenario 3: Peak control

The results of the percentage of peaks that exceeds the 150 % is given for the situation with and the situation without previous waiting queue control. This is visible in Table 6.6. It is visible that the situation with previous waiting queue control can reduce the number of peaks larger than 150% in the process. The difference is statistical significant. The 95% confidence interval $\mu \pm 2\sigma$ for the difference is 2,2 $\pm$ 1,5. Zero is not in the confidence interval for the difference and that is the reason to conclude the statistical significant difference.

6.4.3. Conclusions

Especially the patient order control is able to steer the process in the desired direction. The situation can be optimized to a situation where a similar number of patients will start every day. The changing of the boundary values for the preliminary start date can influence the behaviour. The minimum process time is a parameter that will have most effect on the output. Regarding the functional control, it can be stated that the functional control is able to reduce the peaks for the waiting queue lengths of the different process steps.

6.5. Flow

The goal of the improvements is to improve the flow of the radiotherapy preparation process. Therefore, it is important to analyse the effect of the different solutions regarding the flow. For the effect of the flow, several experiments have to be executed. These experiments are described in the experimental plan.

6.5.1. Experimental plan

For the effect of the flow, the different solutions are examined. The adapted control structure and the defunctionalization are tested in the simulation environment.

Patient order control

The main solution is the adding of the patient order control to the system. In the patient order control structure, a preliminary start date is determined. The different process steps are executed on the basis of that start date. In the examination of the effect of the coordination the optimal values for the boundaries are determined. The minimum process time is determined 7 days and the maximum total process time is 21 days. For the situation with and the situation without previous waiting queue control, the effect of the patient order control is examined.

4. **The comparison between the situation with and the situation without patient order control.**

The situation is compared for both the situation with and the situation without previous waiting queue control.

Previous waiting queue control

Previous waiting queue control is meant to improve the flow of the patient orders throughout the different functional sections. The difference in the coordination of the peaks in the process is already examined. Apart from that it is important to measure the effect on the overall flow of the patients: The process time of the simulation part and the standard deviation of the total process time and the

```
'P1'    3    60   300   17   6
'P2'    2    30   90    6    3
'P3'    4    50   120   12   2
'P4'    1    5    15    6    1
'P5'    2    40   120   12   4

'P6'    3    60   300   17   6
'P7'    2    30   90    6    3
'P8'    4    50   120   12   2
'P9'    1    5    15    6    1
'P10'    2    40   120   12   4
```

Figure 6.13: Input file for 10 process steps case

number of starters. Can previous waiting queue control result in a reduction of those values too. This result in another measure scenario:

5. **The comparison between the situation with and without previous waiting queue control**

This will be examined for the situation with and without patient order control to examine eventual amplifying or phasing out effects.

Defunctionalization

Defunctionalization is the combining of multiple process steps in one process step. This can be modelled by the reduction of the number of tasks in the model. The merging of different tasks will result in longer process times of the merged tasks. The question that needs to be answered by the model is the effect of the defunctionalization on the total process time of the combination of the different process steps: The sum of the time required for the execution of the tasks and the waiting time in the queues. Can defunctionalization result in the desired reduction of the process time. The total process time is the main measurement for this simulation research.

And next the question that needs to be answered is the following: What is the side-effect to the process time variation? The expectation is that the reduction of process steps will reduce the possibility of the smoothing out of the process. Therefore it is necessary to investigate in the standard deviation of both the number of starters and the process time standard deviation.

For the research of the defunctionalization the model can be extended to 10 process steps. In the situation with ten process steps, the duration of the tasks and the capacity of the sections is halved. This leads to a changed input file (See Figure 6.13).

In the case of the extension to ten process steps, more functions are created. This is the opposite of the desired defunctionalization behaviour. However, this can still show the relation between the number of process steps (and scaling capacity and task duration). The five process steps case is the more defunctionalized situation. It leads to the following scenario:

6. **The comparison between the more defunctionalized case (5 process steps) and the less defunctionalized case (10 process steps)**

6.5.2. Results

The different scenario's discussed in the experimental plan are executed. The results are given below. The three different control parameters as described in Section 6.1 are compared for the three different scenario's.

Results scenario 4: Patient order control

In Table 6.7 the results of the different scenario's are compared regarding the three different flow parameters. This results in the following statements:

Table 6.7: Results scenario 4 and 5

Patient Order Control	Previous waiting queue control	Av. process time sec. part	St. dev. process time	St. dev. number of starters
No	No	8,61 (0,12)	3,21 (0,04)	2,38 (0,12)
No	Yes	8,58 (0,09)	3,15 (0,03)	2,59 (0,09)
Yes	No	8,41 (0,20)	3,02 (0,03)	1,28 (0,19)
Yes	Yes	8,51 (0,11)	3,03 (0,03)	1,19 (0,20)

Table 6.8: Results scenario 6

Number of process steps	Av. process time sec. part	St. dev. process time	St. dev. number of starters
10	14,98 (0,22)	3,35 (0,05)	2,31 (0,11)
5	8,61 (0,12)	3,21 (0,04)	2,38 (0,12)

- The process time with patient order control structure seems to result in lower values. However, the difference is not statistical significant.
- The variation in the total process time can be reduced by the patient order control structure. This difference is statistical significant.
- The variation in the output schedule (the standard deviation of the number of starters) is reduced. This difference is statistical significant.

Results scenario 5: Previous waiting queue control

The results given in Table 6.7 can also be used to draw conclusions regarding the effect of the previous waiting queue control. When comparing the values for the three overall flow parameters it can be concluded that the effect of the previous waiting queue control on the flow of the patient orders is minimal. None of the differences are statistical significant.

Earlier, it is shown that the previous waiting queue control is able to reduce the peaks in the process. In the case of peaks of the section before the current section, the capacity of the section is increased. A logic conclusion should be that the average process time is reduced. However, the opposite control behaviour is incorporated too. When the previous waiting queue is short, the capacity of the section is decreased. The combination of these two control actions will result in similar process times compared to the situation without previous waiting queue control. This is a reason for the limited effect of the patient order control structure on the process time. It is the reason for a similar standard deviation of the starters schedule too. If process times are similar, the patient can start their treatment at the same point. Due to that the standard deviation of the starters is comparable. Previous waiting queue control does not have influence on the order of the execution of the tasks for the different sections. The negligible effect of the previous waiting queue control on the standard deviation of the process time can be explained by that fact.

Results scenario 6: Task number variation

The variation of the number of tasks can result in conclusions regarding the potential effect of defunctionalization. The situation with 5 process steps represents the more defunctionalized situation. The results are visible in Table 6.8. It is visible that the process time is significantly reduced by the defunctionalization. This is due to the fact that the number of buffers is reduced. It is the expected result. The effect of the defunctionalization on the other two flow parameters is not statistical significant.

6.5.3. Conclusion

Above the flow through the preparation process is discussed. It can be concluded that especially the patient order control structure is able to improve the flow. In the first part of the process a high variation in the process times is present. The patient order control structure is able to compensate for this variation in the second part of the preparation process. The patient order control structure can result in a situation with less variation in process times than the current situation. Next to that, the patient order control structure is able to reduce the variation in the number of starters per day, which results in less variation in the number of tasks per day for every process step and a more constant schedule for the linear accelerators.

The adding of the previous waiting queue control does not influence the flow of the patient orders throughout the department. The only contribution is the possibility to reduce the peaks in the process. The decreasing of the number of sections (defunctionalization) will result in a shorter process time. Defunctionalization has no significant effect on the variation of process time and the variation in the output.

6.6. Simulation model conclusions

Solutions are proposed to improve the flow. The effect of these solutions is examined by the use of a simulation model. This can give a basis for the decision if the different solutions will meet the research goal. The three different solutions will be discussed separately on the basis of the definition of the parameter is Section 6.1.

The patient order control structure is the most effective method for improving the flow. A situation with patient order control structure can result in a situation where the variation in the number of starters is reduced and the variation of the process time is reduced. The patient order control structure has no significant effect on the total process time. The control structure is able to steer the flow in this desired situation by the coordination of the preliminary start date based on a given range. The simulation model is able to illustrate the progress of each patient order. This patient order progress is an important control parameter. The conclusion is that the patient order control structure can be considered as an improvement for all three improvement parameters.

The elaboration of the functional control by the previous waiting queue length parameter is another solution that is tested by the simulation model. The previous waiting queue control does not have effect on the overall patient order flow: The process time, The variation in process time and the variation in the number of radiotherapy starts per day are approximately equal. However, the coordination of the waiting queues can result in less high peaks for the waiting queue lengths of the different process steps. This can improve the work flow for the different process steps. By this measure, the insight in the previous waiting queue length is increased. The conclusion is that the solution is coordinated and transparent and the flow through the different sections is improved. The overall flow (where effects can be experienced by the patients) is not improved. The benefits for the internal processes are decisive in the statement that the adding of previous waiting queue control is positive.

The third solution is the combination of process steps by defunctionalization. The simulation model results show positive effects on the process time. The variation in the process is not influenced by the defunctionalization. The simulation model shows no direct effects on the coordination and the transparency. A reduction of functions can result in a simpler coordination and the transparency is improved within the combination of process steps. However, this is not part of the examination in the simulation model. It can be concluded that the main contribution of the defunctionalization is the reducing of the process time.

The conclusion of the simulation model is that especially the patient order control is able to meet the research goal. The adding of the previous waiting queue control and the defunctionalization will further contribute to the meet the research goal.

7

Implementation plan

In Chapter 5, the solution is proposed for the improving of the through-flow of the radiotherapy department. This effect of the solution is examined in Chapter 6. It is concluded that all three aspects contribute to the meeting of the research goal. This chapter will discuss the implementation of the solution. Therefore, several aspects need to be discussed. First the personnel structure is discussed. Next the structural adaptations and the definition of the standards are given. Next to that, a route for the implementation is given.

7.1. Personnel structure

The given solution is only elaborated on the level of the organic structure. The organic structure contains the definition of functions and the grouping of the functions into organs. In this chapter, the personnel structure is determined. The personnel structure is about the coupling of persons to the different functions and the corresponding authority. This is done for the coordinate control, the patient control and the function control. [20]

7.1.1. Coordinate control

The coordinate control coordinates the two sides of the control structure based on the matrix organisation theory: The patient order control and the functional control. In Figure 5.5, the coordinate control structure is given. This control component needs to be placed under the responsibility of some persons. It is important that those people (together) have the authority to influence the different processes. Furthermore it is important that the different aspects of the process are present in the coordinate control organs. Furthermore, enough medical knowledge to judge in decisions is important.

The coordinate control can be located by the heads of the different sections. This is the second layer of the management (See Appendix B. The head of the paramedical section, the head of the medical section and the head of the clinical physicists, together have the authority to influence the full process. Therefore, they can execute the coordinate control of the department.

The coordinate control has to receive an update from the process times of the different functional sections and the total process times from the patient order control. These values can be often extracted from databases. This has to be done in a certain time frame (for example every three months). The proposal is to meet every month for discussing these standards. In this meeting, the actions for improvement can be discussed too. This can be the reordering of the processes or the initiating of new standards.

One of the problems in the radiotherapy is the limited transparency. The coordinate control is able to give more insight in the radiotherapy process. For a good transparency the coordinate control organ can present the flow results to the different heads of the sections in a meeting. During that meeting it is possible to discuss together ways to improve the flow of patient orders. This session can be executed once in three months for example. Next to that a report containing the most important process parameters can be sent to everyone in the department.

7.1.2. Patient order control

The main solution is the adding of patient control to the radiotherapy department. The patient order control consists of function control and process control. The process control is divided in a medical and logistic component. The different control structure schemes are visible in Section 5.2.

Function control

The function control is responsible for the defining of the standards for the process path and the (maximum) duration of the preparation process. Function control is required for each of the diagnosis groups. The function control has to be executed by the doctors due to their medical knowledge. Each of the diagnosis groups contains approximately four doctors. These doctors discuss the most medical issues regarding the treatment of the patients of the specific diagnosis group.

The evaluation of the standards can be done by this group of doctors. During their meetings this can be discussed. The proposal is to discuss the standards once per month. In fact, the standards are the implicit description of the current discussed medical issues.

Medical component

The medical component has to initiate and control the medical situation of the patient belonging to the patient order. This can be executed by the doctor responsible for the patient. In fact, the doctor is (in cooperation with the logistic component) the project manager of the patient and the corresponding patient order.

The initiating of the patient path can replace the 'prescribe treatment' process step. During the prescribe treatment step all relevant (medical) information for the subsequent process steps is determined. In the proposed situation, the information can be given in the form of a prescription of the process path and a range for the corresponding start date of a patient. The range for the start date of a patient is the added value in the proposed situation.

Each diagnosis group can develop standards for the minimum and maximum boundary. As examined in Chapter 6, the minimum boundary is an important value regarding the flow effects. Therefore some iteration is necessary to determine the minimum process time. The minimum process time can be considered as the average time required to execute the different process steps. The value for the maximum boundary has only a limited impact on the flow of the patient orders. However, this value is important to obey the requirements. The values for the maximum boundary can be determined for each diagnosis and are bounded by the values determined in Table 5.2.

The doctors are continuously responsible for the patients. An eventual request for the adaptation of the range for the radiotherapy start date of a patient has to be handled all the time. This is inherent connected to the task of the doctors and not different from the current situation. Whenever a doctor is not available, another doctor from the same diagnosis group can replace him or her.

Logistic component

The logistic component has to be executed by employees having insight in the different schedules of the radiotherapy department. This is the reason to assign this task to the logistic office. Another reason is the fact that the logistic component will execute some of the tasks currently assigned to the logistic office. The logistic office determines the start date and initiates the process path. The initiate step of the logistic component will execute these tasks.

As part of the initiate step, the preliminary start date has to be determined. For the selecting of a start date, a strategy is required. The scheduling strategy used in the simulation model is capable of equalizing the number of starters per day. An equal number of starters can result in a smooth flow for the different processes and an equalized schedule for the linear accelerators. Due to the results of the simulation, the proposed strategy is the following:

1. The patient will start at a day where the number of starters is less than 12 (the average number of starters). The date of placement is the earliest date but not before the date set by the lower boundary.

2. If the number of starters is higher than 12 for all possible days within the system boundary, the patient will start at the date with the lowest number of starters. In the case of equal number of starters, the earliest date is chosen.

Changed scheduling

Whenever the start date is determined the process steps can handle the different patient orders according to the order of the start date. This will automatically imply the ordering of the urgent patients before the non-urgent patients.

The scheduling of the different radiotherapy treatments will be different in the proposed situation. The making of a process path will be decoupled from the scheduling task. Currently all radiotherapy treatments are scheduled in advance. In the proposed situation the appointments of all patients will be scheduled x days ahead. x can have the value of for example three days.

The reserving of slots for most of the starting patients is not necessary anymore. The only exception is for urgent patients. This is in fact a shift from the carved-out strategy to an (adapted) advanced access strategy.

7.1.3. Functional control

The functional control is made explicit in Section 5.2.4. This functional control has to be transferred to the specific situation of the radiotherapy department and the different functional sections. The basis is the proposed structure in Figure 5.6.

The functional control consists of both function control and process control. The function control needs to update the standards for the process time of the 'own' process step. This can be executed by the management of a specific section. Each functional section is managed by one person. This is often the team manager from management layer three. In case, no third management layer is available, the managing of a functional section is executed by the person from the second management layer (Appendix B).

The team manager has to receive a standard for the process times from the coordinate control. The function control has to initiate that value as a basis for the process. In a certain time period (for example every month) the team manager has to receive data from the average process time in the past. This process time is the sum of the actual process time and the waiting time in the queue.

The team manager can execute actions according to the result of the process time of the specific section. One of the actions is the structural deploying of more or less personnel for this specific section. Furthermore, the function control can initiate a more strict value for the work floor for aiming for the best possible patient help.

For controlling the daily behaviour, the process control is present. The process control controls the waiting queue of the process step. In the current situation, the different sections operate separated. For the coping with peaks in the process, the waiting queue length of the previous process step has to be taken into account. This can be done by importing the task list of the previous process step in ARIA. When this waiting queue is longer than on average, the prediction is that more work is coming for the current process step.

Table 7.1: Requirements for time between referral reception and start radiotherapy

Patient group	**Requirement**
Acute patients	100% within 24 hours
Sub acute patients	80% within 7 days 100% within 10 days
Other patients	80% within 21 days 100% within 28 days

Together, the length of the waiting queue of the current process step and the previous process step will determine the input of the 'normal' control. This input is the length of the task lists in ARIA. This values have to be compared to the average values. These average values will be calculated later on. In the control phase a decision can be taken to intervene.
Another measure can be the escalations measure. This is a possibility in the ARIA software. The escalation option is the sending of a message whenever a certain task is passing the due date of a task. This is currently not used due to the fact of the 'acceptance' of the red colour. In the proposed situation the individual patient control and the corresponding predetermined due date will avoid most of the 'red tasks'. Furthermore, the passing of a due date will directly influence this predetermined due date. Therefore, the escalating message is more important in the proposed situation. The escalations can be sent to the team manager of the specific section.

Different control actions are possible in the functional control domain. As visible in Figure 5.6 the possible control actions can be two-wise: Interventions towards the own process and the so called 'functional escalations'. Whenever, the waiting queue of the current or previous process step is too long, the intervention can be to allocate more employee hours to primary process steps. In the case of short queues, this can be the opposite measure.

Whenever a task cannot be finished in the predetermined time, a functional escalation is required. The functional escalation is the request to the patient order control domain for a later start of the patient. The control section has to decide whenever it is required to do a functional escalation or when it can be solved without functional escalation.

7.1.4. Initial standards

The patient order control and the functional control utilise the standards. Especially the standards for the through-flow of patient orders are considered during the research. For the different standards initial values will be determined. These initial values can be updated during the execution of the control.

The most important contribution of this research is the adding of the patient order control. The patient order control uses standards for the maximum process time. These standards are diagnosis-dependent and need to be determined by the specialists. Within a diagnosis group distinction can be made between several cases of disease. The maximum possible value for these standards are given in Table 7.1.

Apart from the standards for the maximum total process time, standards for the maximum process time for each of the individual process times are required. These values are given in Table 7.2. The explanation of the choice for the different standards is given in Table D.

7.2. Implementation route

The solution is given, the solution is examined on its effects on transparency, coordination and flow. Furthermore, the situation is transferred to the situation within the department. However, the solution cannot be implemented as a whole at a certain point in time. The implementation route for the main solution of the patient control is discussed in this section.

[redacted]

The radiotherapy department consists of several specialisms. These specialisms are focusing on specific groups of diagnosis. Examples of diagnosis groups are the head-neck region tumours and lung tumours. For a gradual implementation a suitable disease group has to be chosen. For a feasible implementation it is wise to choose a group having limited variation in process paths. An example of a disease group having limited variation in process paths is the breast cancer group.

Each doctor has several specialisms. The doctors specialized in 'breast cancer' are the first responsible persons for the execution of the medical component of the patient order control. The new tasks of the doctor is to determine the boundaries for the preliminary start date and to act on eventual disturbances. The initial value for the minimum process time can be taken equal to the sum of the maximum standards defined in Table 7.2. The maximum process time can be taken as the maximum requirement of Table 7.1 minus the time the patient order is already present in the department. The different boundaries have to be updated by feedback from the system.

For the specific group of the breast cancer patients, the process paths in ARIA need to be adapted. The task of the logistic office need to be divided in two different sections: The determining of the start date (logistic component) and the actual scheduling of the patients. Furthermore, the due date of the patient path has to made dependent of the determined preliminary start date.

When the situation is evaluated positive after a certain time, the patient control can be elaborated to other specialisms in the department.

8

Conclusions and Recommendations

In Chapter 1 the research is introduced by four different research questions. To conclude the research these questions will be answered below. Next to that, some recommendations will be given for further research.

8.1. Conclusions

What process is required in order to perform radiotherapy and how can that process be modelled?

The process of investigation is the radiotherapy preparation process. The start point of the process is the reception of a referral and the end point of the process is the start of the radiotherapy of a patient. The patient has to visit the radiotherapy department for a consult and for the making of a CT-scan. Before and after these patient appointments several process steps are executed in order to prepare the radiotherapy treatment.

The preparation process is modelled by three different aspect-processes cooperating together: A patient process, an order process and a resources process. Most of the preparation process steps are executed in the domain of the order process. The radiotherapy department has a functional organisation structure to control these processes.

What problems are ascending during the analysis and what is the root cause of these problems?

The patient order flow through the preparation process is restricted. One of the reasons is the presence of waiting queues before each of the process steps. Several patient orders in the waiting queues are executed too late. Another reason is the fact that the view of the executors of the different process steps is often too focused on the own process step. This is one of the reasons for the presence of errors in the information flow between the different process steps. The third reason is the fact that the control of the patient order progress through the different process steps is not available.

The different mentioned reasons can be evaluated as a consequence of a too much functional organized process.

What solution directions can be applied to improve the radiotherapy process?

The main solution direction is the design of a control structure based on the matrix organisation theory. The control structure has two different realisations: A patient order control structure and a functional control structure. The patient order control structure controls the patient order flow based on the date of the radiotherapy start of the patient. This start date is determined in the initiating phase of the control structure. The functional structure is elaborated by the adding of the length of the waiting queue of the previous process step as parameter.

The organisation of the radiotherapy department as a functional organisation structure is a requirement. However, the number of process steps can be reduced to reduce the number of transitions and waiting queues between the different process steps. This is another solution direction for improving the flow of patient orders.

What are effective and implementable improvements for the radiotherapy process?

The patient order control structure is the most effective way to improve the flow in the radiotherapy preparation process. By coordinating the flow, based on the earlier determined start date, the variation in the total process time can be reduced. Furthermore, the control structure can result in a situation where every day a similar number of patients will start their treatment. An equal number of starters per day is a solid basis for a smooth patient order flow.

The adding of the length of the waiting queue of the previous process step as parameter will increase the transparency of the process steps and can result in less peaks in the length of the waiting queues. Next to that, the combining some process steps can reduce the preparation process time.

The different mentioned solutions can be implemented in the preparation process using existing resources. The patient order control structure can be executed in a collaboration between doctors and the logistic office. Furthermore, the existing software can be used in support of the control structure. The combination of the functions is possible in two cases including the combination of the scheduling of the appointment and the informing of the patient about the appointment.

8.2. Recommendations

In this research a patient order control structure is proposed. This patient order control structure initiates a preliminary start date of a patient and makes a patient path for each of the patient orders. The patient path contains due times for the individual tasks of the patient order. The effect of the preliminary start date determination is examined by the simulation model. However, the effect of the adapted process path (scaled to the preliminary start date) is not examined in the simulation model. This has to be examined to know the effect of the scaled due times.

The preparation process is divided into two different sections (See Figure 5.2). The first part of the preparation process is the part before the consult and the making of the CT-scan and the second part of the preparation process is the process afterwards. The patient order control structure is only designed for the second part. It is recommended to develop a patient order control structure for the first part of the preparation process. This requires a different approach but it would be beneficial to be able to influence the full preparation process. Delay in the first part of the process will influence the flow of the patient order in the second part of the process.

During this research, the patient order control is developed for the aspect of the flow of the patient order throughout the process. However, the control structure can control other aspects regarding the quality of the treatment. To enable this, the patient order control structure has to be elaborated by the aspect of the treatment quality.

This research is executed in the radiotherapy department of Amsterdam UMC - location VUmc. The solutions are applied to that specific situation. Especially the design of a patient order control structure is promising for the improving of the flow of patient orders in the preparation process. Therefore, it is recommended to do research on the possibilities to implement the control structure in other hospitals.

The research is executed for the preparation process for radiotherapy. This process is very unique. For other type of preparation processes, a different type of patient order control structure has to be designed. Other preparation processes can be for example the preparation process of an operation.

Other type of preparation processes need an (for that case) specified control structure. Probably, the medical component is less important for other type of preparation process due to the less severe medical situation.

Bibliography

[1] VUmc, *Routeplanner,* http://www.vumcplattegrond.nl/#map (), [Online, 05/01/2018].

[2] VUmc, *Jaarverslag Radiotherapie - 2015/2016*, Tech. Rep. (VUmc, 2017).

[3] H. Kerzner, *Project Management - A Systems Approach to Planning, Scheduling, and Controlling (12th Edition)* (John Wiley Sons, 2017).

[4] CBS, *Nu ook bij vrouwen meeste sterfgevallen door kanker,* https://www.cbs.nl/nl-nl/nieuws/2017/52/nu-ook-bij-vrouwen-meeste-sterfgevallen-door-kanker?_sp=eabc25d6-3088-4a8e-b4fe-048f71ef5b54.1533980307440, [Online, 11/08/2018].

[5] VUmc, *Feiten en cijfers*, Tech. Rep. (VUmc, 2017).

[6] Patient1, *Kanker - een overzicht (medische encyclopedie),* https://www.patient1.nl/encyclopedie/kanker, [Online, 23/12/2017].

[7] NKR, *Cijfers over kanker,* http://www.cijfersoverkanker.nl/, [Online, 25/01/2018].

[8] VUmc, *Home radiotherapie,* https://www.vumc.nl/afdelingen/radiotherapie/ (), [Online, 03/01/2018].

[9] fotografie Digidaan, https://vumc.mediafiler.net/vumc/start/mediabank?listview=overview&fc=browse&queryid=b9f9e64ef55632ff272847dff03e9bfb&order=rank&bsr=9&column=9&fileid=10, [Online beeldbank VUmc, 09/01/2018].

[10] VUmc, *Vernieuwende onderzoeks- en behandelmethoden,* https://www.vumc.nl/afdelingen/thema-kanker/onzewerkwijze/7554021/ (), [Online, 08/01/2017].

[11] M. Murray and D. M. Berwick, *Advanced access: Reducing waiting and delays in primary care,* JAMA **289**, 1035 (2003), /data/journals/jama/4869/jip20008.pdf .

[12] H. P. M. Veeke, J. A. Ottjes, and G. Lodewijks, *The Delft System Approach* (Springer, 2008).

[13] J. Osterholt, *A design of a transportation system for the logistics at location Southat FloraHolland Aalsmeer*, Tech. Rep. (TU Delft and Royal Flora Holland, 2015).

[14] C. Swennenhuis, *Coordinating supply and demand in Haga hospital outpatient planning: Towards a more service-oriented control structure*, Tech. Rep. (TU Delft and Haga Ziekenhuis, 2018).

[15] P. Kalanithi, *When breath becomes air* (Random House, 2016).

[16] P. Bhattacharjee and P. K. Ray, *Patient flow modelling and performance analysis of healthcare delivery processes in hospitals: A review and reflections,* Computers Industrial Engineering **78**, 299 (2014).

[17] NVRO, *Normen wachttijden,* http://www.nvro.nl/images/documenten/kwaliteit/indicatoren/Normen_wachttijden_NVRO_20-11-2000.pdf (2000), [Uit de notulen van de algemene huishoudelijke ledenvergadering Nederlandse Vereniging voor Radiotherapie en Oncologie 24 november 2000 te Utrecht, congrescentrum Jaarbeurs, Online, 24/01/2018].

[18] UMCG, *Informatie over wachttijden radiotherapie,* https://www.umcg.nl/NL/UMCG/Afdelingen/Radiotherapie/patienten/informatie_over_wachttijden/paginas/default.aspx?logout=, [Online, 25/01/2018].

[19] J. L. Kuiper, L. E. Hendriks, A. J. van der Wekken, A. J. de Langen, I. Bahce, E. Thunnissen, D. A. Heideman, Y. Berk, E. J. Buijs, E.-J. M. Speel, F. H. Krouwels, H. J. Smit, H. J. Groen, A.-M. C. Dingemans, and E. F. Smit, *Treatment and survival of patients with egfr-mutated non-small cell lung cancer and leptomeningeal metastasis: A retrospective cohort analysis,* Lung Cancer **89**, 255 (2015).

[20] J. in 't Veld, *Organisatiestructuur en Arbeidsplaats - De organisatie van mensen en middelen; theorie en praktijk* (Stenfert Kroese, 1999).

[21] D. E. Bowen and W. E. Youngdahl, *"lean" service: in defense of a production-line approach,* International journal of service industry management **9**, 207 (1998).

[22] L. R. Burns and D. R. Wholey, *Adoption and abandonment of matrix management programs: Effects of organizational characteristics and interorganizational networks,* The Academy of Management Journal **36**, 106 (1993).

[23] R. B. Fetter and J. L. Freeman, *Diagnosis related groups: Product line management within hospitals.* Academy of Management Review **11**, 41 (1986).

[24] Anylogic, *Why use simulation modeling,* https://www.anylogic.com/use-of-simulation/, [Online, 15/08/2018].

[25] Lazarus, *Lazarus 1.8.4,* https://www.lazarus-ide.org/.

[26] Tomas, *Tomas for lazarus 1.8.4,* Tomasweb.

[27] werktuigbouw.nl, *Werktuigbouw.nl Formuleboekje* (Werktuigbouw.nl).

[28] P. E. C. of Science, *10.4 confidence intervals for the difference between two population proportions or means,* https://onlinecourses.science.psu.edu/stat100/node/57/, [Online, 17/09/2018].

A

Scientific research paper

Improving the patient order flow in the preparation process of a radiotherapy outpatient clinic

A case study at Amsterdam UMC - Location VUmc

Frans de Kok, Hans P. M. Veeke, Dingena L. Schott

1. Introduction

Amsterdam UMC – Location VUmc is an academic hospital where high level research is applied in practice. One of the outpatient clinics of the hospital is the radiotherapy department. Radiotherapy utilises X-ray radiation to damage cancer cells. During their treatment period, cancer patients visit the department once a day to receive a radiotherapy treatment.

Before the radiotherapy treatment an extended preparation process is executed. The preparation process starts when the patient is referred to the radiotherapy department. The preparation process ends when the first radiotherapy treatment starts. Improving the patient order flow in the radiotherapy preparation process is the subject of this research.

2. Process description

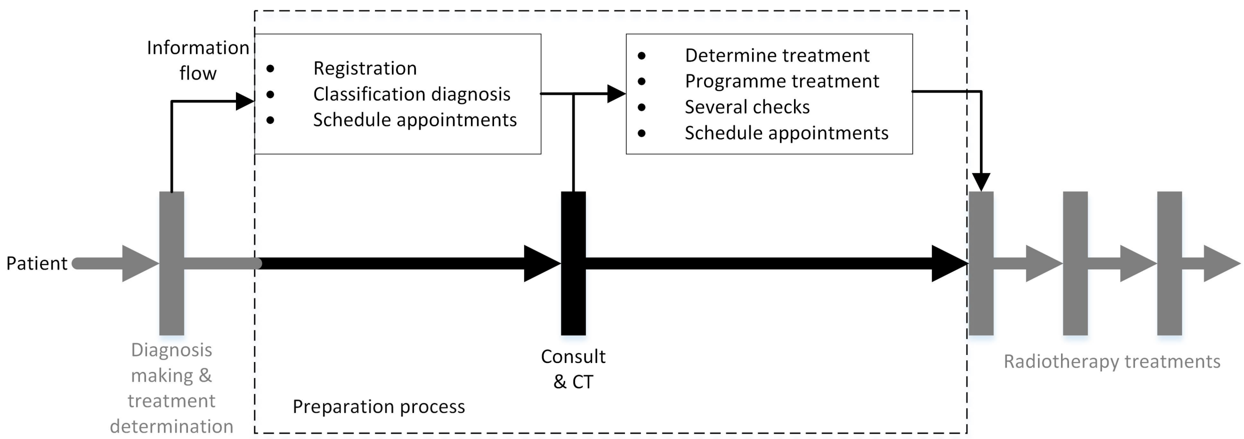


Figure 1: Overview of preparation process

The radiotherapy process is illustrated in Figure 1. Before the radiotherapy preparation process, the diagnosis cancer is made and radiotherapy is chosen as treatment. When the referral is received, the first preparation steps can be executed. These steps are the registration of the patient, the classification of the diagnosis and the scheduling of some appointments for the patient. These appointments consist of at least a consult with a doctor and the execution of a CT-scan. The patient visits the hospital for these appointments.

On basis of the consult and the CT-scan, the remaining preparation steps can be executed. The outline of the treatment is determined, the tumour and critical organs are drawn on the CT-scan and the radiotherapy is programmed. The treatment consists of 1 to 35 radiotherapy sessions. When the appointments are scheduled, the patient can visit the department for these sessions.

3. Analysis

The system is organised as a functional organisation structure [1]. For each of the different process steps, employees with specific qualifications are available. The different mentioned process steps in the preparation process can be considered as an employee executing a task of the patient order. After the execution of the task of the patient order, the patient order is placed in the waiting queue of the next process step(s). There the patient order is waiting to be handled by one of the employees. This process is illustrated in Figure 2. The triangles show the waiting points in the process, the rectangles show process steps.

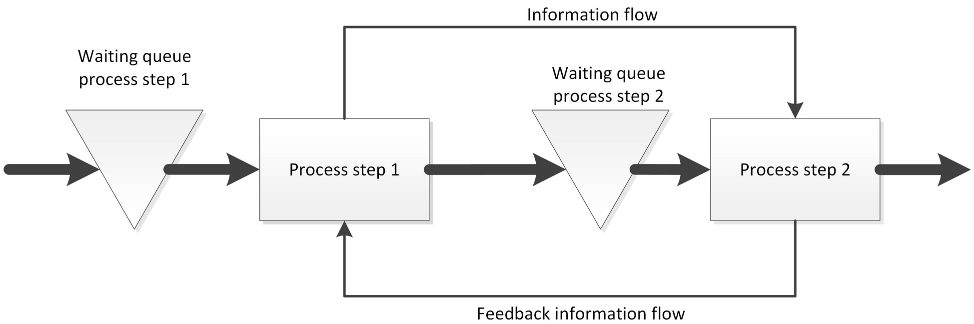


Figure 2: Arbitrary part of functional organisation structure

The preparation process is a complex process: Many different process steps are necessary to prepare the radiotherapy of a patient. Due to the presence of a waiting queue before each of the process steps, the flow is restricted.

An example is the information transfer between the process step 'prescribe treatment' and the process step 'schedule appointments'. The process step 'prescribe treatment' is executed by doctors and the process step 'schedule appointments' is executed by planners. In the case of urgent patients, the doctors have to give information about the urgency class. The urgency class is leading in determining the period till treatment. The information is often given in medical terms and can not be translated to a time till treatment. In that case, a feedback information flow is required to ask for more clearity on the period till treatment.

The information transfer between the different process steps is very important. However, during the information transfer, several errors are made. The reason is often the limited insight in the other (functional different) process step. No overarching control is available to control the flow between the different sections. Interventions occur, but does not rely on organized control structure. The available control is only taking into account the own process step.

4. Research goal

The fact that the radiotherapy department is too much functionally organised is the main reason for the existence of these problems. The functional design is a requirement for the radiotherapy system.

However, within the outline of the functional design, improvements are possible. These improvements have to contribute to more transparency, better coordination and in the end to an improved flow. More transparency is required to get more insight in other sections to smooth the transition between the different sections. Better coordination is required to be able to observe and act on the section overlapping flow of patient (orders). The final goal is to improve the flow of patient throughout the preparation process.

This can be summarized by the research goal:

Redesign the radiotherapy preparation process to create an improved flow of patients with a transparent and coordinated execution.

5. Solutions

The functional design is a prerequisite for the radiotherapy department. However the number of process steps can be reduced by the combination of process steps. An example is the combining of the scheduling of the appointments and the informing of the patients (Figure 4. The reducing of the number of process steps will result in a reduction of the number of transitions between the process steps and a reduction of the number of waiting queues in the department.

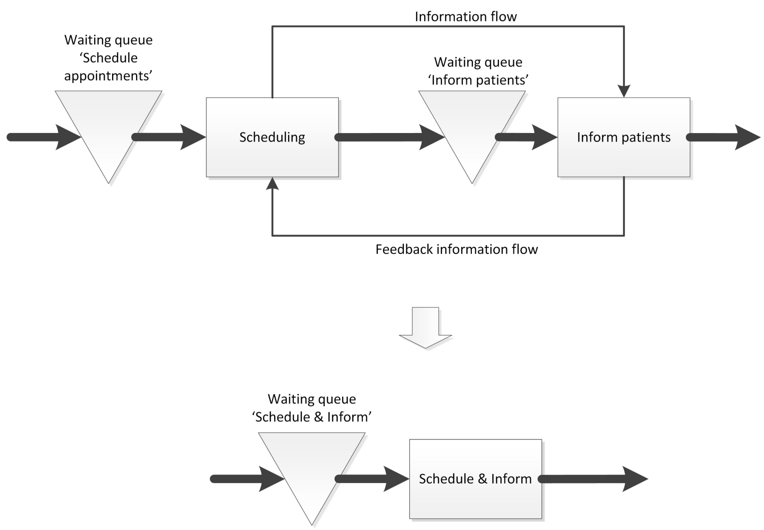


Figure 3: Combination of functions

The main solution for the problem is the design of control structure based on the matrix organisation theory [2]. This control structure consists of both functional control and patient order control. The functional control controls the process executed in every section. This will be enhanced by the adding of the measurement of the waiting queue length of the previous section (Figure 4). This will enhance the transparency by having more insight in the upcoming flow.

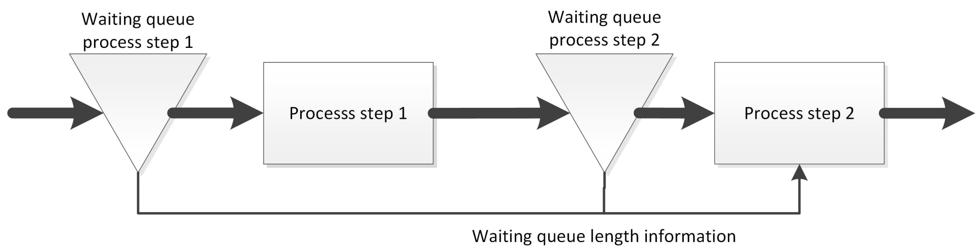


Figure 4: Adding previous waiting queue length as parameter for functional control

The main contribution to meet the research goal is the design of a patient order control structure. It is designed to control the patient order flow in the second part of the preparation process. The start point is the point when the consult is finished and the CT-scan is uploaded. At that point a preliminary radiotherapy start date is determined. The preliminary start date is a basis for the determination of a process path for the subsequent process steps.

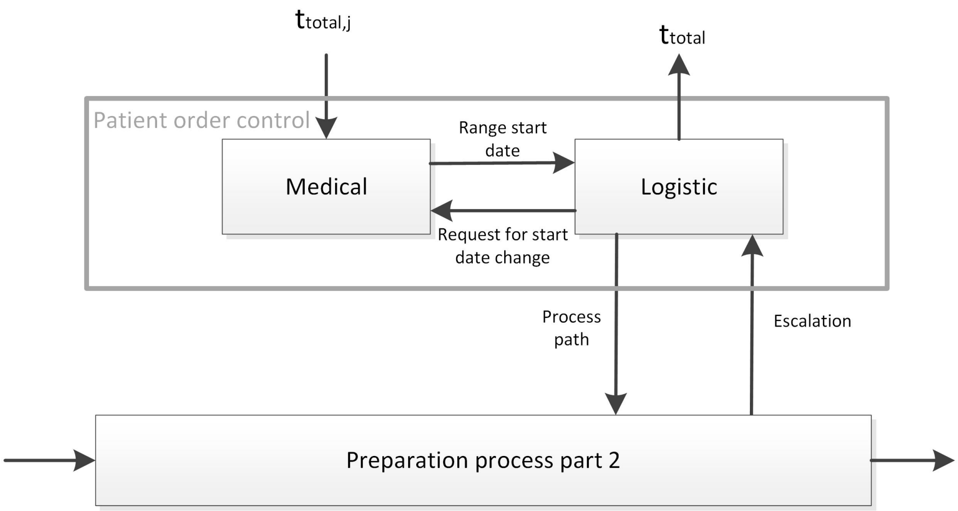


Figure 5: Proposed patient order control structure

The patient order control consists of two different aspects: A medical and logistic aspect. In the initiating phase, the medical component determines the boundaries for preliminary start date based on diagnosis-group specific standards. Between these boundaries, the logistic component can choose a date, which is the end point of the controlled process. The logistic component optimizes the number of radiotherapy starts per day: Each day an equal number of patients starting their treatment have to be realized. If that is the case, a similar number of patient orders have to end the preparation process each day. This will have the following benefits:

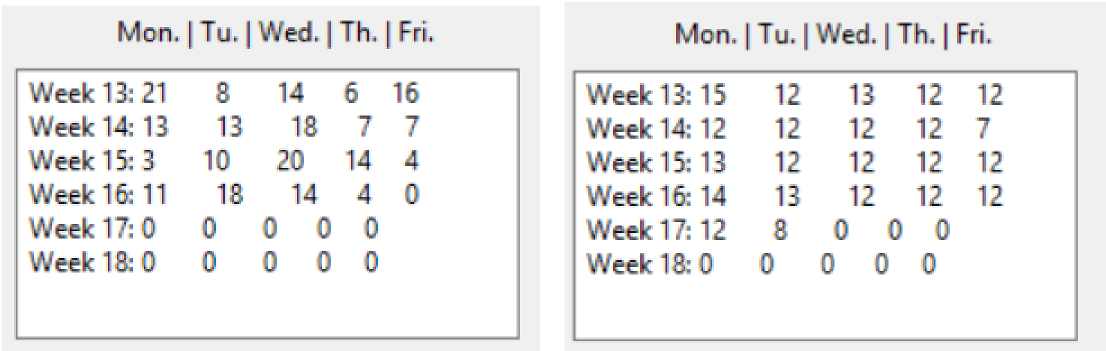
- It can equalize the number of patient orders present at each of the process steps.
- It can result in a homogeneous schedule for the linear accelerators. The schedule consists of start appointments and repetitive appointments for patients. It is assumed that if the number of patients that can start their radiotherapy treatment is equal for each day, the number of repetitive appointments is equal too.

The process steps are executed on the order of the preliminary start date of the patients. If the execution of the different patient order tasks cannot be realized before the determined start date, an escalation takes place. The escalation is a message towards the patient order control. The logistic component can change the start date if possible within the given range. Otherwise, the medical component has to judge if the patient can start its treatment later.

A few days before the first radiotherapy start, the schedule is made definitive and the first radiotherapy appointment is communicated to the patient.

6.Simulation model

For the examination of the effect of the proposed patient order control structure, a simulation model is built. During the experiments, the department is simulated for the period of one year and each scenario is simulated five times. Patient order control is able to steer the system in the desired direction. Figure 6 shows the current situation (left) and the improved situation (right). These figures show the number of radiotherapy starts per day. This is equal to the number of patient orders ending the preparation process. This can have the benefits as described above.



(a) Starters schedule without PC

(b) Starters schedule with PC

Figure 6: Difference in starters schedule due to patient order control

The uniformity of the output schedule is expressed as the standard deviation of the number of starters. In Table 1 It is shown that the patient order control is able to reduce the standard deviation of the number of starters.

Table 1: Simulation results

	Standard deviation number of starters	**Standard deviation process time**
Without patient order control	2,38	3,21
With patient order control	1,28	3,02

The patient order control determines the preliminary start date on the basis of the time of referral and the maximum requirement for the duration of the preparation process. For the avoiding of outliers it is important to result in situation where every patient order (assuming equal circumstances) has an comparable preparation process time. The simulation model shows the ability to reduce the variation in the process time (Table 1). The variation in process time is expressed as the standard deviation of the process time.

7. Implementation

The solution can be implemented in the current structure of the department. The medical component of the patient order control structure belongs to the doctors of the department and the logistic component belongs to the logistic office. For each of the different tumour groups, standards for the upper boundary and lower boundary of the preliminary start date has to be defined. The solution can be implemented gradually. First, it can be implemented for a specific tumour group having limited variation in the process path (for example breast cancer patients). After successful implementation, other tumour groups can follow.

8. Conclusion

The goal of this research was to redesign the radiotherapy preparation process to create an improved flow of patients with a transparent and coordinated execution. The solution is able to improve the transparency in the department. The patient order progress is monitored during the second part of the preparation process and the different process steps have more insight in the upcoming flow. Especially the patient order control structure is able to coordinate the flow based on the determining of the start of the radiotherapy treatment in an earlier phase. The coordination is able to improve the flow through the department by reducing the variation in the schedule for the linear accelerators and by reducing the variation in process time.

Bibliography

[1] J. in ’t Veld, *Organisatiestructuur en Arbeidsplaats - De organisatie van mensen en middelen;theorie en praktijk* (Stenfert Kroese, 1999)
[2] H. Kerzner, *Project Management - A Systems Approach to Planning, Scheduling, and Controlling* (12th Edition) (John Wiley Sons, 2017).

B

Organization Chart Radiotherapy

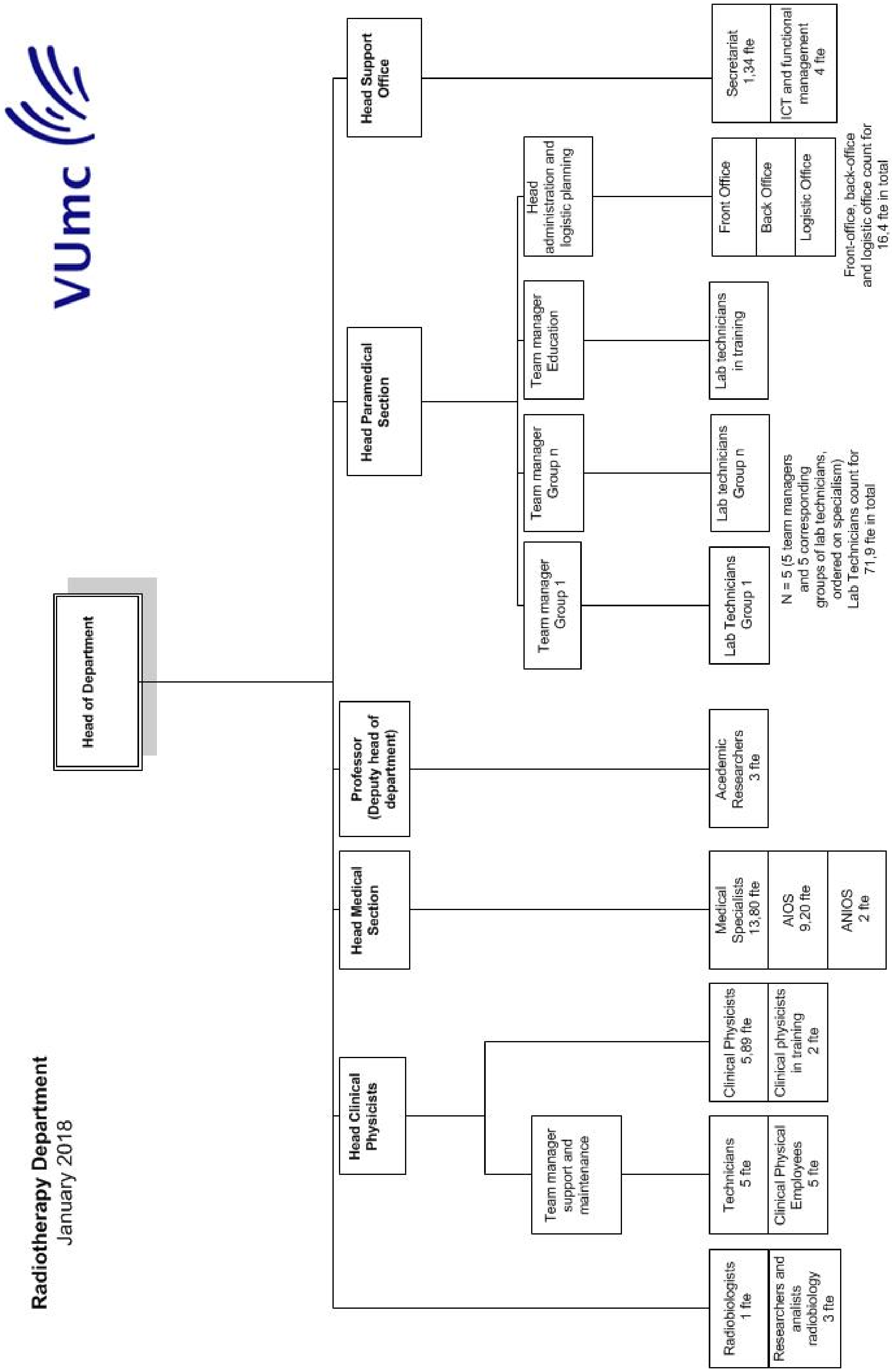


Figure B.1: Organization chart radiotherapy department

C

Modelling by Delft Systems Approach

In this Appendix, the radiotherapy department is modelled by the Delft Systems Approach. The model consists of different aggregation layers.

C.1. Legend

[redacted]

[redacted]

[redacted]

C.2. Aggregation Layer 1

[redacted]

[redacted]

C.3. Aggregation Layer 2

[redacted]

[redacted]

C.4. Aggregation Layer 3

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

C.5. Aggregation Layer 4

[redacted]

[redacted]

D

Process times

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

	[redacted]
[redacted]	[redacted]

[redacted]

[redacted]

[redacted]

[redacted]	[redacted]
[redacted]	[redacted]
[redacted]	[redacted]

[redacted]

[redacted]

- [redacted]
- [redacted]
- [redacted]
- [redacted]

[redacted]

	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]

E

Trace verification

The actual behaviour is described according to the 'Trace' of the model. The Trace of the model describes the different steps of the discrete simulation. The verification is the question if the behaviour is equal to the behaviour described earlier (Section 6.2.1, 6.2.2 and 6.2.4).

```
0.00 Time created
0.00 Time starts at      0.00
0.00 PatientOrderGenerator created
0.00 PatientOrderGenerator starts at      0.00
0.00 SectionsQ created
0.00 P1 created
0.00 waitingQ created
0.00 P1 to tail of SectionsQ
0.00 P1 starts at      0.00
0.00 Employee created
0.00 Employee starts at      0.00
0.00 Employee2 created
0.00 Employee2 starts at      0.00
0.00 Employee3 created
0.00 Employee3 starts at      0.00
0.00 Employee4 created
0.00 Employee4 starts at      0.00
0.00 Employee5 created
0.00 Employee5 starts at      0.00
0.00 Employee6 created
0.00 Employee6 starts at      0.00
0.00 P2 created
0.00 waitingQ created
0.00 P2 to tail of SectionsQ
0.00 P2 starts at      0.00
0.00 Employee7 created
0.00 Employee7 starts at      0.00
0.00 Employee8 created
0.00 Employee8 starts at      0.00
```

Figure E.1: Trace Initialization

The first step in the model is the initialization of the model. The first part of the initialization result is visible in Figure E.1. The Time-Process, the PatientOrderGenerator and the SectionsQ are created once for the full process. Each of the sections (P1..P5) is created with the corresponding waiting queue and the corresponding employees. The number of employees is equal to the number of employees in Figure 6.3.

```
29123.64  PatientOrderGenerator is current now
29123.64 PatientOrder created
29123.64 Tasklist created
29123.64 Task created
29123.64 Task to tail of Tasklist
29123.64 Task2 created
29123.64 Task2 to tail of Tasklist
29123.64 Task3 created
29123.64 Task3 to tail of Tasklist
29123.64 Task4 created
29123.64 Task4 to tail of Tasklist
29123.64 Task5 created
29123.64 Task5 to tail of Tasklist
29123.64 PatientOrder to tail of waitingQ
29123.64 PatientOrderGenerator holds until   29870.55
```

Figure E.2: First patient order generation

The radiotherapy department opens at 8 o'clock. At 8:05, the first patient is generated. This is equal to the time of of 29123 seconds in Figure E.2. Next to the patient order, a task list with 5 tasks is generated. The patient order is connected to the waiting queue of the first section (P1). After the generation, the patient order generator holds for 12.45 minutes before the next patient order is generated.

```
29123.64  Employee is current now
29123.64 PatientOrder out of waitingQ
29123.64 Task out of Tasklist
29123.64 Employee holds until   35676.82
```

Figure E.3: Employee start task

The first order generation will result directly in the availability for an order to be handled by an employee. This is visible in Figure E.3. The patient order will be removed from the waiting queue of the section. Next, the task is removed from the task list of the patient order. The duration of this specific task is 109 minutes. That is between the boundaries for the process time, given in figure 6.3.

```
35676.82  Employee is current now
35676.82 Task out of Elements
35676.82 PatientOrder to sort of waitingQ
```

Figure E.4: Employee end task

When the task is handled, the simulation continues in Figure E.4. The task can be destroyed and the patient order is added to the next waiting queue according the intermediate time. In the current phase of the simulation, this waiting queue is empty. The task can directly be executed by an employee from Section P2.

```
35676.82  Employee7 is current now
35676.82 PatientOrder out of waitingQ
35676.82 Task2 out of Tasklist
35676.82 Employee7 holds until   38215.11
```

Figure E.5: Employee Task 2

The task can directly be executed by an employee from Section P2.

```
48575.73  Employee30 is current now
48575.73 Task5 out of Elements
48575.73 PatientOrder out of Elements
```

Figure E.6: Employee Task 5 end

Task 2, Task 3, Task 4 and Task 5 can be executed in the same way. The end of Task 5 is different. Apart from the destroying of the task, the patient order is destroyed too.

F

Simulation Results

Scenario 1

Runtime: 1 year
Number of process steps: 5
Patient order control: Yes
Previous waiting queue control: No

Table F.1: Results Scenario 1

Combination of boundaries	Av. process time sec. part	St.dev. process time	St. dev. patient starts	Not possible starts
6 and 19	7,46	2,84	3,13	7,73
7 and 20	7,9	2,92	1,64	0,35
8 and 21	8,97	3	1,61	0
9 and 22	10,13	3,02	2,31	0
6 and 19	7,58	2,85	3,02	11,52
7 and 20	7,98	2,93	1,63	2,02
8 and 21	9,15	3	1,45	0
9 and 22	9,92	3,01	2,11	0
6 and 19	7,46	2,66	3,21	7,54
7 and 20	7,91	2,94	1,87	0,06
8 and 21	8,98	3,03	1,67	0
9 and 22	10,14	3,05	2,26	0
6 and 19	7,57	2,87	2,93	10,01
7 and 20	7,98	2,95	1,43	0,72
8 and 21	9,07	3,01	1,3	0
9 and 22	10,27	3,01	2,11	0
6 and 19	7,54	2,79	3,07	10,07
7 and 20	7,91	2,9	1,76	1,88
8 and 21	9,01	2,95	1,5	0
9 and 22	10,19	2,97	2,11	0

Scenario 2

Runtime: 1 year
Number of process steps: 5
Patient order control: Yes
Previous waiting queue control: No
Minimum process time: 7 days

Table F.2: Results Scenario 2

Maximum process time	Av. process time sec. part	St.dev. process time	St. dev. patient starts	Initial delayed starts	Not possible starts
19	7,59	2,88	2,26	5,92	4,09
20	7,9	2,92	1,64	0	0,35
21	8,43	3,03	1,28	0	0,03
22	8,69	3,11	1,18	0	0
23	9,04	3,16	1,01	0	0,03
19	7,59	2,89	2,32	6,13	3,55
20	7,98	2,93	1,63	0	2,02
21	8,49	3,06	1,48	0	0
22	8,85	3,14	1,31	0	0
23	9,03	3,2	1,26	0	0
19	7,65	2,84	2,24	5,75	5,96
20	7,91	2,9	1,76	0	1,88
21	8,37	2,98	1,18	0	0
22	8,66	3,06	1,07	0	0
23	8,83	3,13	0,97	0	0
19	7,57	2,89	2,38	5,3	7,96
20	7,72	2,93	1,92	0	2,82
21	8,11	3,01	1,42	0	0,98
22	8,23	3,06	1,41	0	1,08
23	9,95	3,2	2,37	0	0
19	7,67	2,89	2,06	5,26	4,53
20	7,91	2,94	1,87	0	0,06
21	8,66	3,03	1,02	0	0
22	9,25	3,13	0,91	0	0
23	9,74	3,21	0,75	0	0

Scenario 3

Runtime: 10 years
Number of process steps: 5
Patient order control: No

Table F.3: Results Scenario 3

Previous waiting queue control	Percentage peaks >150%
No	8,50
No	8,38
No	9,49
No	8,86
No	7,73
Yes	6,58
Yes	6,15
Yes	6,45
Yes	6,75
Yes	5,87

Scenario 4 & 5

Runtime: 1 year
Number of process steps: 5
Minimum process time second part: 7 days

Maximum total process time: 21 days
Remark: The situation with patient order control and without previous waiting queue control is simulated in scenario 2.

Table F.4: Results Scenario 4 & 5

Patient order control	**Previous waiting queue control**	**Av. process time sec. part**	**St.dev. process time**	**St. dev. patient starts**
No	No	10,12	3,25	2,51
No	Yes	10,07	3,18	2,63
Yes	Yes	8,66	3,03	1
No	No	9,97	3,25	2,46
No	Yes	10,02	3,18	2,69
Yes	Yes	8,49	3,05	1,48
No	No	10,28	3,19	2,42
No	Yes	10,23	3,15	2,6
Yes	Yes	8,57	3,04	1,03
No	No	10,14	3,17	2,32
No	Yes	10,09	3,12	2,44
Yes	Yes	8,37	2,98	1,15
No	No	10,04	3,18	2,21
No	Yes	9,99	3,14	2,58
Yes	Yes	8,44	3,03	1,28

Scenario 6

Runtime: 1 year
Number of process steps: 10
Patient order control: No
Previous waiting queue control: No
Remark: The situation with 5 process steps is simulated in scenario 4 & 5.

Table F.5: Results Scenario 6

Av. process time sec. part	**St.dev. process time**	**St. dev. patient starts**
16,21	3,39	2,39
16,74	3,39	2,42
16,48	3,29	2,22
16,63	3,39	2,35
16,33	3,31	2,17