UNIVERSITY OF TWENTE. LEIDS UNIVERSITAIR MEDISCH CENTRUM

# Capacity planning for waiting list management at the Radiology department of Leiden University Medical Center.

Master Graduation thesis

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A.J. Schneider
*Industrial Engineering and Management, University of Twente*
*Track Health Care Technology and Management*
*Student number: s1085698*

Dr. ir. I.M.H. Vliegen (1st supervisor)
*Assistant professor, University of Twente*
*School of Management and Governance*
*Operational Methods for Production and Logistics Group*

ir. M.E. Zonderland (2nd supervisor)
*PhD candidate, University of Twente*
*Faculty of Electrical Engineering, Mathematics and Computer Science*
*Stochastic Operations Research Group*

Ir. C.A.J. Bots (external supervisor)
*Manager Department of Radiology*
*Leiden University Medical Centre*

# Management summary

As demand exceeds scarce health care resources waiting lists occur. An important diagnosing-information generating department of a hospital is the Radiology Department. Because of this importance many patients visit the Radiology department. The Radiology department deploys cost intensive resources such as MRI and CT. Currently, many Radiology departments such as in the Leiden University Medical Centre, deal with waiting lists for their resources. This results in delays within patient flow processes throughout the hospital. Therefore an efficient operating Radiology department is required in order to create a smooth process of hospitalization for patients. This study aims to improve waiting list management through developing an integral planning cycle, which relates planning activities at all hierarchical control levels for Radiology departments. In order to analyze waiting lists behavior, a simulation study at the Radiology department at the Leiden University Medical Centre was also performed.

The practice of the Radiology department of Leiden University Medical Centre was used for analyzing the mentioned improvements. The Radiology department deploys resources, such as MRI and CT, by available personnel. The stochastic nature of demand results in fluctuations over time. The supply-driven planning makes it difficult to allocate resources to demand and to anticipate to changes in demand. The current planning function of the Radiology department has a fragmented design, because many different parties are involved and generate individual schedules (e.g. radiologists' rostering and paramedics' rostering are fragmented). It uses different planning techniques, different planning horizons and different planning software. In order to perform images at the Radiology department, personnel are needed at the same place at the same time. This requires alignment of planning.

To integrate and relate all planning activities at the different hierarchical control levels (e.g. strategic, tactical and operational) of the Radiology department, we introduced a planning cycle. This planning cycle is demand driven and relates planning activities such as; forecasting, rough cut capacity planning, block scheduling, staff rostering and appointment systems. This planning cycle also incorporates activities like managing waiting lists and it implies active response to changing waiting lists.

In order to get insight how waiting lists response to potential intervention of the Radiology department a discrete-event simulation

model was developed. This model incorporates the department dynamics and can be used to analyze interventions to decrease waiting lists. To quantify input variables data was acquired of the year 2010. The model was validated by a one-sample t-test on utilization rates and access times.

The potential interventions for the Radiology department are: extended operational hours, additional staff, efficiency improvement of service times and efficiency improvement through decreasing the level required personnel. Because of the many potential interventions that can be analyzed with the model, this study only gave general results of the interventions. To show the potential of this model there was also analyzed one specific scenario. The general results derived from the model were;

| *Scenario* | *Most promising intervention* |
|---|---|
| Increasing access times | Additional staff |
| Increasing waiting times | Shorter service times |
| Increasing overtime | Extension of operational hours |
| Increasing access ratio | Additional staff or decrease required staff per procedure |

The specific scenario implies a shift in staff rostering. Shifting a paramedic for one day (8.15 hours) from CT to MRI resulted in an increase of production of 133 patients at MRI and a decrease of 298 patients at CT. This can be valuable information for the management of Radiology departments to anticipate changing waiting lists.

Both the planning cycle and simulation model are generally applicable for Radiology departments and can be tailored to individual preferences. Because of the general design many capacity planning scenarios can be analyzed using this simulation model. Further research on capacity planning at Radiology departments could be implementing different appointment systems in this simulation model for scheduling patients.

# Management samenvatting

Als een gevolg van een toenemende vraag naar schaarse middelen in de gezondheidszorg onstaan wachtlijsten. Ziekenhuisafdelingen zoals de afdeling Radiologie van het Leids Universitair Medisch Centrum, hebben daarom te maken met groeiende wachtlijsten. Radiologie afdelingen leveren belangrijke diagnostische informatie voor specialisten. Veel patiënten die een ziekenhuis betreden zullen dan ook langs de afdeling Radiologie komen. Wanneer er vertragingen zijn bij Radiologie, heeft dit direct gevolgen voor het gehele patiëntenproces in een ziekenhuis. Daarnaast maken afdelingen Radiologie gebruik van kostintensieve middelen zoals CT en MRI, daarom is optimale benutting van deze middelen maatschappelijk gewenst. Dit onderzoek richt zich dan ook op het optimaleseren van wachtlijsten van Radiologie afdelingen. Voor dit onderzoek is gebruik gemaakt van data van het Leids Universitair Medisch Centrum.

De afdeling Radiologie van het Leids Universitair Medisch Centrum stelt middelen zoals CT en MRI beschikbaar op basis van personele capaciteit. Deze aanbodgestuurde planning maakt het moeilijk om middelen te relateren aan de vraag en daarnaast te anticiperen op een veranderende (stochastische) vraag. De huidige planningfunctie van de afdeling Radiologie heeft een gefragmenteerd ontwerp. Veel verschillende partijen zijn betrokken en genereren individuele planningen en roosters (bijvoorbeeld het radiologenrooster en paramedicirooster zijn gefragmenteerd). Er worden verschillende planningstechnieken, verschillende planningshorizon en verschillende planningsoftware gebruikt. Om beelden op de afdeling Radiologie uit te voeren, is personeel nodig op dezelfde plaats op hetzelfde moment. Dit vraagt om een integrale planning.

Om te kunnen sturen en anticiperen op een stochastische vraag en het integreren van verschillende planningsactiviteiten hebben wij een planningscyclus ontworpen. Hierin zijn alle planningsactiviteiten van verschillende hiërarchische managementniveau's (strategisch, tactisch en operationeel) van de afdeling Radiologie aan elkaar gerelateerd en geïntegreerd. Deze planningcyclus is vraaggestuurd en heeft betrekking op planning van activiteiten, zoals: forecasting, rough cut capaciteitsplanning, 'block scheduling', personeelroosteren en benoemingssystemen. Deze planningscyclus omvat ook het managen van wachtlijsten en impliceert actieve anticipatie op dynamische wachtlijsten.

Om inzicht te krijgen in het gedrag van de wachtlijsten van de afdelinge Radiolgie hebben we een discrete-event simulatie model ontwikkeld. Dit model bevat de afdelingsdynamiek en kan worden gebruikt om interventies te analyseren met als doel wachtlijsten te verminderen. Invoervariabelen

zijn gekwantificeerd op basis van gegevens uit het jaar 2010. Het model werd gevalideerd door een t-toets voor één steekproef op de bezettingsgraad en de toegangstijd van de afdeling.

De potentiële interventies voor de afdeling Radiologie zijn: uitbreiden van operationele uren, extra inzet van personeel, efficiëntieverbetering van doorlooptijden en efficiëntieverbetering door het verminderen van het benodigde personeel. Omwille van de duur van dit onderzoek en de vele mogelijke interventies die kunnen worden geanalyseerd met het model hebben we alleen algemene resultaten van de interventies geanalyseerd. Daarnaast hebben we één specifiek scenario geanalyseerd om de potentie van model te tonen. De algemene resultaten die zijn afgeleid uit het model waren;

| *Scenario* | *Meest belovende interventie* |
|---|---|
| Toename van toegangstijden | Inzet van extra personeel |
| Toename van wachttijden | Efficiëntieverbetering van doorlooptijden |
| Toename van overuren | Verlengen van operationele uren |
| Toename van toegansratio | Inzet van extra personeel of efficiëntie verbetering van het benodigde aantal personeel |

Het specifieke scenario wat was ontwikkeld impliceert een verschuiving in het personeelsrooster. Hierin verschoven we een paramedicus voor een dag (8.15 uur) per week van CT naar MRI. Dit resulteerde in een toename van de productie van de 133 patiënten op MRI en een daling van 298 patiënten op CT op jaarbasis. Dit kan waardevolle informatie zijn voor het managementteam van de afdelingen Radiologie om te kunnen anticiperen op wachtlijsten en wat eventuele gevolgen zijn van veranderingen in capaciteitsplanning.

Zowel de planningscyclus als het simulatiemodel zijn algemeen toepasbaar voor Radiologie afdelingen en kunnen worden afgestemd op individuele voorkeuren. Vanwege dit algemene ontwerp kunnen vele capaciteitsplanningscenario's worden geanalyseerd met behulp van dit simulatiemodel. Verder onderzoek naar capaciteitsplanning op Radiologie-afdelingen zou zich kunnen richten op de invoering van verschillende afspraaksystemen in dit simulatiemodel voor het plannen van patiënten en analyseren welke verbeteringen dit zou kunnen opleveren.

# Preface

In July 2007, I received my applied Bachelor's degree in Healthcare Engineering. However, I was not fully satisfied at that moment. The focus of this education was too broad. This gave me the idea that I had learned a lot of everything, but too little specific knowledge. Besides, I was not completely challenged. Therefore I decided to develop myself further and after speaking to some alumni of the Industrial Engineering and Management Master of the University of Twente I decided that this was the perfect Master for me.

The final phase of my Master is writing this thesis. I also start a new phase in my life, the working life. Therefore I think this is a good moment to look back- and forwards. I will never regret the decision getting this Master's degree. It challenged me and taught me specific knowledge of phenomena I am interested in. I met new friends and admire the dedicated researchers of my Master. I could have never achieved this Master without some important people in my life. I would like to express my gratitude to my parents, Ton and Nolleke, for encouraging me and giving me this opportunity. You created the preconditions for me studying this Master. I would also like to thank Anne, as well as her family. You were always there for me to cheer me up after a setback. I could not have done this without you all.

The lectures of Erwin Hans convinced me to focus on health care operations research. Doing my research and writing my thesis at a hospital was therefore a logical corollary. I wrote my thesis at the Leiden University Medical Center. During my thesis, I soon found out that practice was more complicated as it was presented during lectures. Writing this thesis learned me that introducing operations research (OR) in an health care environment comes with many challenges. Despite the progress already made, this is an ongoing process in which you have to convince people of the added value of OR techniques. Introducing operations research in healthcare requires not only knowledge about numbers, but also knowledge and experience in change management. Every change in a health care environment comes with a human factor. Getting people out of old patterns and introduces them to new instances is much more sophisticated than to solve complex mathematical equations.

There are a lot of people I would like to thank for contributing to the completion of this thesis. First I would like to thank my supervisors from the University of Twente, Ingrid Vliegen and Maartje Zonderland. With your extensive experience and knowledge in health care operations research, you pushed me to strive to the best. With your 'good is not good enough' mentality you challenged me a lot. You kept me on track and guarded the scientific value with critical reviews. I would also like to thank my internal supervisors Corina Bots and Frank Maagdenberg. Your cooperative and enthusiastic attitude and your dedication to fulfill this project successfully gave me the inspiration I needed. There are many people who are not mentioned above, but have not forgotten. I would also to express my gratitude them.

As a 'logical consequence' I recently started working at the Leiden Medical Center as a logistics consultant. I am really looking forward to apply all the theory I have learned during my Master's.

Thomas Schneider December 2011, Amsterdam

*There is nothing more difficult to take in hand, more perilous to conduct, or more uncertain in its success, than to take the lead in the introduction of a new order of things. Because the innovator has for enemies all those who have done well under the old conditions and lukewarm defenders in those who may do well under the new.*

Machiavelli (1469-1527)

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# 1 Introduction

## 1.1 Motivation

In most Western countries health care expenditures tend to increase (OECD, 2010). In order to manage this growth, many of these Western countries shift the health care industry from a public to a (semi) private industry (Maarse, 2006). This shift comes with pressure to perform. For instance, waiting lists become more and more a policy concern (Siciliani & Hurst, 2005). In order to enhance productivity and in this way reduce waiting lists, half of all OECD countries replaced their budget allocation for public health care from fixed budgets to reimbursement on output to enhance productivity (van de Vijsel et al., 2011). This influenced the operability and behavior of care providers (e.g. hospitals, nursing homes and general practitioners). Care providers have to take into account an increased number of dimensions in medical decision-making. For instance efficiency and cost-effectiveness have become important performance indicators in research and practice. These dimensions introduced competition among colleagues and outputs are comparable through benchmarking.

Changes in society forced governments of Western countries to introduce the (managed) competition. These changes could be categorized as follows; technological innovations (increase in demand through supplier induced demand and an extension of life), demographic changes (Centraal Bureau voor de Statistiek, 2010) (ageing leads to an increase in demand and decrease in supply of manpower), transition in epidemiological profile (as a result of the ageing society there is a shift from life style diseases to chronic diseases and imply an increase of long term care). On a macro-economic scale, these changes have an effect on the balance of demand and supply. The changes stated above create a macro-economic gap in this balance and forces societies to manage their health care industry more efficient.

The Leiden University Medical Center (LUMC) also faces external pressure, as mentioned above, to improve efficiency. In the present study we analyzed the planning function (e.g. planning related activities) of the Radiology department at LUMC to improve efficiency and waiting lists. We started with analyzing the problems of Radiology department to further improve efficiency and in which context these problems occurred.

## 1.2 Leiden University Medical Center

Leiden University Medical Centre is one of the eight university medical centers in the Netherlands, employs around 7000 people and owns around 300 beds. Besides the care and cure that is delivered via several specialties, university medical centers distinguish themselves from other hospitals mainly because of their partnerships with universities on education (by offering studies such as medicine and biomedicine) and performing research. University medical centers' health care focuses on the special branches of health care, also called 'highly specialized care'. This means that these centers deal with rare and complex medical issues for which there are often no straightforward treatments.

## 1.3 The Radiology department

The department of Radiology at LUMC performs both imaging and image-guided interventions (IGIs) and analyzes a variety of disease processes. Together with paramedics, radiologists support other specialties in diagnosing diseases. Radiologists are specialized in analyzing images, where paramedics (e.g. radiographers) are specialized in making the best image. The LUMC's Radiology department includes general Radiology, nuclear medicine, medical image processing (also known as the Laboratory for Clinical en Experimental Image processing) and high field MRI (Gorter Research Center). As one of the ten trauma centers in the Netherlands, the LUMC also has to deal with complex and comprehensive emergency care, in which fast and qualitative imaging is crucial. Imaging is performed using different imaging techniques; X-rays, ultrasound, magnetic resonance and computed tomography. The applications of the different techniques are called modalities. Additionally, patient therapy with (radio)pharmaceuticals and image-guided interventions is available. The Radiology department carries out almost 200,000 procedures per year, requested by medical specialists and general physicians (management information system Radiology department LUMC, 2011).

The Radiology department plays a crucial role in the patient flow process. To establish a diagnosis, doctors need diagnostic information. The largest source of diagnostic information in a hospital currently comes from the Radiology department. Without images, it will be a major challenge for doctors to establish a diagnosis. And even with available images this is challenging. Therefore almost every patient will visit the department of Radiology or other diagnostic information generating departments (e.g. clinical neurophysiology or the laboratory). Based on the information derived from Radiology a physician can make a logical and deliberate judgment of which treatment fits best.

As significant investments are required for the sophisticated modalities used at the Radiology department, they are in low numbers and efficient utilization is therefore important. This results in a shared resource (modality) for patient care and research. Because of the relative low number of modalities, they appear to be bottlenecks in many patient care processes, and therefore lead to suboptimal patient service and cost-savings (Elkhuizen et al., 2007).

### *1.3.1 Financial structure Radiology department*

The LUMC is divided in divisions that consist of several departments, such as Radiology. The department of Radiology has a hybrid cost structure. It mainly receives its financial assets based on a fixed annual budget from the central division. The budget is historically determined and not based on output performances (e.g. procedures performed). Additionally, the department receives so called target outputs performance for specific procedures, because these are cost intensive and/or important for the LUMC to maintain.

### *1.3.2 Organization*

The organization framework of the Radiology department is divided in three managerial areas; patient care, research and education. Most personnel are involved in all managerial areas. This means that capacity is shared among the three areas. Production figures are mainly focused on the patient care area, because the processes in this area are, to a certain extent, similar to manufacturing processes (e.g. job shop process). Because efficiency improvement in this managerial area is important and research on improving efficiency of manufacturing processes is widely available this study will focus on this area.

The organization of patient care area is based on a matrix structure. This structure is historically formed, because of the different backgrounds of paramedics and radiologists. Paramedics are specialized on one or more modalities, while radiologists are specialized in certain areas of the human body. Radiographers and radiologists work together based on their specialization. This means that radiologists work cross-modality but within their own specialty (part of the human body), while paramedics work cross-sectional and are specialized in a modality. Next to their specialization radiologists and paramedics, perform procedures on one or two other sections/modalities. Depending on their specialization, both radiologists and paramedics work together on a combination of modality and section to diagnose and/or treat patients.

The Management Board of the Radiology department consists of a professor in Radiology (head of the department), a radiologist (medical manager) and an operations manager.

## 1.4 Scope

The LUMC's Radiology department delivers care and cure by imaging and image-guided interventions (IGIs). In current practice planning and control are segregated. Different planning functions such as capacity planning (for instance MRI and CT) and personnel rostering are stand-alone. Even personnel rostering for radiologists, paramedics and administrative employees is fragmented and use different planning tools (software packages). This fragmented design leads to a suboptimal deployment of the scarce resources available at the Radiology department. Namely, in the fragmented design, all planning functions have to communicate with each other, in order to align resources. This takes time and makes decision making slow and inefficient. Alignment is crucial for the Radiology department's production, since staff is needed at the same time at the same place. Since the different planning functions are physically separated, there is also not much mutual understanding and insight in each other's (planning) competences, skills and tactics.

The rostering (scheduling) and planning of personnel and resources is currently supply-driven, which means that planning is based on availability of resources and personnel. Since personnel are the constraining factor (primarily by paramedics, but also the availability of radiologists is constraining production) the availability of personnel is the main criteria for (partly) opening and/or closing the department. Therefore, the department's production decision making is almost independent of the demand (e.g. waiting lists). For instance, current block planning (dividing available time slots of resources on sections) is not based on demand and therefore has less flexibility to respond to changes in (stochastic) health care processes. When waiting lists take on extreme proportions, ad hoc (and mostly rigorous) measures will be taken. This makes it difficult to related capacity to waiting lists. Another efficiency problem is that rostering is currently performed by scarce and costly personnel, for example paramedics and radiologists, while administrative employees could, at least partially, replace the cost intensive personnel (suboptimal deployment of staff).

### *1.4.1 Problem statement*

Based on the problems described above the following problem statement has been formulated:

*Because of the current supply-driven planning of the department of Radiology, it is difficult to relate resources to actual demand. A lacking infrastructure and alignment of the planning function hinders serving a stochastic demand (waiting lists) and carrying out the department's mission.*

In order to analyze the problem statement several questions have been answered:

1. What is the problem context and what is the current performance of the Radiology department? Chapter 2 will answer these questions.

   *Result(s): A problem analysis that delineates the project. Specified performance indicators and current performance measures.*

2. What can be found in literature on waiting lists management and planning activities? This question is answered in Chapter 3.

   *Result(s): Literature study including a theoretical analysis of the problem and possible solutions (e.g. optimization techniques) which will be combined in a theoretical model.*

3. Can the current situation of waiting list management be conceptualized? Chapter 4 focuses on this question.

   *Result(s): A validated and verified model to analyze possible interventions. Also a sensitivity analysis of the model will be performed in order to analyze the model's behavior when supply or demand is changed.*

4. What is the most promising intervention for waiting list management? Chapter 5 gives an extensive overview on the results of the simulation study.

   *Result(s): A simulation study that analyzed promising intervention.*

5. What can be concluded from the results and what are the managerial implications of both the planning cycle and waiting list management? This is the final question and is answered in chapter 6.

   *Result(s): Recommendations based on the outcomes of the analysis and how they should be implemented. Furthermore, any general recommendations that are not derived from the analysis, but could be an improvement for the department will be presented.*

### *1.4.2 Research objective*

The earlier mentioned research questions showed one purpose, namely;

*In this thesis we develop a demand-driven and centralized management system that incorporates all planning related activities, called a planning cycle, which aims to align the personnel and material capacity with the demand of the Radiology department. The system will incorporate the stochastic nature of the health care production processes and demand. This planning cycle is followed by a simulation study that has analyzed potential intervention of waiting lists management. This is ultimately expected to lead to an improved performance of the department.*

# 2 Context

In this chapter the context in which the Radiology department operates will be described from an operations research perspective. We describe the demand of the department for their capacity (also described). The processes carried out at the department will be presented. This chapter finishes with an analysis how these processes are managed and current production figures.

## 2.1 Clients (demand)

In 2010, around 200,000 procedures on the different modalities were performed. Procedures in this sense mean visualizations of the human body inside or interventions combined with imaging. Trends show that the number of procedures still increases, but the level of growth is decreasing (Forrest, 2011) and shifts from conventional imaging techniques (e.g. X-radiation) to more sophisticated applications of imaging like MRI and or CT (Bhargavan & Sunshine, 2005). Clients of the Radiology department can be characterized as follows;

*Patient care*: a distinction is made between direct and indirect demand for patient care, because Radiology services are (still) secondary care and therefore patients could only visit the Radiology department via a specialist's reference. Strictly taken, only General Practitioners and/or specialists can request a scan, so the direct demand comes from them, but is driven by the patient. On the other hand, patients demand a solution for their illness and so indirectly the demand for a scan comes from them. Furthermore patients can be classified based on their specific needs as follow:

- Inpatients; *are admitted to a hospital for at least one night*
- Outpatients; *are patients who are hospitalized for maximum 24 hours (no overnight stay)*
- Emergency patients; *are patients in need of immediate assistance in connection with an experienced possibly serious or life-threatening situation in the short term, due to a health problem or injury that occurred suddenly or worsens* (Council for Public Health and Health Care, 2003).

*Research:* imaging used for scientific research.

## 2.2 Process description

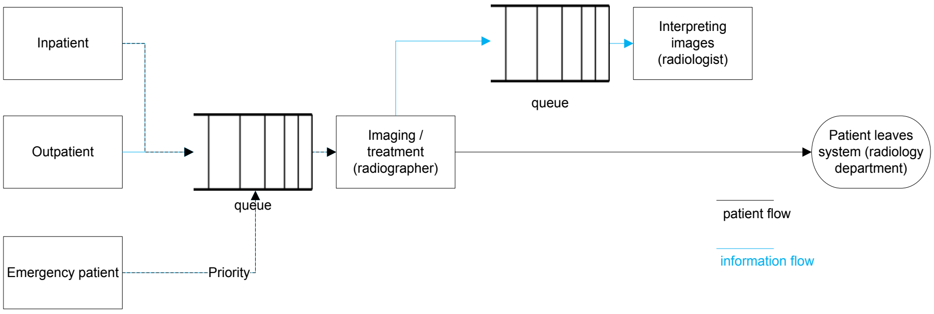
At the Radiology department, a procedure consists basically of two parts; the actual imaging of a part of the inside body or complete body, and interpreting the scans made. A paramedic will perform the actual imaging followed by a radiologist's interpretation of the images made. Sometimes a procedure will be directly supervised by a radiologist, because of complex inside structures in the human body. But the trend is towards less direct supervision of radiologists during imaging procedures.

Interventions can be performed during procedures and are called Image Guided Interventions (IGIs). These IGIs differ from diagnostic procedures, because they can have therapeutic purposes. At the Radiology department of LUMC, applications of IGIs are; catheterization (both for drainage or medication), angioplasty (widening a narrowed or obstructed blood vessel), aneurysm coiling (blood-filled balloon-like bulge in the wall of a blood vessel that will be filled with platinum coils and will result in clotting or a thrombotic reaction and, if successful, will eliminate the aneurysm), punctures, radio frequent interstitial tumor ablation (creating localized necrotic lesions with radiofrequency ablation) and stenting (tubing a natural passage/conduit in the body to prevent, or counteract, a disease-induced, localized flow constriction).

Depending on which procedure is performed, there are basically three processes at the Radiology department: a standard process, a direct interpreting process and an image guided intervention process;

During a *standard process* (see Figure 1) a standard procedure is performed. This starts with entering a patient the Radiology department (walk in principle or an appointment). The patient then might has to wait before the image can be made. A paramedic (mostly a diagnostic radiographer) will produce the actual image. After the image made, the patient will leave the Radiology department, but the image will have to be interpreted by a radiologist. This is where the procedure ends.

Figure 1: Standard process Radiology department



An *image guided intervention process* is a multidisciplinaire procedures (see figure 1)Several specialties cooperate to perform the intervention. This procedures demand both a radiologist and a paramedic at the same time at the same place and therefore this procedure differs from other procedures. Another distinction compared to the other procedures is that around 60% of the patients has an urgent demand (thuswill have to be treated on that exact day). This subsequently influences the planning of patients and capacity planning.

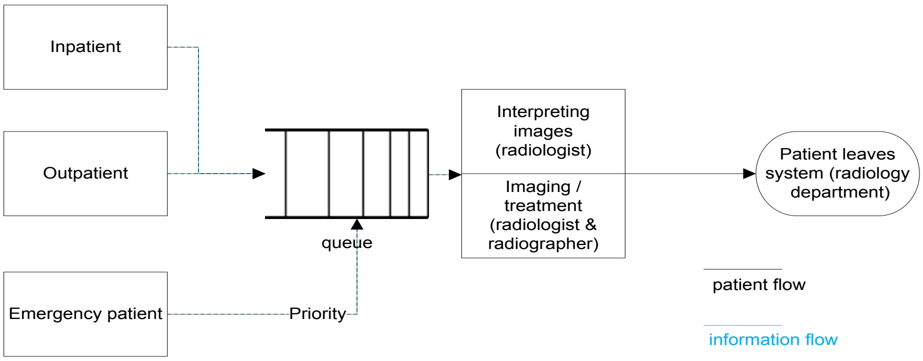


Figure 2: Image guided intervention process

Sometimes a radiologist wants to check the image made directly, because it is a complicated structure. Therefore the radiologist directly judge whether the image meets its requirements and gives feedback if the image has to be produced again or not. This process is called a *direct interpreting process* (figure 3);

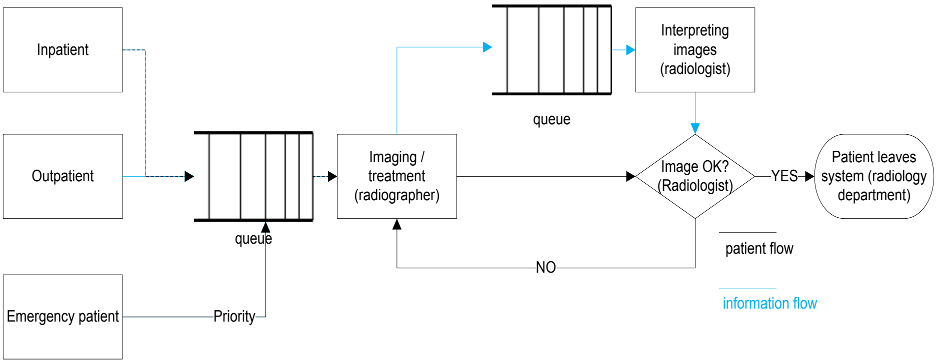


Figure 3: Direct interpreting process Radiology department

## 2.3 Capacity

The production level of the Radiology department is constrained by material and personnel. Material capacity of the department consists of the earlier mentioned modalities (imaging techniques), the manpower capacity consists of radiographers and radiologists. Modalities are strategic resources, because they require significant investments and are directly related to the mission. Personnel planning could both be strategic (radiologists) or tactical (temporary personnel). This section will explain in more detail the current capacity of the Radiology department.

### 2.3.1 *Materials*

Different modalities are available on the Radiology department;

- Angiography rooms
  *This imaging technique uses contrast agents and x-ray to visualize the lumen of blood vessels and organs. Sometimes also an intervention will take place.*

- Echography rooms
  *Penetrating the human body using ultrasound, reveals structures inside via reflection signatures.*

- MRI scanners
  *Using the property of nuclear magnetic resonance, nuclei of atoms inside the human body can be imaged. Via powerful magnetic fields, nuclei at different locations inside the human body rotate at different speeds and so different structures can be detected. Scanners could have different properties of Tesla units. This unit derives the magnetic induction of the magnetic field produced around a MRI scanner. The higher the Tesla unit produced is the better distinction can be made between nuclei.*

- X-rays
  *Röntgen (radiation) uses electromagnetic radiation of a certain wavelength. A photographic digital detector will detect the waves produced, and structures inside the human body will be visible because some structures (e.g. bones) absorp more radiation than others such as skin.*

- CT scanners
  *Computed Tomography (CT) is an imaging technique that employs computerized tomography (imaging by sectioning) and X-radiation to generate (3D) images of inside structures.The higher the number of slices, the larger a body part can be imaged in a single scan.*

- Mammo
  *Mammography uses low-dose X-radiation or ultrasound for imaging breasts and strives to detect early stage breast cancer. Mammotome is an IGI for breast biopsy and/or punctures and are also performed at the mammo rooms. The soft scan is a new procedure of imaging breasts for research goals based on echography.*

- GE rooms
  *Swallowing a contrast paste, it is possible to visualize soft tissues inside the human body via x ray. Mostly used for gastrointestinal research.*

### 2.3.2 *Personnel*

The personnel needed for production on this department consists of radiologists, paramedics and administrative employees. Depending on the kind of intervention or procedure performed, they will cooperate.

## 2.4 Production figures

Since the patient care area of the Radiology department mainly focuses on production and performs relatively simple and repetitive procedures, it is eminently a manufacturing department in health care. As mentioned earlier, it is crucial that the Radiology department production is maintained. If not, it could slow down the whole patient process of hospitalization or outpatient processes. As mentioned earlier the demand for health care resources increases and has a stochastic nature. This increase in demand can also be derived from the figure below;

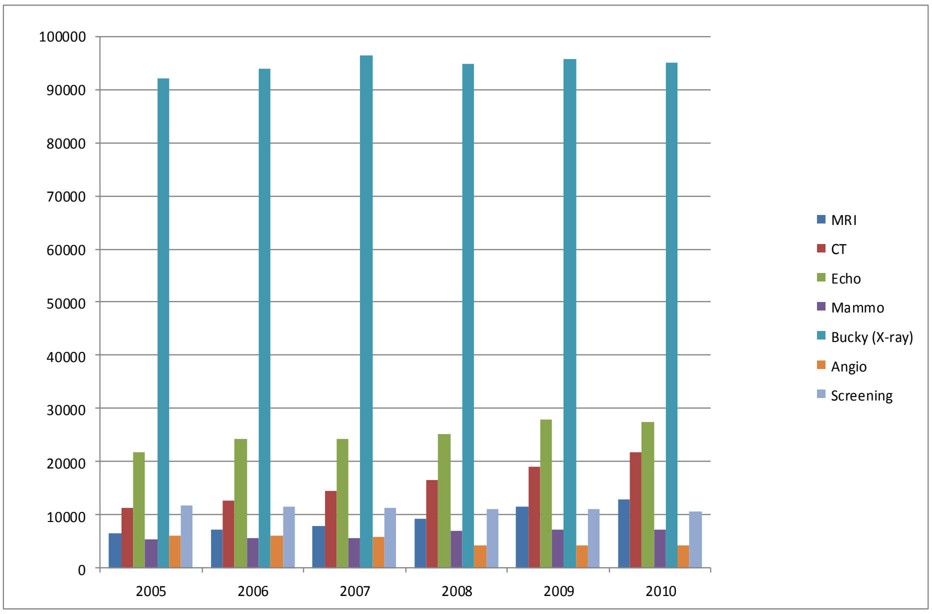


Figure 4: Production figures Radiology department LUMC 2005-2010 (derived from: Management Information system, 2011)

As already stated, the demand for health care resources, such as the modalities of a Radiology department is stochastic and varies over time. As can been seen from figure 5, the demand for the Radiology department of the LUMC also varies over time, because the access times are fluctuating over the year.

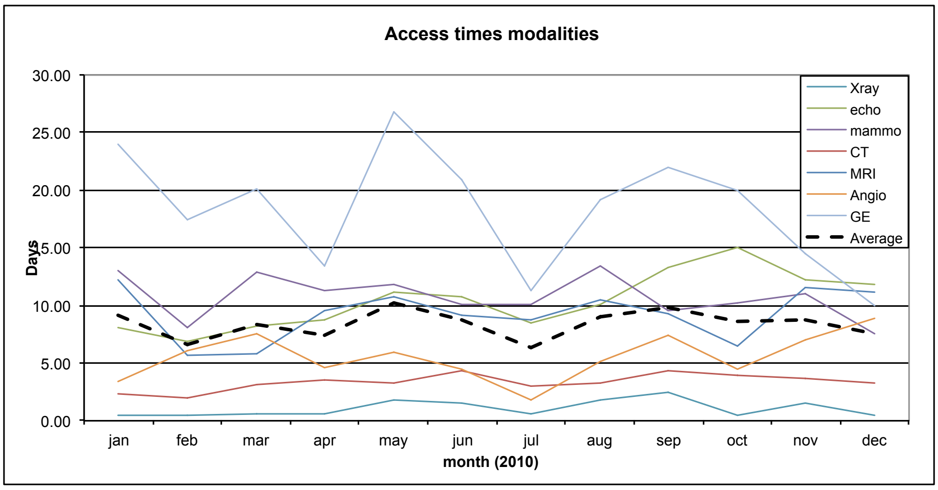
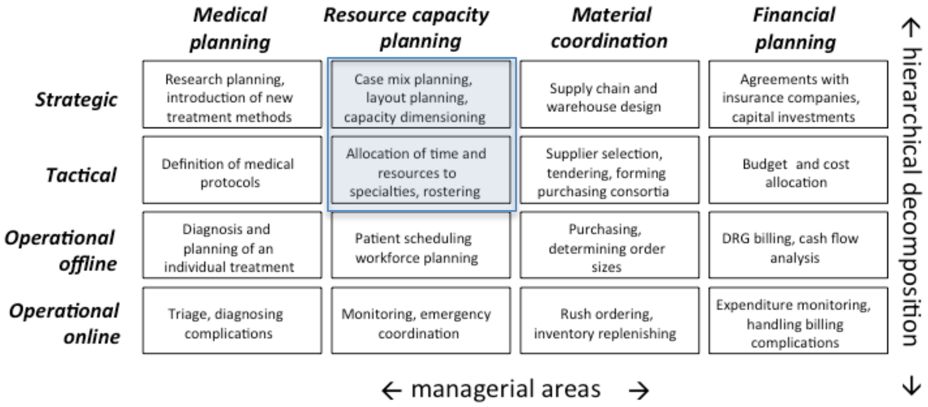


Figure 5: Access times of modalities at Radiology department LUMC 2010 (derived from: management information system, 2011)

## 2.5 Planning & Control

According to Graves (2002), planning and control addresses the coordination of capacity and production flows to realize organizational objectives. In order to give insight into which managerial areas are involved we use a hierarchal framework for health care planning and control (Hans et al., 2011). The framework structures the various planning and control functions and their relations. This helps to identify and position managerial problems. It is a matrix consisting of managerial areas in health care and a hierarchical decomposition of control levels. The managerial areas include; medical planning (decision making by clinicians), resource capacity planning (dimensioning, planning, scheduling, monitoring, and control of renewable resources), materials planning (acquisition, storage, distribution and retrieval of consumable resources/materials), and financial planning (managing costs and revenues).

Hans et al. (2011) use the 'classical' hierarchical decomposition of control levels, often used in manufacturing planning and control. This decomposition applies the following distinction of levels; strategic (defining mission and decision making to translate this into design, dimensioning, and development of the health care delivery process), tactical (the organization of the operations / execution of the health care delivery process), operational offline (short term decision making in advance, e.g. fixed horizon), operational online (the stochastic nature of health care processes demands for reactive decision making, e.g. rolling horizon). This decomposition gives a clear structure of different control levels and is directly related to operations in health care. Large organizations, such as hospitals, have a strong decomposition of hierarchical control levels compared to small flat organizations (e.g. clinics), which do not need many hierarchical levels.



| | Medical planning | Resource capacity planning | Material coordination | Financial planning |
|---|---|---|---|---|
| **Strategic** | Research planning, introduction of new treatment methods | Case mix planning, layout planning, capacity dimensioning | Supply chain and warehouse design | Agreements with insurance companies, capital investments |
| **Tactical** | Definition of medical protocols | Allocation of time and resources to specialties, rostering | Supplier selection, tendering, forming purchasing consortia | Budget and cost allocation |
| **Operational offline** | Diagnosis and planning of an individual treatment | Patient scheduling workforce planning | Purchasing, determining order sizes | DRG billing, cash flow analysis |
| **Operational online** | Triage, diagnosing complications | Monitoring, emergency coordination | Rush ordering, inventory replenishing | Expenditure monitoring, handling billing complications |

Figure 6: Hierarchical framework health care planning and control with example applications (Hans et al., 2011)

### 2.5.1 *Current planning functions*

As mentioned earlier, the current planning functions of personnel are supply-driven. The rostering horizon for personnel depends on the type personnel (e.g. paramedics use different horizon compared to radiologists and administrative employees). This personnel rostering is performed on the tactical control level.

Patients scheduling is performed by administrative employees and depends primarily on available personnel and secondarily on available material (e.g. available time on modalities). Some modalities (CT, X-ray and Angio) have walk-in timeslots, which means that patients can arrive without appointment, but could have to wait some time before treated (scanned).

Current management on a tactical level is negligible. Changes in allocation of resources via block planning to specialties/sections are rare and not based on actual demand (e.g. waiting lists), because there are no structural insights in these figures. Strategic planning mainly focuses on the level of radiologists, purchasing new modalities and special imaging or procedures for prestige.

This project mainly focuses on the upper levels of hierarchical control of the ‘resource capacity planning’ management area (shaded area depicted in figure 6) To centralize the different planning functions in a planning cycle, a new framework is developed that relate all planning activities of Radiology department and introduces new tactical activities. This developing process took place on the strategic level. On a lower control level (the tactical level) the new activities are used to analyze if current resources can meet demand. More details can be found in chapter 3.1.

## 2.6 Performance indicators

To judge whether the proposed interventions of this study actual improve the manageability of waiting lists, performance indicators will be defined. Based on these indicators we are able to objectify the differences in current performance and the performance of the proposed interventions. Based on interviews with most the management of the Radiology department and simulation model preferences the following indicators have been established:

### *2.6.1 Performance indicators*

For the department of Radiology the following indicators are important:

- *Number of procedures performed*
  The main performance indicator is the absolute production level. In a time series analysis this indicator shows an improvement or decline of the overall performance of the department.

- *Access time of patients*
  We define access time as the average time between the date of performance and the application date. This number indicates a performance of the Radiology Department, because the time a patient spends on the waiting list for an image should be minimized in order to create a high service level. Sometimes specialists request an image to be performed over several week or months. This is no access time for a patient, because there are reasons to make the scan on a later point in time instead of as soon as possible (e.g. the patient does not have to wait).

- *Access ratio*
  To analyze whether a waiting list for a modality will change a ratio for the access time per modality will be determined. This generates insight in the arrival rate (e.g. number of arrivals per time unit) and the number of patients served (per time unit), because this ratio will be determined by:
  Access ratio $= \frac{\#\, arrivals}{\#\, served\ patients}$.
  If this ratio is $> 1$, the access time (and queue length) will increase because the number of arrivals is larger than the number of patients served. The other way around, if this ratio is $< 1$ the access time will

decrease. This is valuable information for resource allocation (e.g. block planning) because it is a determinant of waiting lists.

- *Utilization level*

  To determine to which extent the available time on modalities is used for patient care, we will calculate the utilization level. This ratio is calculated as follow:

  Utilization $= \frac{operating\ time}{available\ time}$.

  Through this indicator we are able to judge whether the current tactical planning results in a robust schedule. If the utilization rate is too high, the probability of the number delays will increase. This relation between utilization rate and waiting time is described by the Pollaczek-Khintchine formula (Pollaczek, 1930):

  $EW_q = \frac{\rho}{2\mu(1-\rho)}\left(1 + CV_s^2\right)$ , where:

  $EW_q =$ expected waitingtime

  $\mu =$ expected service time

  $\rho =$ utilization rate $\left(\frac{\lambda}{\mu}\right)$

  $CV_s^2 =$ squared coefficient of variation of the service time

  Since this formula is insensitive for the distribution of the service time, the only requirement is that it has a Poisson arrival process. According to Kendall's notation this is a M/G/1 queue.

  The relation between the waiting time and the utilization rate can be expressed in figure 6 and 7 on the next page.

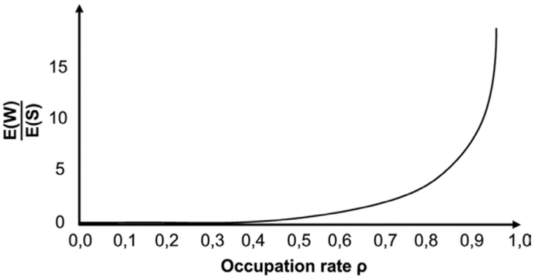


Figure 8: Pollaczek-Khintchine curve. Graphics by (Zonderland, 2009)

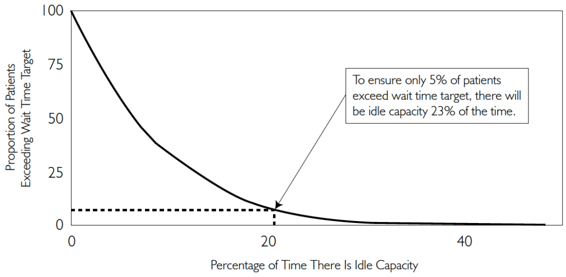


Figure 7: Theoretical relationship between wait time targets and idle capacity (calculations based on a single server exponential queuing model with arrival rate of 10 patients per week, service rate varies between 10 to 16 patients per week and a target of one). Graphics from: (Patrick & Puterman, 2008)

Figure 7 clearly shows that if the utilization rate (e.g. occupation rate) increases, the waiting time will increase (almost exponentially). For efficiency and quality reasons we want to minimize the number of adjustments made in schedules. Another perspective of the relation between the utilization rate and the waiting time given by (Hillier & Lieberman, 2006) is showed in figure 6. This theoretically justifies earlier statements that percentage of idle time $(1-\rho)$ should not exceed 20% to ensure 5% of patients exceed waiting time.

- *FTE per scan hour*
  This efficiency indicator gives insight in the number of FTEs needed (of radiologists, paramedics and administrative personnel) to facilitate one scan hour for each modality. If efficiency of personnel decreases, the ratio will increase. This will give the management of the Department of Radiology a control parameter for personnel.

- *Number of rescheduled patients*
  Based on the used block planning, this indicator shows the level of robustness of the planning tool used for block planning. If the level of delays (e.g. patient will have to come back later) increases, this could imply a less robust planning system. The robustness will decrease because; if delays occur the variability in production will increase if delays occur. Subsequently, this increase in variability will result more disturbances in the planning (e.g. a decrease in robustness of planning systems)

## 2.7 Results context analysis

The problems analyzed in this chapter will be brought together in this bottleneck analysis. As stated in the research objective, the control of waiting lists is difficult for the Radiology department. Health care processes are inherently uncertain because demand varies over time. On the other hand, supply of the Radiology department is almost static (supply driven). This results in dynamic waiting lists. To respond to the stochastic nature of health care processes and the resulting waiting lists, capacity should be allocated based on this demand.

Waiting lists (e.g. queues) occur through exceeding demand or because of variability in the process. This is almost always the case in a cost intensive and specialized environment, such as hospitals. This phenomenal is desirable, because it drives us to use these scarce resources efficiently. With the current supply driven resource capacity allocation it is difficult to control waiting lists, because allocation of resources is segregated of demand. Therefore it is also difficult to establish the required extra capacity. On the other hand, if the demand (and thus the waiting lists) for a modality decreases, it is difficult to determine the amount of capacity that could be allocated elsewhere (e.g. to other modalities). To tackle this problem we will develop a planning cycle, which describes the planning techniques to be taken to improve responsiveness on the stochastic demand. In order to intervene with waiting lists we have also developed a simulation study in which we simulated possible interventions and the behavior of the waiting lists on these interventions.

# 3 Literature review

In this review we focus on topics that relate to the problem statement and bottleneck analysis. In Section 3.1 the theory used for developing the planning cycle is reviewed. Followed by a review of literature on waiting list management (Section 3.2). And in Section 3.3 a specific method for analyzing waiting list is described.

## 3.1 Planning cycle

A planning cycle is an iterative process (annually) that is developed on a strategic level. It addresses all planning related functions and captures their mutual relations. The planning cycle itself will mainly focus on the "in between" planning functions. It incorporates analysis on a tactical level such as forecasting, trend analysis, rough cut capacity planning, block planning and waiting list management. Currently none of these analyses are performed on a frequently basis at the Radiology department.

As mentioned earlier we applied the framework for planning and control in health care (Hans et al., 2011) in order to locate the control level and managerial area of developing the planning cycle. Among stakeholders (management, radiologists, paramedics, schedulers and administrative personnel) consensus was achieved that this activity took place on a strategic level located in the resource capacity managerial area. Although the planning cycle itself will be applied at lower organizational levels (e.g. tactical and organizational), the development of this cycle is a strategic matter, because it encompasses structural decision-making. Via this cycle directions of lower organizational levels will be determined and dimensions the department (prioritization). In order to carry out the cycle, aggregate information is needed in order to determine if strategic resources (e.g. MRI) can meet demand. And which possible interventions are available if capacity cannot meet demand?

## 3.2 Waiting list management

For over half a century, waiting lists have been subject of public and political interests. Therefore waiting lists also have been subject of a great deal of scientific research (Worthington, 1987). Waiting lists exist as a result of the earlier mentioned phenomena of unbalanced supply and demand and the inherent stochastic nature of health care processes which leads to randomness in demand and throughput (Vanberkel & Blake, 2007). The continuous imbalance between demand and supply and the stochastic nature make it difficult to improve productivity

(Baker et al., 2004). Waiting lists occur particularly in countries with a public funded health care (compulsory health insurance). They are external queues (or buffers) that facilitate a constant arrival of patients and exclude external dynamics. This is called workload control (Land & Gaalman, 1996). These external queues strive us to use health care resources efficient and minimize downtime. Waiting list management aims to optimize the waiting list. Optimizing in this sense means minimizing waiting lists, but remaining a constant arrival of patients (this requires a waiting list). And therefore waiting lists are, up to some extent, a sort of evil good. Waiting list management is a tactical activity, because it requires a sublevel of aggregated information (e.g. data) compared to the strategic level and has a medium planning horizon (year). Waiting list management addresses organizing and/or executing the health care delivery process (Hans et al., 2011). It is based on forecasts and incorporates uncertainty and decisions taken, based on waiting list management, have consequences for the lower control levels (e.g. operational off- and online).

Until 2001 fixed budgets were used in order to allocate (financial) resources among health care providers in the Netherlands. For this reason, waiting lists were managed focusing on the supply side (e.g. increasing supply) to reduce waiting lists (van de Vijsel et al., 2011). This implies that costs were not related to production and therefore there were no (financial) incentives to improve productivity. Starting in 2001, the budget system has been revised. Fixed budgets were replaced by output driven budgets and specialists' fees were (partly) related to the production of a hospital. This new budget framework did have promising initial outcomes. Unfortunately, after a year the waiting lists tended to increase again. This increase is a result of supplier-induced demand (e.g. technologies innovations facilitating new treatments) and a lower entry barrier (Emery, Forster, & Shojania, 2009; van de Vijsel et al., 2011). Because of short waiting lists, specialists and general practitioners refer patients more easily. They create their own waiting list of patients based on priority. When the waiting lists at a hospital are declining, GPs and specialist will refer more patients from their own waiting list. This is called a decreased entrance barrier.

To improve balance between demand and supply other interventions were taken. Examples are decreased service times or controlling demand. Decreasing service time (e.g. increasing efficiency) had the same temporarily outcome as the earlier mentioned intervention of increasing supply. The reasons for this were in line with the intervention of increasing supply. The last intervention (controlling demand), however, is an ethical discussion. It implies changing behavior of referral parties (e.g. specialists and general practitioners) for transparent and coherent (medical) decision-making. This last intervention is difficult to control and/or manage. Therefore it is a long-term intervention.

One of the most recent subjects in waiting list management research is the setting of advanced access systems and walk-in systems. These are systems in which (almost) no appointments are needed to use resources of hospitals (for example MRI and CT). Patients just can walk-in for the service they need, after referral. In The Netherlands research focusing on walk-in systems has been performed at several hospitals (Gilles et al., 2007; Kranenburg et al., 2009).

Bailey (1952) pioneered using Operations Research (OR) techniques to analyze and predict waiting lists' behavior (e.g. queues in health care). From this point on, scientific research using OR techniques analyzing waiting lists increased. Unfortunately, literature on waiting lists of Radiology services is limited compared to waiting lists of surgical procedures (Brasted, 2008).

Literature that analyzes queues using OR theory, can basically be classified in two techniques; analytical and simulation models. This literature review will further focus on these models.

### *3.2.1 Analytical models*

Analytical models can be further classified as; queuing models, Markov chains and other.

Since Bailey (1952), system analysis in health care using queuing models has increased (Fries, 1976) (Jacobson et al., 2006). Because classical queues are not directly applicable in health care a lot of research is focused on queues adjusted to health care settings. For instance the implication of variable arrival rates on the queue length (Worthington, 1987), (Cochran & Broyles, 2010), (Roche et al., 2007) (Rosenquist, 1987). Priority queuing disciplines are also subject of research in health care (McQuarrie, 1983) (Siddharthan et al., 1996), (Haussmann, 1970) (Mullen, 2003).These priorities are based on different patient classification, such as inpatients versus outpatients or urgent patients versus non-urgent patients. Also different priority disciplines are compared to the first-come first-serve principle (Goddard & Tavakoli, 2008). Queuing models render a more simplistic view on reality than simulation models do. Besides, they require less data. When models incorporate a network of several queues, they become very hard to solve. The Radiology department could be modeled as a network of queues. Including all specific characteristics (e.g. opening and closing time of department) of the Radiology department in a queuing model, it would be very hard to solve. For instance, one specific characteristic that should be incorporated in the model is the level of throughput of the department. This depends not only on the number of servers, but also on the number of available personnel that should utilize these servers (which is dynamic over a week). Incorporating this dynamic throughput is difficult.

Markov chains are also frequently used in scheduling patients (admissions) from waiting lists. The Markov chain incorporates a transition matrix representing transition probabilities from one state to another. Markov chains are random processes that are memoryless (Markov property). This implies that the next state depends only on the current state and not on earlier states. For instance, Kolisch and Sickinger (2007) used this technique to model a scheduling problem for two CT-scanners incorporating different patient groups with different arrival rates and costs. Other research focused on scheduling problems of MRI (Green et al., 2006) or X-ray (Lev et al., 1976). Other applications of Markov chains in healthcare are numerous. For instance, in order to control elective admissions to prevent idleness or extreme demand Markov chains can be used (Nunes et al., 2009). Markov chains provide a steady state policy that can be used in decision-making. For modeling the Radiology department as Markov chains the same arguments are applicable as if using queuing models (specific characteristics of the department are hard to solve or require a change of model).

Other techniques such as; dynamic programming, (non)linear programming or stochastic programming were used less often (Cayirli & Veral, 2003). The limiting factor of this mathematical programming is, analyzing a complete department, that it will require many instances and become complex. Incorporating all different classes of patients, arrival rates, queue disciplines, specialties, servers, paths, modalities, service times, etcetera it will be difficult to find any optimum (local or global respectively). Incorporating all interventions as mentioned earlier will also be more difficult to implement in analytical models. Therefore we did not use this technique.

### 3.2.2 *Simulation models*

Because of the complexity of health care processes it could be difficult to analyze these processes through queuing theory (Carter, 2002). Simulation models on the other hand, can incorporate complex process flows with random arrival rates, service times and servers. Simulation models also help us to analyze behavior of a system and evaluate various strategies, generally typed as "what-if?" questions (Jacobson et al., 2006). The technique is used for analyzing many different settings. A disadvantage of a simulation study is its experimental nature, and therefore results cannot be guaranteed to greater than its statistical limits (Tofts, 1998). And therefore elaborate validation of the model is essential. As we looked at the dynamics that have to be simulated, there was overall consensus that the complete department needed to be analyzed in order to support the integral planning cycle. To analyze complete system dynamics for strategic or managerial (e.g. tactical) purposes, simulation techniques fit best (Jun et al., 2011). A thorough and comprehensive study among applications of simulation studies (N = 1200) in health care was performed (England & Roberts, 1978). They categorized the reviewed studies into 21 areas of application and derived general model characteristics. One area, a Radiology department, was classified as follows; *"a multichannel queuing model where patients arrive randomly to a queue in a single line and await service by multiple servers. Different patients may require different service times. Output measures include queue length, waiting time and utilization".* This is the essence of simulation studies on a Radiology department. Analyzing waiting list management is often performed through simulation, because of its complex and integral (modality transcending or even department transcending) modeling approach.

To model the Radiology department we came to consensus that a simulation study serves best the needs of this department. Of course, this model will apply other techniques such as queues and/or Markov chain techniques in order to develop a representative model of this department.

## 3.3 Discrete event simulation

Production simulations are mainly performed with discrete-event simulators. This special type of simulation study implies a chronological sequence of events. The simulator "jumps" from event (state change) to event in discrete time intervals (Law, 2007). A state change is a change in a variable of the model, for instance 'arrival of patient'.

Law (2007) outlines necessary key steps to perform a simulation study. We used these steps to perform out study:
1. Problem analysis and a plan of the study
2. Collection of data and conceptual model design
3. Model validation

4. Constructing a computer representation of the model
5. Model verification
6. Experimental design
7. Production runs
8. Statistical analysis of results
9. Interpretation of results

### 3.3.1 *Input variables*

In this section we describe the required input variables for the simulation model. As stated earlier, a Radiology department should be modeled as a multichannel queuing system with random arrival rates of patients to queues and waiting different services by multiple servers with different services times (England & Roberts, 1978). Others present a general taxonomy of methodologies used in simulation studies based on a comprehensive literature review (Cayirli & Veral, 2003). They outline external factors that influence scheduling systems, such as a Radiology department and queues as a part of this department;

Table 1 Problem definition and formulation (Cayirli & Veral, 2003)

1. Nature of Decision-Making
   1.1 Static
   1.2 Dynamic
2. Modeling of Clinic Environments
   2.1 Number of services
   2.2 Number of doctors
   2.3 Number of appointments
   2.4 Arrival process
      2.4.1 Patient punctuality
      2.4.2 Presence of no-shows
      2.4.3 Presence of regular and emergency walk-ins (preemptive or non-preemptive)
      2.4.4 Presence of companions
2.5 Service times (empirical of theoretical distribution)
2.6 Lateness of doctors
2.7 Queue discipline (FCFS, by appointment time, priority)

We used these variables as initial setup for our simulation model. We disagree on the first factor that a choice must be made between both (static or dynamic) natures developing a simulation model. In the model developed we used both offline (static) as well as online (dynamic) policies, because both are present at the Radiology department. We made a clear distinction between both natures, because we agreed that both natures demand different approaches and techniques.

### 3.3.2 *Throughput system*

A throughput system is the actual model build. Focusing on logistical behavior of the system, with special interest for waiting list management, an appointment system with "good performance" is vital.

Because an appointment system brings demand and supply together. If this system is not well coordinated the department could be operating inefficient. Cayirli & Veral (2003) also developed taxonomy for appointment systems. Based on this outline the appointment systems implemented in the simulation model will be classified. They present the taxonomy as stated in table 2;

Table 2: Appointment system taxonomy (Cayirli & Veral, 2003)

1. Appointment rule
  1.1 Block size
    1.1.1 Individual
    1.1.2 Multiple
    1.1.3 Variable
  1.2 Appointment interval
    1.2.1 Fixed
    1.2.2 Variable
  1.3.Initial block
    1.3.1 With
    1.3.1Without
  1.4 Any combination above
2. Patient classification
  2.1 None (homogeneous patients)
  2.2 Use patient classification for:
    2.2.1 Sequencing patients at time of booking
    2.2.2 Adjusting appointment intervals to match service time characteristics of classes
    2.2.3 Any combination above
3. Adjustments
  3.1 For no-shows
    3.1.1 None
    3.1.2 Overbooking extra patients to predetermined slots
    3.1.3 Decreasing appointment intervals proportionally
  3.2 For walk-ins, second consultations, urgent patients, emergency patients
    3.2.1 None
    3.2.2 Leaving predetermined slots open
    3.2.3 Increasing appointment intervals proportionally
  3.3. Any combination above

Per modality different appointment systems are applied. Based on above taxonomy the different appointment systems will be implemented in the simulation model.

### 3.3.3 *Output variables*

Outputs of simulation model are the performance indicators, also called decision variables. Based on these indicators we are able to judge whether a new strategy/intervention could be an improvement. Still a model is a simplification of reality, and therefore we have no complete guarantee the strategy/intervention will work out as promised. As earlier mentioned, England & Roberts (1976) stated that important outputs of a Radiology department are; queue length, waiting time and utilization. Cayirli and Veral (2003) developed an even more comprehensive list of performance measures for a Radiology department;

Table 3: Outputs of simulation model (Cayirli & Veral, 2003)

1. Cost-based measures
   1.1 Waiting time of patients
   1.2 Flow time of patients
   1.3 Idle time of doctor(s)
   1.4 Overtime of doctor(s)
2. Time-based measures
   2.1 Mean, Maximum and frequency distribution of patients' waiting time
   2.2 Mean, variance and frequency distribution of doctors' idle time
   2.3 Mean, maximum and frequency distribution of doctors' over time
   2.4 Mean and frequency distribution of patients' flow time
   2.5 Percentage of patients seen within 30 minutes of their appointment time
3. Congestion measures
   3.1 Mean and frequency distribution of number of patients in queue
   3.1 Mean and frequency distribution of number of patients in system
4. Fairness measures
   4.1. Mean waiting time of patients according to their place in the clinic
   4.2 Variance of waiting times
   4.3 Variance of queue sizes
5. Others
   5.1 Productivity (doctors)
   5.2 Mean doctor utilization
   5.3 Delay between requests and appointments
   5.4 Percentage of urgent patients served
   5.5 Likelihood of patients receiving the slots they requested
   5.6 Clinic effectiveness

# 4 Planning cycle

Through intensive debate with stakeholders (planning related personnel and management team), a planning cycle was developed for the Radiology department that analyzes the midterm capacity planning (horizon of one year respectively). The outcome of the developing process is a flow chart incorporating all planning activities on the tactical and operational hierarchal levels.

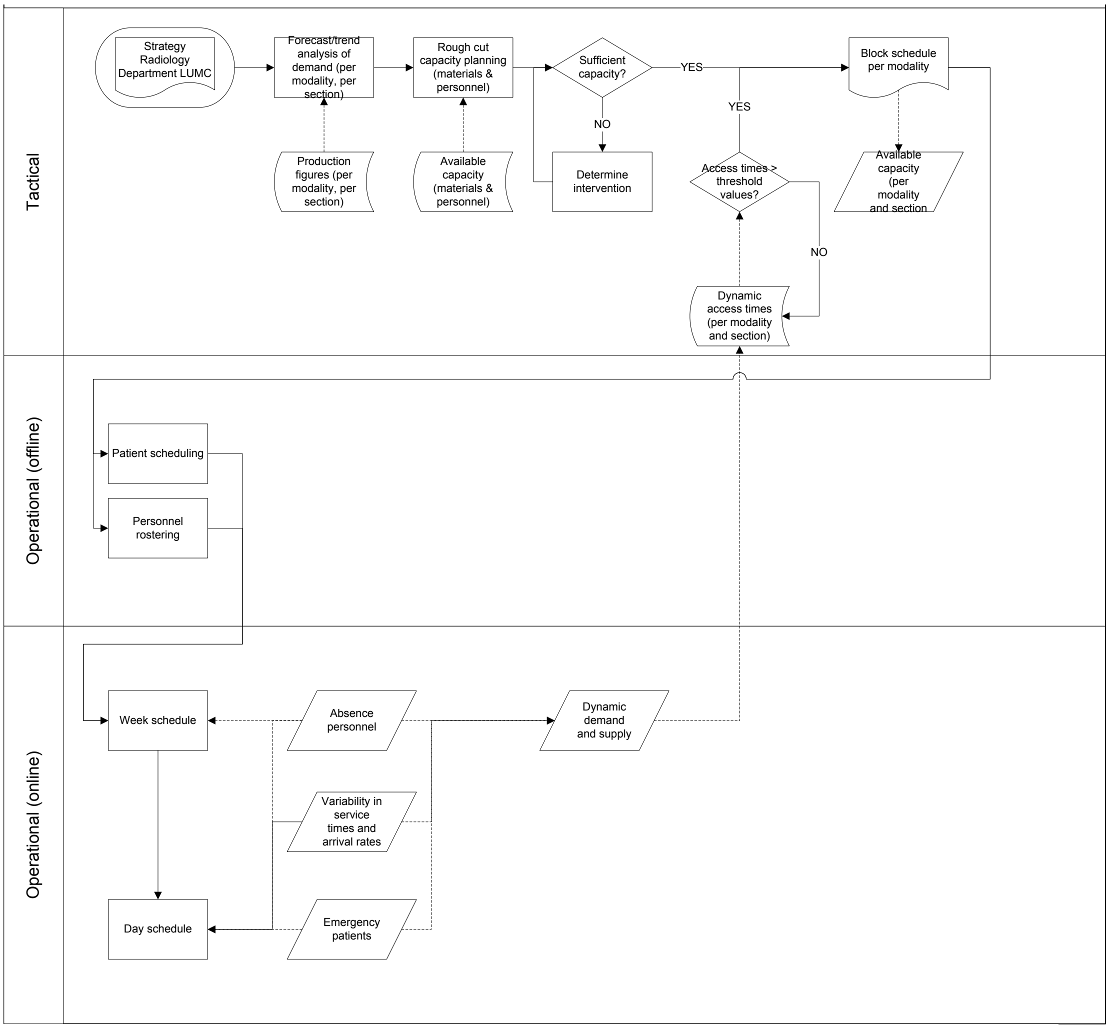


Figure 9: Planning cycle Radiology department LUMC

The planning cycle, as depicted above, starts with the strategy of Radiology department as input. This input is important because the strategy influences lower control levels. For this reason, planning has to take this in to account. For instance, if the Radiology department states in its strategy it wants to become market leader of a specific procedure (because, for example, it generates significant income or prestige) this should also be implemented in lower control levels.

Using the strategy as a starting point for this cycle, the next step is forecasting the demand for the coming year. Both qualitative and quantitative techniques will be used in order to generate a reliable prediction for the production of the department during the coming year. These predictions are mainly focused on growth (positive or negative) and mutual shifts between sections and modalities.

When the demand is clear, this demand should be related to capacity of the department. In other terms, the demand dimensions the capacity. This step of the planning cycle roughly distributes capacity among modalities and sections and should raise the following questions: Should capacity be shifted within the department? Is there enough capacity available? If capacity cannot meet the demand interventions should be taken to create equilibrium.

The distribution of capacity among modalities and sections results in block schedules for each modality. These block schedules determine the available amount of time a section will have on a certain modality and so the level of required personnel (radiologists, paramedics and administrative employees). In the planning cycle this block planning will become an important tool to actively manage the department's production. Because the block schedule is a dynamic schedule, it will be updated every quartile depending on the waiting lists.

These block schedules influence the rostering of personnel and the patients scheduling. Depending on the required image or intervention, patients can only be scheduled within the relevant blocks of the block schedule. So block schedules influence the patient schedules and personnel rostering, while these activities will influence the week- and day schedules. Block schedules will therefore also indirectly influence these week- and day schedules. In summary, demand and supply will vary over time. This varying demand and supply influence the waiting lists. The waiting lists will be managed actively via updating the block schedules every quartile. This implies shifts in capacity depending on increasing or decreasing waiting lists for modalities and sections (demand driven control). Ultimately, this planning cycle should lead to an improvement of production performance of the Radiology department. As can be seen in the flow chart, there is decision diamond for waiting lists. This repetitive decision (every quartile) will determine if waiting lists have to be managed actively (e.g. waiting lists increases to high) via adjustments in the block schedule. In order to determine how much block schedules should be adjusted to manage the occurred waiting lists, the waiting lists' behavior will be analyzed via a simulation study and will be described in the following chapter. A more elaborate description of all activities within the planning cycle is presented in Appendix A (in Dutch).

# 5 Experimental Approach

This chapter formulates the interventions we would like to analyze in our simulation model in order to improve waiting list management (Section 5.1). Followed by a description of the conceptual model in Section 5.2, which we used to represent the department's behavior. Appendix B shows the layout of simulation model as is developed in the software.

## 5.1 Potential interventions waiting list management

Waiting lists management aims to align demand and supply constrained by limiting factors. As described earlier waiting lists are queues as result of exceeding demand (compared to supply), inferior capacity utilization through planning and scheduling (incorporating variability), supplier induced demand and external queues of first line specialists. Dealing with a complete department and for the sake of this project it was too intensive, and therefore not efficient, to analyze all different planning and scheduling techniques used and to improve those. Currently all modalities use different scheduling techniques, different blocks for appointments and walk-in patients, and different personnel settings. As personnel are assigned to multiple modalities or sections (even during a single day) it is important to integrally model the department's capacity. In order to manage waiting lists, their behavior should be analyzed. To analyze this behavior several scenarios are described of which we think they influence the behavior of waiting lists (e.g. decrease or increase).

Consensus was achieved among the management team on the potential intervention in order to manage waiting lists. The following interventions were formulated:

1. Extension of operational hours
   *The effect of extending the operational hours with 1 hour per modality per day.*
2. Additional staffing
   *Adding 1 staff to the pool of staff members per modality per day.*
3. Efficiency improvement of service times (e.g. 10% shorter service times)
   *The effect of shorter service times per modality.*
4. Decrease required FTE per scan (e.g. from 1.5 to 1.0 FTE)
   *Some modalities require more than 1 staff to perform a procedure. We will investigate the effect of decreasing this number per modality.*

## 5.2 Conceptual model

We developed a conceptual model of the Radiology department. A conceptual model aims to include only system behavior that matters for the purpose of a study. We used the work of (Robinson, 2004) and (Law, 2007) as guidelines for developing the model. Based on these two sources we derived the following states during the development of the conceptual model: objective, input (data collection), content (level of detail), output (performance measures), assumptions (validation) and simplifications.

### *5.2.1 Model objective*

The model objectives are derived from the problem as described in Chapter 2 (Context and Scope respectively).

- The model gives a reliable representation of the patient flow processes and report flow processes at the Radiology department in the LUMC. This includes arrival rates, service times and patient/scan characteristics.
- The model incorporates the stochastic nature of arrivals of patients and service times.
- The model output is unambiguous, and gives insight in access time, access time ratio, waiting time of emergencies, utilization, production, and number of rescheduled patients.
- The model must incorporate the level of detail required, flexibility, logically build and therefore easy to use. Parameters must be easy to change to easily implement different interventions.
- The model must be generable in order to analyze other Radiology departments.

### *5.2.2 Input*

In order to perform a reliable analysis on the effects of the interventions on waiting list we determined the input variables based on the work of Cayirli and Veral (2003):

- Capacity
  - Number of servers per modality: the number of servers is the amount of modalities available at the Radiology department of a certain modality group. Assumed is that all servers of a modality group are interchangeable.
  - Number of radiologists: the number of radiologists is determined per section (body part) and based on the initial week roster of radiologists and measured by FTE.
  - Number of paramedics: the number paramedics (e.g. radiographers) is determined per modality and based on the initial week roster of paramedics and measured by FTE.

- Patient attributes
    - Classification: as mentioned in Chapter 2, the model incorporates three different patients classes with different queuing disciplines: walk in patients, patients with an appointments, and emergency patients. The order of classes just mentioned is also used for the priority rule with an increasing order respectively. Patients of the same class are prioritized on the First Come First Serve principle.
    - Service times: depending the class of patients, the modality and section required a service time is generated according to a theoretical distribution. This distribution is derived from empirical data. This service time includes the total time needed for patient from the moment he or she enters the room till the moment he or she leaves. No specific properties were included such as; preparation time for contrast.
    - Arrival rates of patients/appointment requests depend on classes, modality, and section level. The arrival rates used are static because it was too intensive analyzing all different arrival rates of all different patient classifications.

- Scan file attributes (attributes of a made scan)
    - Classification: scan files are classified on section and modality.
    - Service times: scan interpretations by radiologists require different processing times depending on modality and section. Because of lacking available data, the service times for interpretation are determined via so called Sanders points and therefore deterministic.

- Appointment scheduling
    - This model incorporates a simple heuristic. Each appointment request comes with a certain time interval from which the appointment should be scheduled, for instance a request with the time interval ‘week’ means that the appointment should be scheduled not earlier than next week. The heuristics accounts for the time available per day per modality if a new request arrives. When the request cannot be planned on the first requested day of this modality, because there is no time available, the heuristic will go to day $i + 1$ until there is a day were the appointment can be scheduled. A requested consists of a time interval, a modality and section. An expected service time will be determined based on the requested modality and section, which will be used to schedule the request.

    - This heuristic does not incorporate predetermined blocks on modalities for sections. So every patient can be treated the whole day if paramedic(s) and or radiologist(s) is/are available
    - If walk in patients are still waiting at the end of day, they will get an appointment 'as soon as possible'.

### 5.2.3 *Content*

Based on the schematically simplified process flows at the Radiology department, see section 3.2, we set out, per location, all actions taken in the model.

- Request arrival;
    - Assign patient characteristics.
    - Depending on type of patient route to: appointment list (modality specific) or online appointment system.

- Appointments (offline) system;
    - Assign appointment interval (e.g. from which point in time is the procedure requested, for instance a week or a month etcetera), based on an empirical distribution.
    - Determine first opportunity for this appointment and schedule patient for this day.

- Appointments (online) system;
    - If server is available, check if appointments are made for this day and this modality.
    - If walk in or emergency patient arrives route patient to modality.

- Waiting room
    - Sort patient based on earlier mentioned priority rule.
    - Leaving waiting room:
    - If enough time is available (closing time modality)
    - If combined procedure
        - Check if radiologist is available
        - Check if paramedic is available
        - Determine procedure time
        - Route patient to available server(s) of modality
        - If walk in or emergency patient determine waiting time
    - Else (not combined procedure)
        - Check if paramedic is available
        - Determine procedure time
        - Route patient to available server(s) of modality
        - If emergency patient determine waiting time

- Modality
    - Determine start time of procedure
    - Perform procedure with assigned procedure time
    - When finished:
        - Determine outputs (performance indicators)
        - If procedure is not combined (radiologists not needed during procedure):
            - Send scan file to section.
            - Route patient to 'drain'.
            - Paramedic(s) becomes available.
        - Else
            - Route patient to 'drain'.
            - Radiologist becomes available.
            - Paramedic(s) becomes available.

- Section
    - Determine start time
    - Analyze scan file
    - When finished:
        - Determine time section was used
        - Send scan file to drain

- Drain
    - Patient/scan leaves department

### 5.2.4 *Output*

The outputs of the model are the performance indicators mentioned in chapter 3.6.

### 5.2.5 *Assumptions and simplifications*

In this section we will describe all assumptions and simplifications we made and are therefore not further tested, but validated using logical thinking.

- Static arrival rates are not realistic. Therefore many other studies used dynamic arrival rates (arrival rates change during the day of week). For the sake of this project we assume that static arrival rates can be used and give reliable results, as we are not dealing with a scheduling problem but with a resource capacity problem. Therefore the influence of this assumption, as we think, will be marginal. Also other studies could present reliable results using static arrival rates

(Bruin et al., 2007). Another assumption on the arrival rates is that they fit the Poisson distribution. Also this assumption for the arrival process is used in many other studies. Using static arrival rates also implies that no seasonality will be incorporated.

- Downtime during a day is assumed to be identical among all modalities and sections. We incorporated downtimes as a total sum of all breaks (of personnel) during the day and we subtract this from the total time available. This results in a total downtime of 45 minutes per day per modality.
- Lateness of radiologists and paramedics is assumed to be negligible.
- Patients are assumed to be always on time, because we do not generate a day-to-day schedule for patients, but only assign patients to a certain day and not to a specific time of this day.
- To perform a procedure it is assumed only a paramedic and/or radiologists are needed. This assumption covers most of the procedures at the Radiology department. For interventions anesthesia staff is needed, but as these staff comes from another department, they are not included.
- All modalities open (8.00 AM) and close (4.15 PM) at the same time.
- The department operates 50 weeks per year.
- All servers of a modality are assumed to be interchangeable and identical.
- No time is incorporated for the transfer from the waiting room to the modality.
- Preparation time is included in the service time.
- The modality X-ray is not included, because this modality has no access time as a result of the ‘appointment system/rule’ used.
- Failure time is not included, because data was not available and experts found it difficult to give a reliable number of interval and duration (e.g. repair time) of failures.

# 6 Computational experiments

This chapter describes how the experiments of the simulation model were constructed, validated, verified and performed and finally presents the results from these experiments.

## 6.1 Input data analysis

To create useful input data for the simulation model, we quantify the input parameters. This quantification is based on data analysis as presented below.

*Arrival rates*

As stated in section 4.2.1 we use static arrival rates for this model. We generated three arrival rates according to earlier specified patient classification; *appointment patients, walk-in patients and emergency patients.* Based on historical data and performing a trend analysis, the expected total number of arrivals for the year 2011 could be determined. This total number of arrivals per patient class is divided by the total operating time (minutes) of the Radiology department in one year. This ratio gives the mean inter-arrival time $\lambda_i$ (with $i$ for every patient class).

Further patient characteristics (modality and section selection) were determined via empirical distributions based on historical data of the year 2010.

*Service times*

In order to determine the service times of modalities and or sections, the service times of the month June 2011 were fitted to a theoretical distribution and tested. Unfortunately the service times of the sections (interpreting a scan by a radiologist), derived from the MIS, were not representative for the actual service times. This was caused through unreliable time measures of the MIS. The number of incorporated distributions in the simulation software package Tecnomatrix Plant Simulation of Siemens, which was used to perform the simulation study, limited the number of potential theoretical distributions. Via the software package Model Risk of Vose Software the data was fitted to potential distributions, followed by nonparametric statistical testing using the software package XLStat of Addinsoft to determine if the theoretical distribution fits the data significantly. Selection of theoretical distributions was based on two criteria; the Bayesian information criterion (or Schwarz criterion) and the Akaike information criterion. Schwarz criterion is a selection index aiding the choice between competing distributions and is partly based on the likelihood function.

The formula for Schwarz information criterion (SIC) is (Liddle, 2007):
$SIC = -2L_m + m \cdot \ln(n)$ where:
$n =$ number of observations
$L_m =$ maximized value of the log-likelihood function for the estimated model
$m =$ number of parameters in the model

The Akaike information criterion (AIC) is closely related to the BIC and the formula is given below (Akaike, 1974):
$AIC = 2k - 2\ln(L)$, where:
$k =$ number of parameters
$L =$ maximized value of the likelihood function for the estimated model

The statistical testing was based on the Pearson's Chi-square ($\chi^2$)- and the Kolmogorov-Smirnov (K-S) Goodness-of-fit tests. Both tests can be used to determine if a sample significantly represents a population with a specific distribution. The difference between the tests is that the K-S test is restricted to continuous distributions, while the Chi-square test also can be applied to discrete distributions. No discrete distributions were tested during the data fitting, so both tests were applied.

Some remarks should be placed on the service times. While validating the service times with stakeholders, caution was applied by the time measurements of the MIS. This measurement is subject to human 'mistakes' (personnel) and could influence the accuracy of data derived from the MIS. Another remark is that the MIS not fully accommodates the workflow processes at the Radiology department. For instance, post processing of made scans is no separate step of the MIS, while in reality it is. This means that paramedics leave patients on the modality (in the MIS) till post processing is finished. Otherwise the scans will become directly available for radiologists in the Picture Archiving and Communication System, while post processing should be performed in advance. This results in longer (and unreliable) service times, while patients already left the modality.

The remarks stated above also account for the service times of radiologists interpreting the images. According to the MIS, an interpretation of a scan could be finished after a couple of days. The MIS accounts all these days just for interpreting a single scan, while in reality radiologists interprets a scan in less then 50 minutes. Therefore the time measurements of the MIS for service times of radiologists were so unreliable, these could not be used for the simulation model. The only other option available was to use a theoretical service time. This theoretical service time is based on, so called, Sander points. Sander points is a national system of registration for procedures performed (interpreting images) by radiologists. Each procedure is associated with a number of points. The number of point is a reflection of the time and the burden of the procedure performed by a radiologist. One Sander point equals one minute. These theoretical service times are expected to be more representative and are also currently used in management decision-making.

*Number of servers*

The simulation model included the current level of servers per modality.

*Number of personnel*

This model also incorporates the level of manpower for the day of the week. As mentioned earlier, this is important for the throughput level of the department because this depends both on the number of servers and the level of manpower. All input variable are summarized in table 5.

Table 4: Quantifiable theoretical input variables simulation model (all distribution were tested using an alpha of .05)

*Input variables*

| Input variable | Input type | Description | Estimators | Values | Test / criterion values |
|---|---|---|---|---|---|
| $\text{Service}_{\text{GE-2\&3}}$ | Lognormal distribution | Service times at GE modality for sections 2 & 3 | $\hat{\mu} = 3.498$<br>$\hat{\sigma} = 0.650$ | $E[X] = 40.822$<br>$Var\ (X) = 843.322$ | $\chi^2 =$ .466 K-S = .944<br>SIC = -527.498 AIC = -523.595 |
| $\text{Service}_{\text{mammo-3}}$ | Lognormal distribution | Service times at Mammo modality for section 3 | $\hat{\mu} = 3.004$<br>$\hat{\sigma} = 0.668$ | $E[X] = 22.223$<br>$Var\ (X) = 357.739$ | $\chi^2 =$ .257 K-S = .386<br>SIC = -1754.352 AIC = -1747.648 |
| $\text{Service}_{\text{angio-5}}$ | Lognormal distribution | Sevice times at Angio modality for section 5 | $\hat{\mu} = 4.052$<br>$\hat{\sigma} = 0.817$ | $E[X] = 78.289$<br>$Var\ (X) = 4511.810$ | $\chi^2 =$ K-S =<br>SIC = -1768.920 AIC = -1762.757 |
| $\text{Service}_{\text{CT-1}}$ | Gamma distribution | Service times at CT modality for section 1 | K = 1.92<br>$\beta = 6.12$ | $E[X] = 11.750$<br>$Var\ (X) = 71.912$ | $\chi^2 =$ .249 K-S = .382<br>SIC = -2451.515 AIC = -2444.026 |
| $\text{Service}_{\text{CT-2}}$ | Lognormal distribution | Service times at CT modality for section 2 | $\hat{\mu} = 2.965$<br>$\hat{\sigma} = 0.509$ | $E[X] = 11.211$<br>$Var\ (X) = 33.989$ | $\chi^2 =$ .326 K-S = .509<br>SIC = -444.523 AIC = -446.582 |
| $\text{Service}_{\text{CT-3}}$ | Lognormal distribution | Service times at CT modality for section 3 | $\hat{\mu} = 2.981$<br>$\hat{\sigma} = 0.671$ | $E[X] = 15.544$<br>$Var\ (X) = 68.724$ | $\chi^2 =$ .441 K-S = .429<br>SIC = -1858,394 AIC = -1851.563 |
| $\text{Service}_{\text{CT-4}}$ | Lognormal distribution | Service times at CT modality for section 4 | $\hat{\mu} = 2.981$<br>$\hat{\sigma} = 0.671$ | $E[X] = 11.894$<br>$Var\ (X) = 36.237$ | $\chi^2 =$ .567 K-S = .730<br>SIC = -3355,507 AIC = -3347.445 |
| $\text{Service}_{\text{CT-5}}$ | Lognormal distribution | Service times at CT modality for section 5 | $\hat{\mu} = 5.782$<br>$\hat{\sigma} = 0.821$ | $E[X] = 50.58$<br>$Var\ (X) = 1303.932$ | $\chi^2 =$ .321 K-S = .573<br>SIC = -2295,703 AIC = -2247.545 |
| $\text{Service}_{\text{echo-2\&4}}$ | Lognormal distribution | Service times at echo modality for sections 2&4 | $\hat{\mu} = 3.171$<br>$\hat{\sigma} = 0.514$ | $E[X] = 19.113$<br>$Var\ (X) = 34.692$ | $\chi^2 =$ .083 K-S = .104<br>SIC = -7399.389 AIC = -7389.707 |
| $\text{Service}_{\text{MRI-1}}$ | Lognormal distribution | Service times at MRI modality for section 1 | $\hat{\mu} = 3.922$<br>$\hat{\sigma} = 0.562$ | $E[X] = 36.121$<br>$Var\ (X) = 843321$ | $\chi^2 =$ .154 K-S = .218<br>SIC = -2182.495 AIC = -2175.689 |
| $\text{Service}_{\text{MRI-2}}$ | Lognormal distribution | Service times at MRI modality for section 2 | $\hat{\mu} = 4.018$<br>$\hat{\sigma} = 0.438$ | $E[X] = 40.612$<br>$Var\ (X) = 390.063$ | $\chi^2 =$ .158 K-S = .967<br>SIC = -1124.765 AIC = -1119.279 |
| $\text{Service}_{\text{MRI-3}}$ | Lognormal distribution | Service times at MRI modality for section 3 | $\hat{\mu} = 4.763$<br>$\hat{\sigma} = 0.521$ | $E[X] = 44.271$<br>$Var\ (X) = 1185{,}425$ | $\chi^2 =$ .158 K-S = .967<br>SIC = -1045.765 AIC = -2239.963 |
| $\text{Service}_{\text{MRI-4}}$ | Lognormal distribution | Service times at MRI modality for section 4 | $\hat{\mu} = 4.156$<br>$\hat{\sigma} = 0.335$ | $E[X] = 41.017$<br>$Var\ (X) = 501.312$ | $\chi^2 =$ .204 K-S = .946<br>SIC = -639.467 AIC = -635.212 |

Table 5: Quantifiable empirical input variables simulation model

*Input variables*

| Input variable | Input type | Description | Values |
|---|---|---|---|
| $P_{Angio}$ | Empirical distribution | Frequency a random arrived request is an Angio procedure | .04 |
| $P_{CT}$ | Empirical distribution | Frequency a random arrived request is an CT procedure | .27 |
| $P_{MRI}$ | Empirical distribution | Frequency a random arrived request is an MRI procedure | .16 |
| $P_{Mammo}$ | Empirical distribution | Frequency a random arrived request is Mammo procedure | .09 |
| $P_{Echo}$ | Empirical distribution | Frequency a random arrived request is an Echo procedure | .32 |
| $P_{GE}$ | Empirical distribution | Frequency a random arrived request is an GE procedure | .12 |
| $P_{CT-1}$ | Empirical distribution | Frequency a random arrived request for CT is for section 1 | .32 |
| $P_{CT-2}$ | Empirical distribution | Frequency a random arrived request for CT is for section 2 | .06 |
| $P_{CT-3}$ | Empirical distribution | Frequency a random arrived request for CT is for section 3 | .19 |
| $P_{CT-4}$ | Empirical distribution | Frequency a random arrived request for CT is for section 4 | .35 |
| $P_{CT-5}$ | Empirical distribution | Frequency a random arrived request for CT is for section 5 | .08 |
| $P_{MRI-1}$ | Empirical distribution | Frequency a random arrived request for MRI for section 1 | .50 |
| $P_{MRI-2}$ | Empirical distribution | Frequency a random arrived request for CT is for section 2 | .25 |
| $P_{MRI-3}$ | Empirical distribution | Frequency a random arrived request for CT is for section 2 | .10 |
| $P_{MRI-4}$ | Empirical distribution | Frequency a random arrived request for CT is for section 4 | .15 |
| $P_{EM-angio}$ | Empirical distribution | Frequency a random arrived emergency patient is for angio | .03 |
| $P_{EM-CT}$ | Empirical distribution | Frequency a random arrived emergency patient is for CT | .72 |
| $P_{EM-Echo}$ | Empirical distribution | Frequency a random arrived emergency patient is for echo | .25 |
| $\lambda_{app}$ | Poisson distribution | Arrival rate of requests for appointment (minutes) | 2.71 |
| $\lambda_{walk-in}$ | Poisson distribution | Arrival rate of walk-in patients (minutes) | 14.14 |
| $\lambda_{EM}$ | Poisson distribution | Arrival rate of emergency patients (minutes) | 160.00 |

## 6.2 Verification & validation simulation model

### 6.2.1 *Model and process verification*

Verification and validation have been associated with computer models as long as they exist and aim to increase credibility of the model. Verification ensures that the computer program is performing as it was intended to perform, while validation ensures that whatever the model purports to represent, it does so accurately (Jagdev et al., 1995). Both phases of the developing process of simulation models can be performed using qualitative as well as quantitative techniques. Qualitative techniques employed in this study are; system observations, a literature review, interviews with stakeholders, structural meetings with management, walkthroughs and using available expert knowledge. Finally consensus was achieved among management of the Radiology department what should be included and or excluded from the model. Quantitative techniques helped us to determine if there was significant statistical coherence between the real world dynamics and the simulation model.

### 6.2.2 *Simulation type*

In order to determine which quantitative techniques could be used for validating and verifying the model the type of simulation had to be determined. Simulations can be typed, with regards to output analysis, in terminating or nonterminating studies (Law, 2007). A terminating simulation is study for which a 'natural' event specifies the run length (e.g. opening and closing times or a yearly cycle), while nonterminating studies do not have a natural event that specifies the run length. Nonterminating models are often used to determine system behavior in the long run or so called steady state, because these systems eventually convergence to a status quo.

In this simulation study both types are present, a nonterminating planning process and a terminating day-to-day operation process. The model begins with an empty system (no appointments made), and therefore it requires a warm-up period, because the initial transient is not representative for the behavior of the department (e.g. low access times). During a warm-up period the performance depend on the initial system conditions (empty system) and is called transient system behavior. By omitting the data of the warm-up period, better judgments can be made on the actual system behavior, because these performances are independent of the initial conditions. Our approach for statistical analysis is therefore hybrid, which incorporates statistical techniques of both terminating and non-terminating simulation studies.

### 6.2.3 *Validation of the model*

First we will analyze the initial situation at the Radiology department. This gives us insight in the validation of the model. Currently data is available on access times, but this data is not accurate. Access time, in this data, is accounted for as the time (in days) between an arrival of a request at the department until the time of the appointment. This implies an incorporation of access time of follow up requests and other appointments with another signature then 'as soon as possible'. Strictly, this is no access time, because as it is widely defined as '*the number of days* *between the specialist's statement that some kind of facility is necessary for a patient* (in this case a procedure on a modality), *and the moment this patient is actually making use of this facility* (Elkhuizen et al., 2007). Therefore validation of the model could only quantitatively be achieved via the yearly production of the department. This measure was believed to be the only reliable and common accepted real data that could be compared with the real data. A one sample t-test was performed ($t(9) = -1{,}609$, $p > 0.05$) to determine if there was no statistical difference between the real data (production of year 2010) and the simulated data.

Also the access times of all modalities were minimal (max 4.36 days during 10 runs). This was accepted as a representative measure to determine if the model could achieve the same production without delays. (e.g. access times).

### 6.2.4 *Warm up period*

For determining the warm-up period the method of Welch was used. To determine whether the model passed its transient state we have used to average utilization level of the department. Welch's method is based on generating and plotting of moving averages. The utilization measure, as we believe, is a reliable output to determine the influenced of the transient state of the model. The longest warm-up period required per scenario (e.g. intervention) will be the warm-up period for all interventions.

### 6.2.5 *Run length and number replications*

Robinson (2004) uses the confidence interval method to determine the run length of a simulation study. This method implies a convergence method and measures the cumulative mean averages for multiple replications (e.g. days) until a convergence of less than 0.02 is obtained. Next to the narrowness of the confidence interval, the graph of the cumulative mean should be reasonably flat. Based on these measures, a sufficient run length for this study of 136 days was determined. However, we decided to extent the run length to 250 days for the interpretation of the model performances (annual results) and have to possibility of incorporating seasonality. These results could be compared to reality performances, because these are always presented annually.

The number of replications was calculated using the replication/deletion approach for means described by Law (2007). This approach aims to achieve a probability of 0.95 that the true mean lays within the confidence interval by adding (or deleting) replications. This should give reasonably good statistical performance. We used an initialization setting of the department. This implies an expected production for 2011, based on trend analysis of the production figure presented in Section 0. For the determination of the number of replication we used the average access times and waiting times of each run and each modality. We tested this for all interventions. This resulted in a number of 6 replications to obtain an alpha of at most 0.05 that the true means lie within the confidence interval.

Summarizing this section the following preferences of the model are determined:

- The model is validated both qualitative as quantitative.
- The warm up period of the model takes 30 days in order to derive reliable results (results from the steady state of the system).
- The required run length was 136 days, but extended to 250 days for managerial reasons.
- 6 replications of 250 days were needed to obtain statistical significant results.

## 6.3 Analysis results interventions

At this point, the statistical error is limited to acceptable levels and we are now able to analyze the results of the interventions.

### *6.3.1 General results*

As many scenarios could be analyzed with the model, we first give insight in general results of earlier mentioned interventions.

As mentioned earlier we did an initial run with the expected production for 2011, which was transformed into arrival rates of the different patient classes. We will depict the results of each intervention per modality. All results presented in the tables below are day averages of the data generated by the simulation model. Some tables are not presenting any data of waiting times. This is a result of no arrivals of emergency patients at this modality. The units of each performance indicator are:

| | |
|---|---|
| Access times: | average number of days per patient |
| Waiting times: | average number of minutes per patient |
| Overtime: | average number of minutes per day |
| Rescheduled: | number of rescheduled patients |
| Production: | average number of patients per day |

Table 6: Results MRI

| *Intervention*<br>*Performance* | *Init* | *Extended operating hrs* | *Added staff* | *Efficiency Improvement* | *Decrease required fte* |
|---|---|---|---|---|---|
| *Access times (days)* | 4,72 | 4.87 | 3,22 | 3,24 | 3,83 |
| *Waiting times (min)* | | | | | |
| *Overtime (min)* | 45.07 | 36.06 | 65.92 | 48.54 | 31.99 |
| *Access ratio (patients)* | 1,14 | 1.16 | 1,09 | 1,11 | 1,06 |
| *Utilization* | 0,97 | 1.00 | 1,00 | 0,89 | 1,00 |
| *Rescheduled patients* | 1,77 | 1.07 | 1,44 | 1,92 | 0,65 |
| *Production* | 29,22 | 32.22 | 29,31 | 29,90 | 30,51 |

Currently, the MRI has to deal with disproportionate access times. The results show that increasing the level of available staff will have the best effects on access times. During this study 1 FTE was added to the paramedic staff and resulted in an almost completed diminishing of the access times. The downside of adding staff is that this will result in higher overtime. This is a result of the additional MRI that comes available with the added staff, while in practice this is currently not the case. When more MRIs are available the probability of overtime will increase, because for instances now every day there are 3 MRI operational instead of 2 in the initial situation.

Table 7: Results CT

| *Intervention*<br>*Performance* | *Init* | *Extended operating hrs* | *Added staff* | *Efficiency Improvement* | *Decrease required fte* |
|---|---|---|---|---|---|
| *Access times (days)* | 4,70 | 7.36 | 0,28 | 0,20 | 6,31 |
| *Waiting times (min)* | 1,84 | 1,71 | 2,32 | 1,91 | 2,33 |
| *Overtime (min)* | 30,92 | 28,44 | 33,15 | 27,92 | 29,09 |
| *Access ratio (days)* | 1,11 | 1,14 | 1,06 | 1,07 | 1,13 |
| *Utilization* | 0,81 | 0,90 | 0,83 | 0,75 | 0,80 |
| *Rescheduled (patients)* | 14,59 | 14,98 | 10,08 | 8,07 | 14,19 |
| *Production* | 70,86 | 78,62 | 71,87 | 71,93 | 69,89 |

Currently there are no problems at the CTs, we therefore not specifically focusing on these results at this moment.

Table 8: Results Angio

| *Intervention*<br>*Performance* | *Init* | *Extended operating hrs* | *Added staff* | *Efficiency Improvement* | *Decrease required fte* |
|---|---|---|---|---|---|
| *Access times (days)* | 64,32 | 65,40 | 25,66 | 52,04 | 64,16 |
| *Waiting times (min)* | 0,95 | 0,73 | 2,65 | 0,90 | 2,00 |
| *Overtime (min)* | 76.81 | 78,15 | 105,34 | 73,26 | 64,76 |
| *Access ratio (days)* | 2,43 | 2,50 | 1,49 | 2,11 | 2,27 |
| *Utilization* | 0,94 | 0,98 | 1,00 | 0,95 | 1,00 |
| *Rescheduled (patients)* | 1,92 | 2,15 | 2,26 | 2,16 | 1,88 |
| *Production (Patients)* | 8,13 | 9,11 | 11,44 | 9,28 | 8,33 |

The salient results of the angiography rooms are the extremely high access times and access ratios. These are different from figures in practice. A reason for this could be the mismatch between the production figures from the MIS and the real-life figures. Adding staff will, also in this case, be the best promising intervention to deal with these access times. But as we mentioned, these results are not representative for the practice of the angiography rooms.

Table 9: Results Mammo

| *Intervention* / *Performance* | *Init* | *Extended operating hrs* | *Added staff* | *Efficiency Improvement* | *Decrease required fte* |
|---|---|---|---|---|---|
| *Access times* | 6,84 | 10.36 | 0,01 | 0,19 | 0,27 |
| *Waiting times* | | | | | |
| *Overtime* | 7.24 | 6.02 | 19.24 | 11.65 | 11.44 |
| *Access ratio* | 0,87 | 0.89 | 1,05 | 0,85 | 0,86 |
| *Utilization* | 0,92 | 0,96 | 0,83 | 0,86 | 0,97 |
| *Rescheduled* | 0,77 | 0.71 | 0,38 | 0,96 | 0,84 |
| *Production* | 20,51 | 22.60 | 21,08 | 21,35 | 21,38 |

Currently there are also no problems at the Mammography rooms, we therefore not specifically focusing on these results.

Table 10: Results Echo

| *Intervention* / *Performance* | *Init* | *Extended operating hrs* | *Added staff* | *Efficiency Improvement* | *Decrease required fte* |
|---|---|---|---|---|---|
| *Access times* | 0,48 | 2.97 | 0,20 | 0,26 | 0,32 |
| *Waiting times* | 0,83 | 0,51 | 0,80 | 0,53 | 0,72 |
| *Overtime* | 24.46 | 22.45 | 26.03 | 20.05 | 26.50 |
| *Access ratio* | 1,08 | 1.15 | 1,08 | 1,09 | 1,08 |
| *Utilization* | 0,81 | 0.87 | 0,81 | 0,74 | 0,82 |
| *Rescheduled* | 17,47 | 18.34 | 13,26 | 17,04 | 18,84 |
| *Production* | 73,77 | 80.18 | 73,53 | 73,96 | 73,57 |

Echography rooms are currently also dealing with increasing access times. As stated at the MRI results, adding staff is also the most promising intervention.

Table 11: Results GE

| *Intervention* / *Performance* | *Init* | *Extended operating hrs* | *Added staff* | *Efficiency Improvement* | *Decrease required fte* |
|---|---|---|---|---|---|
| *Access times* | 0,36 | 0.34 | 0,36 | 0,37 | 0,35 |
| *Waiting times* | | | | | |
| *Overtime* | 1,54 | 1.57 | 1,72 | 1,29 | 1,77 |
| *Access ratio* | 0,47 | 0.52 | 0,48 | 0,48 | 0,48 |
| *Utilization* | 0,25 | 0.27 | 0,25 | 0,22 | 0,24 |
| *Rescheduled* | 0,35 | 0.35 | 0,36 | 0,39 | 0,35 |
| *Production* | 1,76 | 1.98 | 1,78 | 1,77 | 1,75 |

Currently the problem at the GE rooms is that the level of demand is low. Therefore they only open these rooms if there are enough patients on the waiting list to fill a complete day. This dynamic can also be seen in the results. The GE modalities have low performances.

Summarizing the general results depicted above every performance demands a different approach (e.g. intervention);

Table 12: Most promising interventions of potential problems

| **Potential problem** | **Most promising intervention** |
|---|---|
| *Increasing access times* | Adding staff |
| *Increasing waiting times* | Shorter service times |
| *Increasing overtime* | Extent operational hours |
| *Increasing access ratio* | Adding staff or decrease required staff per procedure |

In order to increase production the best intervention is to extend operational hours. It will not decrease the access times, because capacity is not equally divided during a week and therefore patients could have to wait longer before they actually are scanned.

### *6.3.2 Specific scenario results*

As mentioned earlier the model can simulate many scenarios in which the following variables could be changed:

- Number of servers
- Number of paramedics
- Number of radiologists
- Service times
- Number of arrivals (all type of patients)
- Operational hours
- Downtime servers because of failure

Analyzing all possible scenarios, based on the variables above, becomes too intensive for the sake of this study. But management of Radiology department could use this model for deliberate capacity planning decision through implementing scenarios in the model. To show the potential of this model we have picked a specific example of a scenario construction.

The scenario we selected is derived from practice. If the demand on a random day is really high compared to average days at the MRI, personnel of other modalities, for instance CT, will be transferred to operate at the MRI. For this scenario we therefore simulated that a paramedic was transferred from the CT to MRI for 8.15 hours (a single day) per week to the MRI. The results derived from our model were:

Table 13: Results scenario MRI/CT

| *Intervention*<br>*Performance* | *Init MRI* | *Scenario MRI* | *Init CT* | *Scenario CT* |
|---|---|---|---|---|
| *Access times (days)* | 4,72 | 2.29 | 4,70 | 8.04 |
| *Waiting times (min)* | | | 1,84 | 1.97 |
| *Overtime (min)* | 45.07 | 54.23 | 30,92 | 29.40 |
| *Access ratio (patients)* | 1,14 | 1.12 | 1,11 | 1.16 |
| *Utilization* | 0,97 | 0.97 | 0,81 | 0.80 |
| *Rescheduled patients* | 1,77 | 1.87 | 14,59 | 13.41 |
| *Production* | 29,22 | 29.75 | 70,86 | 69.67 |

When a paramedic is transferred from CT to MRI for one day per week the production of MRI increases with 133 scans on a yearly basis, while on the other hand the production of CT decreases with 298. With these results the management can determine if waiting lists decreases enough if 8.15 hours per week for one year additional staff will be deployed at the MRI and on the other hand if the waiting list will not increase to much at CT. The reason for an increasing number of rescheduled patients and overtime at the MRI and vice versa (e.g. decreasing number) at CT can be related to this transfer of staff. This transfer directly resulted in an additional opening of an MRI and a closing of a CT. As mentioned earlier in this section, the probability of rescheduled patients is higher with current appointment tactics, because simply there can be processed more patients on 3 than 2 operational servers. Vice versa, there can be processed fewer patients on 2 servers compared to 3 operational servers. The more servers are available, the higher the probability of overtime and rescheduled patients (MRI) and the other way around (CT).

# 7 Conclusions and recommendations

In our problem statement, we emphasized it was difficult for the Radiology department the related capacity to demand and therefore adjustment to a changing demand was also difficult. Introducing a planning cycle, which relates all planning activities on a tactical and operational level, and performing a simulation study, the department could now relate capacity to its demand dynamically. It has also obtained insights in waiting lists' behavior.

The management team is convinced of the added value of implementing this cycle and therefore the planning cycle is currently being developed further in practice.

As already mentioned, the model is not only developed for general insights as presented in the previous Section. Managers of a Radiology department could use it to simulate many scenarios in order to make deliberate decisions for the capacity dimensioning problems they are facing or to analyze expected changes in the future.

## 7.1 General recommendations

This research contributes to the awareness of waiting list management. The results of research present several guidelines for capacity planning on a Radiology department. The capacity planning process aims to align supply and demand and eventually minimize access- and waiting times for patients. This process is described in the planning cycle of this research. The sensitivity of production dynamics at a Radiology department could be analyzed with the simulation of this research. This sensitivity gives insights on the systemic behavior to environmental changes and how the system dynamics anticipated through deliberate interventions. With the knowledge of this study a Radiology department can take interventions more deliberate, which should reduce the consequences of environmental change. The planning cycle and simulation model are generalizable and therefore applicable to every Radiology department. The two instruments can give insights of systemic behavior related to the capacity planning of Radiology department.

## 7.2 Further research

This research also aims to improve efficiency at the Radiology department analyzing and introducing tactical planning. Further research for this department could focus on scheduling problems that occur (e.g. appointment system analysis). We believe that significant improvement could be achieved if the appointment system of the department will be studied. Research topics for these scheduling problems could be; open access systems (walk in systems) (Kranenburg et al., 2009) and cyclic appointment schedules for scheduled and unscheduled arrivals. These topics are relatively new, but have promising outcomes on waiting - and access times.

This simulation study could be further tailored to the department dynamics by including non-stationary arrival rates. The current simulation model uses static arrival rates, but in practice arrival rates vary during the day (non-stationary). Also seasonality, which is currently also not included, could be included.

# 8 Managerial implications

This chapter focuses on the practical implications of the planning cycle and the simulation study for the Radiology department. First the practical considerations of the planning cycle and the simulation study will be described, followed by presenting the critical success factors.

## 8.1 Practical implications

As the planning cycle was closing developed with the stakeholders of the planning activities at the Radiology department, there is consensus about the sequence of steps and analysis as presented in the cycle. Introducing the cycle in practice requires strong determination and charismatic leadership of the management team. All planning activities at the department will be subordinated to the predicted demand and strategy. This will leave no room for personal preferences, proprietary or appropriation of capacity. Convincing the highly educated staff of the added value of this cycle requires therefore strong centralized and charismatic leadership. Lacking leadership will lead to a failure of introducing the cycle.

Introducing the planning cycle and using the insight of the simulation model will give the manager of the Radiology department deliberate choices of interventions in respond to changes instead of the current ad-hoc interventions. Through this centralized method, problems of missing required personnel to proceed should be minimal. This depends even well on the scheduling tactics used, which are not studied in this research. Capacity planning will now be directly linked to the (expected) demand, which will increase the transparency of the planning activities and therefore could increase the willingness of personnel.

The simulation study and planning cycle require also reliable and commonly accepted data (e.g. time measures). During this project this phase required a lot of alignment with the specialist of modalities and sections. This could be done more efficiently in future by creating more reliable time measures. This requires better support of the enterprise resource planning system of the process at the Radiology department.

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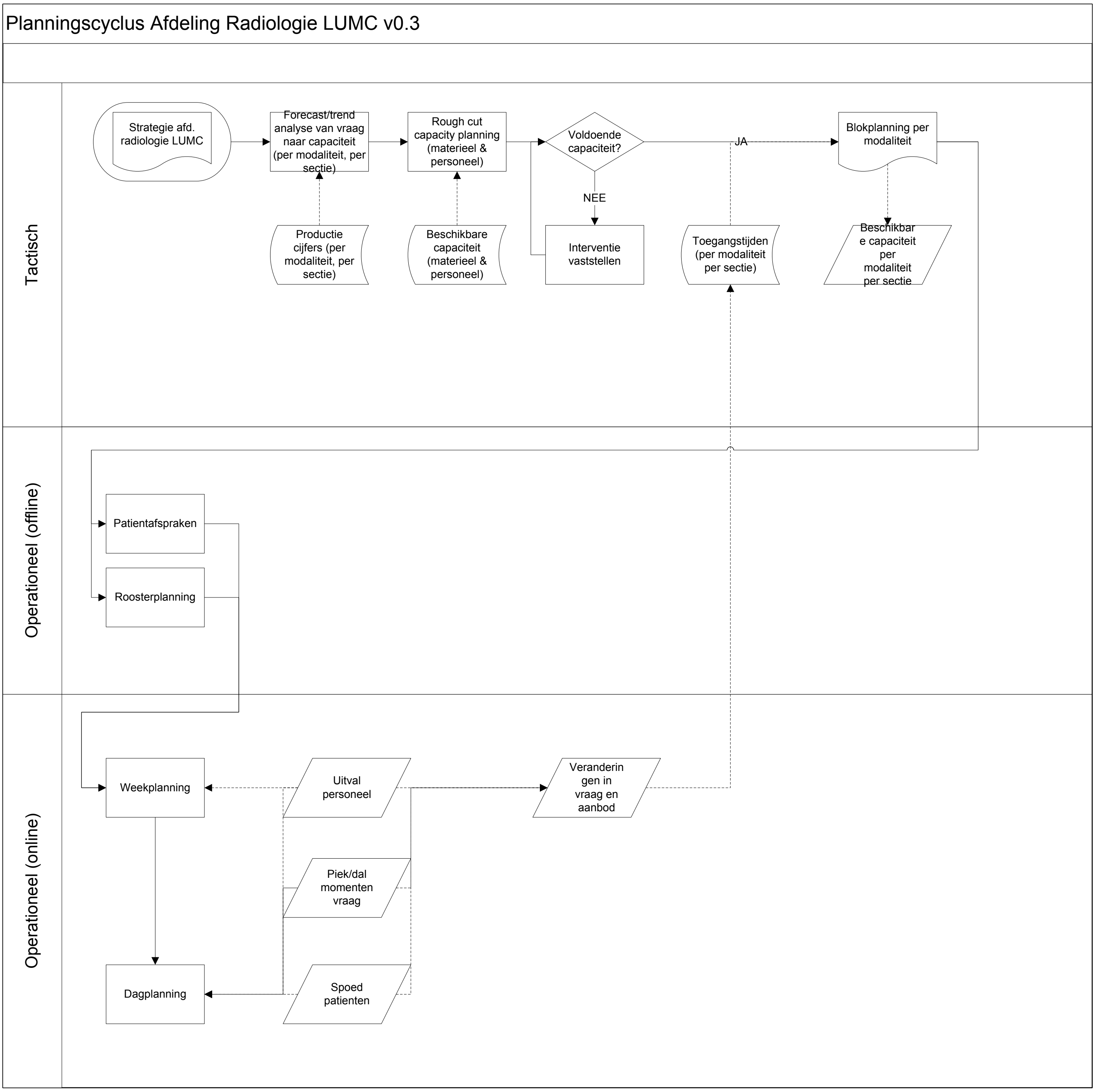
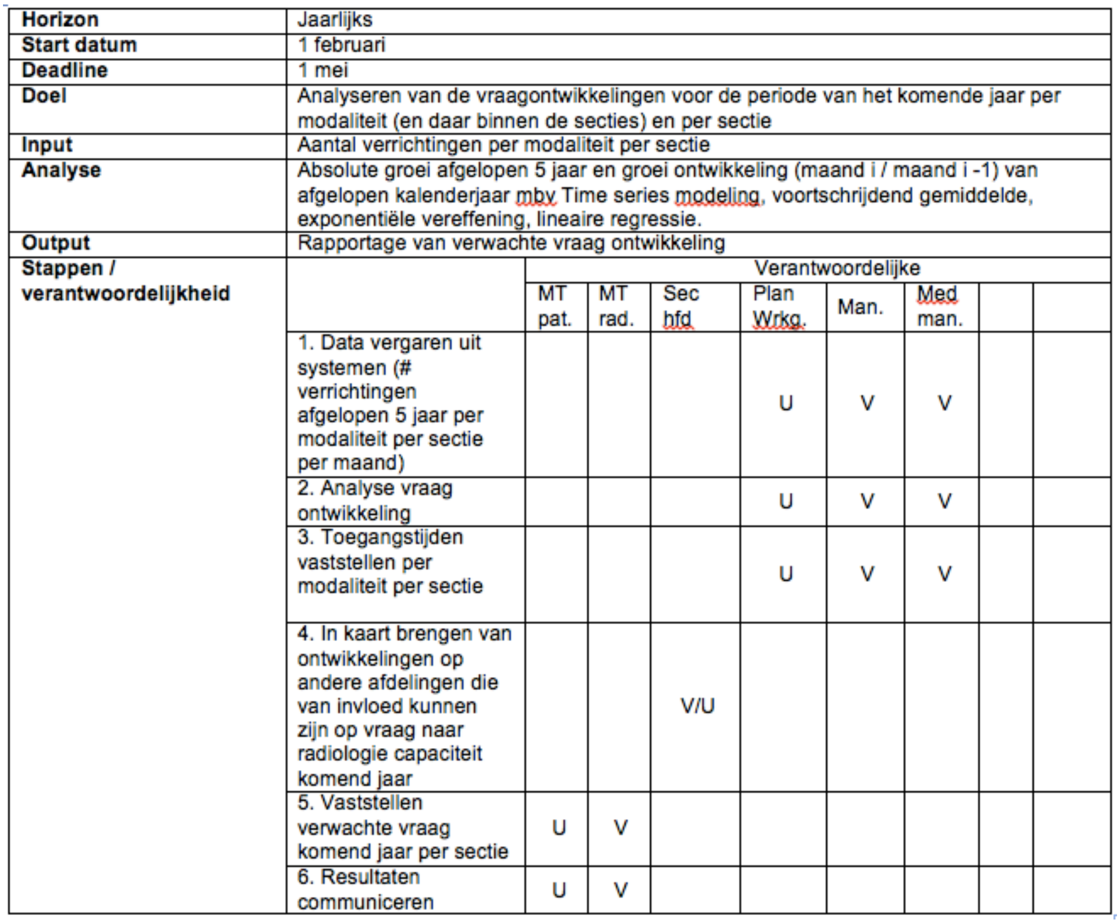
# Appendix A - Planning cycle



Hieronder zal elke activiteit, zoals hierboven gepresenteerd, worden beschreven.

# Activeiten

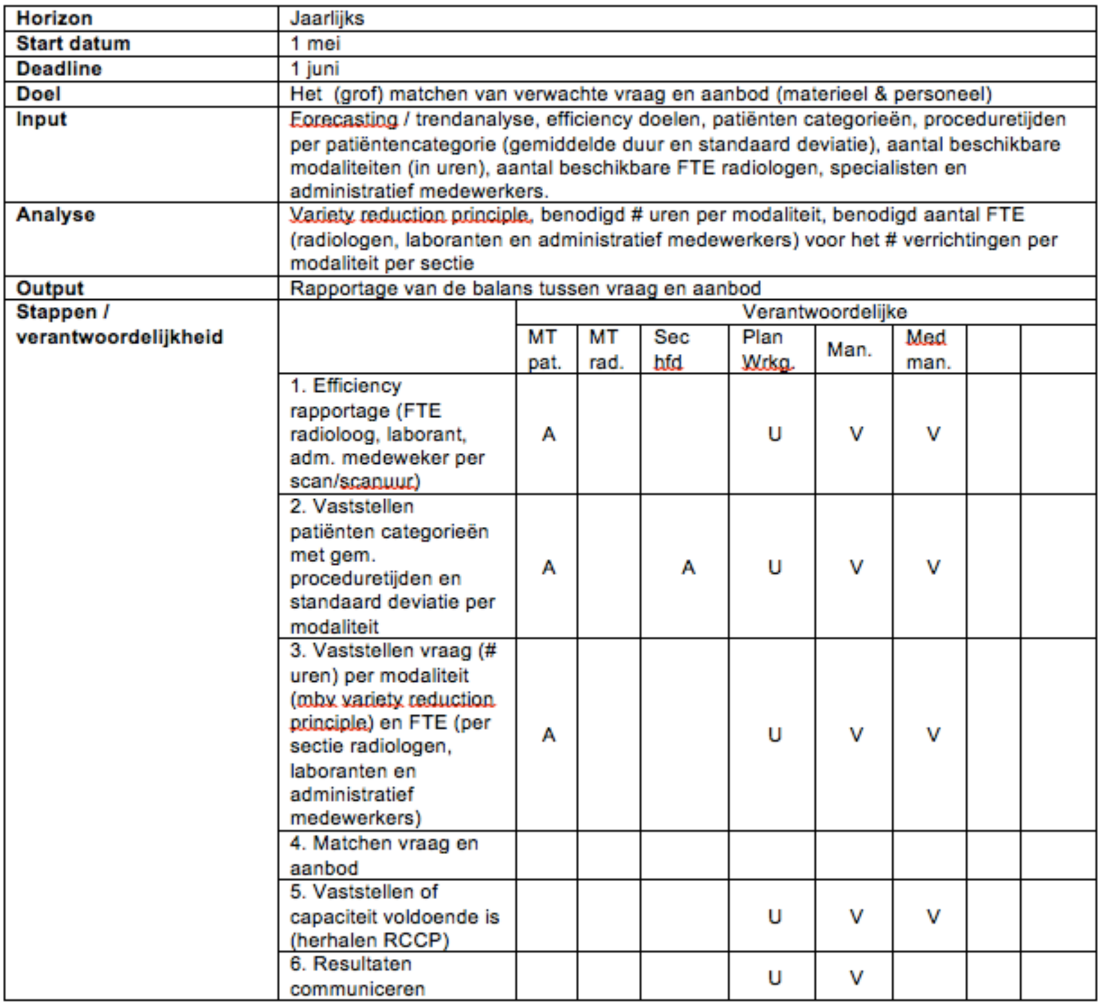
Forecasting / trend analyse



| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Horizon** | Jaarlijks | | | | | | | | |
| **Start datum** | 1 februari | | | | | | | | |
| **Deadline** | 1 mei | | | | | | | | |
| **Doel** | Analyseren van de vraagontwikkelingen voor de periode van het komende jaar per modaliteit (en daar binnen de secties) en per sectie | | | | | | | | |
| **Input** | Aantal verrichtingen per modaliteit per sectie | | | | | | | | |
| **Analyse** | Absolute groei afgelopen 5 jaar en groei ontwikkeling (maand i / maand i -1) van afgelopen kalenderjaar mby Time series modeling, voortschrijdend gemiddelde, exponentiële vereffening, lineaire regressie. | | | | | | | | |
| **Output** | Rapportage van verwachte vraag ontwikkeling | | | | | | | | |
| **Stappen / verantwoordelijkheid** | | Verantwoordelijke | | | | | | | |
| | | MT pat. | MT rad. | Sec hfd | Plan Wrkg. | Man. | Med man. | | |
| | 1. Data vergaren uit systemen (# verrichtingen afgelopen 5 jaar per modaliteit per sectie per maand) | | | | U | V | V | | |
| | 2. Analyse vraag ontwikkeling | | | | U | V | V | | |
| | 3. Toegangstijden vaststellen per modaliteit per sectie | | | | U | V | V | | |
| | 4. In kaart brengen van ontwikkelingen op andere afdelingen die van invloed kunnen zijn op vraag naar radiologie capaciteit komend jaar | | | V/U | | | | | |
| | 5. Vaststellen verwachte vraag komend jaar per sectie | U | V | | | | | | |
| | 6. Resultaten communiceren | U | V | | | | | | |

V = verantwoordelijk U = uitvoerend A = adviserend

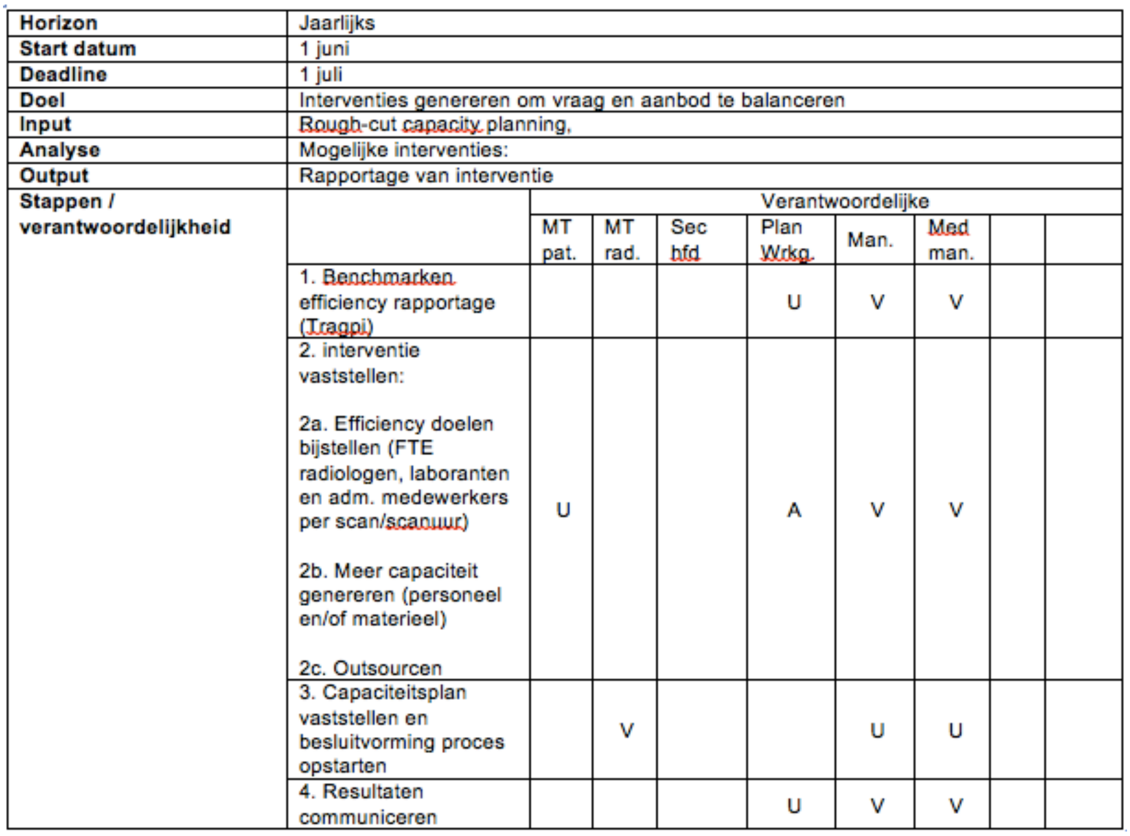
## Rough-cut capacity planning (RCCP)



| | |
|---|---|
| **Horizon** | Jaarlijks |
| **Start datum** | 1 mei |
| **Deadline** | 1 juni |
| **Doel** | Het (grof) matchen van verwachte vraag en aanbod (materieel & personeel) |
| **Input** | Forecasting / trendanalyse, efficiency doelen, patiënten categorieën, proceduretijden per patiëntencategorie (gemiddelde duur en standaard deviatie), aantal beschikbare modaliteiten (in uren), aantal beschikbare FTE radiologen, specialisten en administratief medewerkers. |
| **Analyse** | Variety reduction principle, benodigd # uren per modaliteit, benodigd aantal FTE (radiologen, laboranten en administratief medewerkers) voor het # verrichtingen per modaliteit per sectie |
| **Output** | Rapportage van de balans tussen vraag en aanbod |

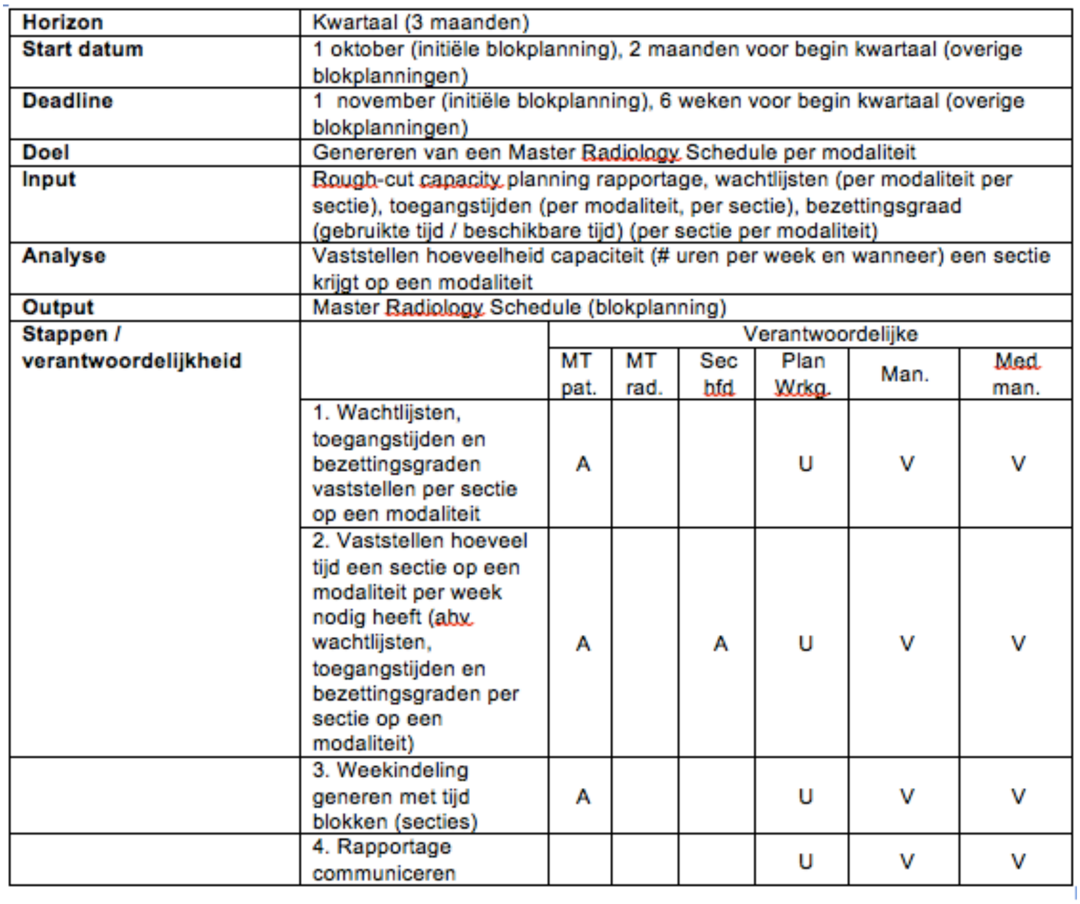
| **Stappen / verantwoordelijkheid** | | Verantwoordelijke | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | MT pat. | MT rad. | Sec hfd | Plan Wrkg. | Man. | Med man. | | |
| | 1. Efficiency rapportage (FTE radioloog, laborant, adm. medeweker per scan/scanuur) | A | | | U | V | V | | |
| | 2. Vaststellen patiënten categorieën met gem. proceduretijden en standaard deviatie per modaliteit | A | | A | U | V | V | | |
| | 3. Vaststellen vraag (# uren) per modaliteit (mbv variety reduction principle) en FTE (per sectie radiologen, laboranten en administratief medewerkers) | A | | | U | V | V | | |
| | 4. Matchen vraag en aanbod | | | | | | | | |
| | 5. Vaststellen of capaciteit voldoende is (herhalen RCCP) | | | | U | V | V | | |
| | 6. Resultaten communiceren | | | | U | V | | | |

## Interventie vaststellen bij onvoldoende capaciteit



| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Horizon** | Jaarlijks | | | | | | | | |
| **Start datum** | 1 juni | | | | | | | | |
| **Deadline** | 1 juli | | | | | | | | |
| **Doel** | Interventies genereren om vraag en aanbod te balanceren | | | | | | | | |
| **Input** | Rough-cut capacity planning, | | | | | | | | |
| **Analyse** | Mogelijke interventies: | | | | | | | | |
| **Output** | Rapportage van interventie | | | | | | | | |
| **Stappen / verantwoordelijkheid** | | Verantwoordelijke | | | | | | | |
| | | MT pat. | MT rad. | Sec hfd | Plan Wrkg. | Man. | Med man. | | |
| | 1. Benchmarken efficiency rapportage (Tragpi) | | | | U | V | V | | |
| | 2. interventie vaststellen:<br>2a. Efficiency doelen bijstellen (FTE radiologen, laboranten en adm. medewerkers per scan/scanuur)<br>2b. Meer capaciteit genereren (personeel en/of materieel)<br>2c. Outsourcen | U | | | A | V | V | | |
| | 3. Capaciteitsplan vaststellen en besluitvorming proces opstarten | | V | | | U | U | | |
| | 4. Resultaten communiceren | | | | U | V | V | | |

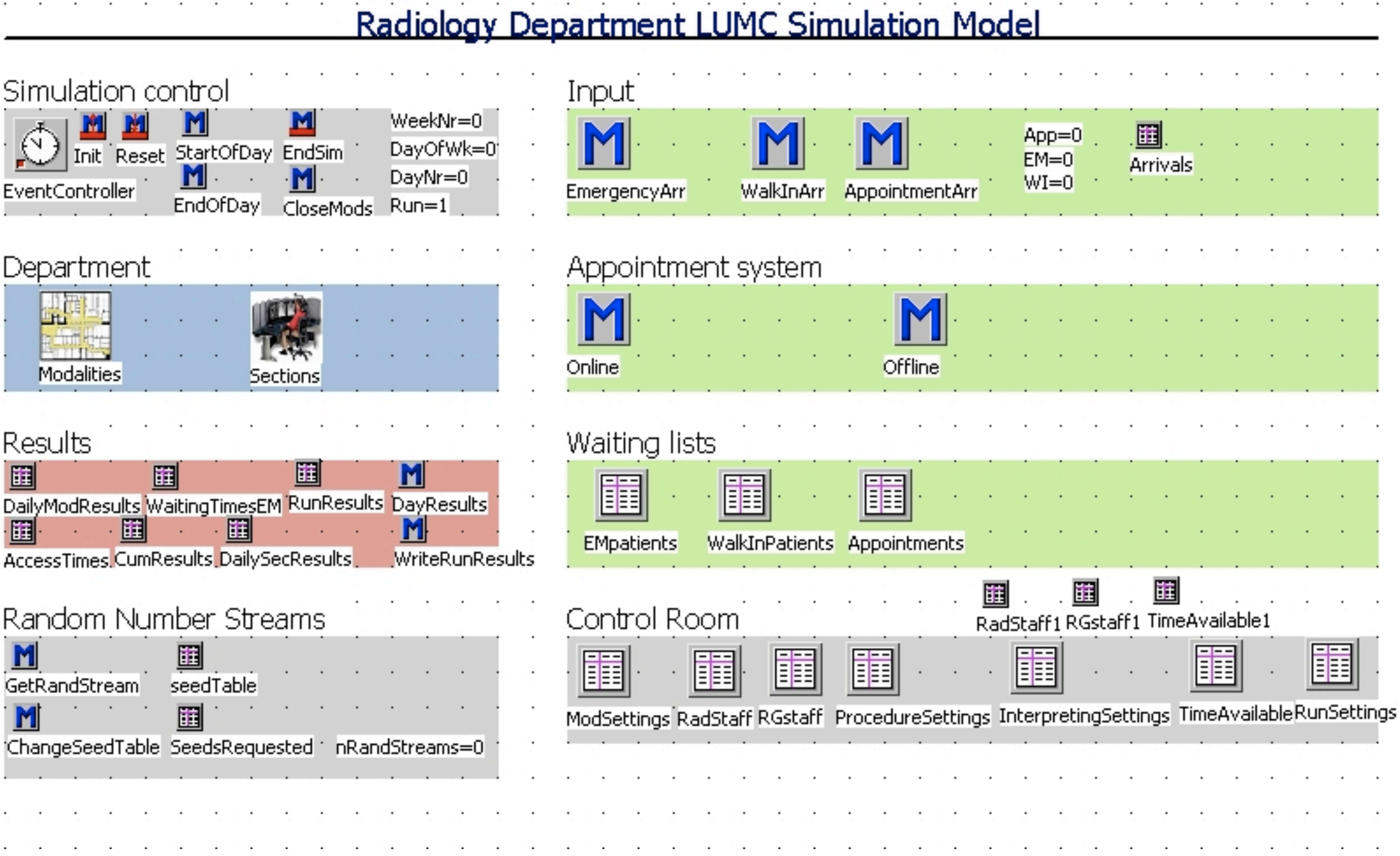
## Blokplanning



| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **Horizon** | Kwartaal (3 maanden) | | | | | | |
| **Start datum** | 1 oktober (initiële blokplanning), 2 maanden voor begin kwartaal (overige blokplanningen) | | | | | | |
| **Deadline** | 1 november (initiële blokplanning), 6 weken voor begin kwartaal (overige blokplanningen) | | | | | | |
| **Doel** | Genereren van een Master Radiology Schedule per modaliteit | | | | | | |
| **Input** | Rough-cut capacity planning rapportage, wachtlijsten (per modaliteit per sectie), toegangstijden (per modaliteit, per sectie), bezettingsgraad (gebruikte tijd / beschikbare tijd) (per sectie per modaliteit) | | | | | | |
| **Analyse** | Vaststellen hoeveelheid capaciteit (# uren per week en wanneer) een sectie krijgt op een modaliteit | | | | | | |
| **Output** | Master Radiology Schedule (blokplanning) | | | | | | |
| **Stappen / verantwoordelijkheid** | | Verantwoordelijke | | | | | |
| | | MT pat. | MT rad. | Sec hfd | Plan Wrkg. | Man. | Med. man. |
| | 1. Wachtlijsten, toegangstijden en bezettingsgraden vaststellen per sectie op een modaliteit | A | | | U | V | V |
| | 2. Vaststellen hoeveel tijd een sectie op een modaliteit per week nodig heeft (ahv. wachtlijsten, toegangstijden en bezettingsgraden per sectie op een modaliteit) | A | | A | U | V | V |
| | 3. Weekindeling generen met tijd blokken (secties) | A | | | U | V | V |
| | 4. Rapportage communiceren | | | | U | V | V |

De overige activiteiten in de planningscyclus zullen op dit moment niet verder uitgewerkt worden, omdat binnen deze activiteiten geen veranderingen zullen plaatsvinden. Wel zullen deze activiteiten zich aanpassen aan de hierboven beschreven activiteiten.

# Appendix B – Simulation model



WeekNr=0
DayOfWk=0
DayNr=0
Run=1

App=0
EM=0
WI=0

nRandStreams=0

Modalities:

Sections:

Process flows of modalities and sections: