Master thesis

Capacity management at the radiology department of Isala

Managing the variability of scheduled and unscheduled patient arrivals

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isala

Summary

Problem description

The radiology department is a fundamental shared resource within the service delivery process of Isala Zwolle. Alignment between the different requesting specialties is required in order to provide specialists with a predictable and reliable access time as well as to maintain a high utilisation. In the current situation, the radiology department faces a highly fluctuating demand to which capacity does not match. By generating insight in the factors that predict the incoming requests, we are able to reduce the variability in the demand and to cover the remaining fluctuations by flexible capacity.

Approach

To generate insight in the factors that predict the variability in the performance and to identify opportunities for improvement, we describe the current performance and benchmark the different modalities. The key performance indicators (KPIs) of the benchmark are based on four perspectives: the patient (represented by the specialist), technicians of the radiology department, management of Isala, and insurers. Based on discussions, observations, and a literature study, the predictors for the variability and the bottlenecks become clear. The echography shows the highest opportunity for improvement. Therefore, we further focus on the echography. Based on the bottlenecks, we establish interventions and simulate the effect of the interventions using Plant Simulation.

Context analysis

Based on meetings with the stakeholders and observations we identify the main bottlenecks that negatively impact the performance. The main bottlenecks are: a shortage of emergency slots because of a lack of insight in the emergency arrivals, an incorrect or incorrectly used block schedule, no insight in the targeted time window of patients resulting in using the general sequencing rule FCFS. These bottlenecks disturb the patient flow and generate a mismatch between demand and supply. Accordingly, this results in an increase of the access time, waiting time, workload and avoidable costs. Furthermore, we identify the major predictors for the variability in demand. Based on current insight, the major predictors are: the visits of specialists, discharge moment, breaks of technicians, and the number of echo mammae requests.

Interventions

After identifying the bottlenecks, we design and evaluate new interventions to improve the performance. By means of a discrete-event simulation, we analyse three interventions:

1. **Emergency echo:** Each day, one echo is dedicated to emergency patients and inpatients. This intervention aims to reduce the disruption of unscheduled patients for the scheduled patients and to increase the availability for unscheduled patients.
2. **Optimisation of slot allocation:** By forecasting the arrival rates and arrival patterns, we allocate slots to specific request types at the required time. We use aggregated slots for the less urgent cases to smooth the utilisation over the days.
3. **Off-peak scheduling:** This method focuses on the operational level and schedules patients based on their time window and the daily utilisation level instead of the FCFS scheduling rule. Patients with a longer time window allow planners to reduce the variability in the utilisation and to reduce the access time for urgent patients.
4. **Adapting the staffing level:** Each part of the day is scheduled with 5 technicians except for the Tuesday and Thursday afternoons (4 technicians). With this intervention, we assess the effect of reducing the staffing levels after we reduced the variability in demand.

Results

The interventions can improve the performance, but we need to take into account the trade-off between different KPIs. By improving the block schedule and using off-peak scheduling, we expect major improvements for the access time (2 days), same-day access ratio (48%), and patients served within their time window (38%). Finally, if management decides that the decrease in costs significantly outweigh the increased access time and decreased same-day access, costs can reduce with approximately 28,000 euro per year. With the outcome of these interventions, we show the additional value of scheduling based on forecasted demand and changing the patient scheduling approach.

Conclusions & Recommendations

In this research, we identify the factors that affect the variability in demand and bottlenecks that negatively affect the performance. Based on this insight, it is possible to reduce the variability by changing the scheduling process at the radiology department (back-end). However, it would also be fruitful to reduce the variability of requests at their origin at the outpatient clinics (front-end). After reducing the variability of the demand, we show that adapting the staffing level can further increase the utilisation and reduce costs. We recommend the echo unit to further implement the new scheduling approach and to also improve the scheduling practices at the other modalities. Finally, implementing these interventions requires a future oriented focus in order to more accurately predict future demand.

Samenvatting

Probleem beschrijving

De afdeling radiologie is een fundamentele gedeelde afdeling in de zorgketen van Isala Zwolle. Afstemming tussen de verschillende aanvragende specialisten is nodig om specialisten te voorzien van een voorspelbare en betrouwbare toegangstijd en om een hoge bezettingsgraad te handhaven. In de huidige situatie van de afdeling radiologie is er veel variabiliteit in de vraag waar de beschikbare capaciteit niet op is aangepast. Door het genereren van inzicht in de factoren die het binnenkomende aantal aanvragen voorspellen, kan de variabiliteit van de vraag worden verminderd en kan de resterende variabiliteit worden opgevangen door te ademen met de personele inzet.

Aanpak

Om inzicht te krijgen in de factoren die de variabiliteit voorspellen en de mogelijkheden tot verbetering, beschrijven we de huidige prestaties en benchmarken we de verschillende modaliteiten. De KPI's van de benchmark zijn gebaseerd op vier perspectieven: de patiënt (vertegenwoordigd door de specialist), laboranten van de afdeling radiologie, management van Isala en verzekeraars. Op basis van gesprekken, observaties, en een literatuurstudie, worden de de voorspellers van de variabiliteit en de knelpunten duidelijk. De echografie toont de grootste mogelijkheid tot verbetering. Daarom focust deze studie zich verder op de echografie. Op basis van de knelpunten ontwikkelen we interventies en simuleren we het effect van de interventies met Plant Simulation.

Context beschrijving

Op basis van gesprekken met de stakeholders en observaties identificeren we de belangrijkste knelpunten die een negatieve invloed hebben op de prestaties. De belangrijkste knelpunten zijn: een tekort van spoed slots als gevolg van een gebrek aan inzicht in het aankomstpatroon van spoed patiënten, een onjuist of onjuist gebruikt blok schema, geen inzicht in tijdsbestek waarin patiënten moeten worden gezien door de afdeling radiologie en het gebruik van de algemene plannings regel FCFS. Deze knelpunten verstoren de patiëntenstroom en genereren een mismatch tussen vraag en aanbod. Vervolgens leidt dit tot een een toename van de toegangstijd, wachttijd, werkdruk en vermijdbare kosten. Daarnaast identificeren we de belangrijkste voorspellers voor de variabiliteit in de vraag. Op basis van de huidige inzichten zijn de belangrijkste voorspellers: het visite lopen van specialisten, ontslag moment, pauzes van laboranten en het aantal echo mammae aanvragen.

Interventies

Na inventarisatie van de knelpunten, ontwerpen en evalueren we nieuwe interventies om de prestatie te verbeteren. Door middel van een discrete-event simulatie analyseren we de volgende interventies:

1. **Spoed echo:** Elke dag wordt er een echo gereserveerd voor spoed- en klinische patiënten. Het doel van deze interventie is om de verstoring door ongeplande patiënten op geplande patiënten te verminderen en om de beschikbaarheid voor ongeplande patiënten te verhogen.
2. **Optimalisatie van het blokkenschema**: Door het voorspellen van aankomsten, reserveren we slots voor bepaalde aanvraag types op het gewenste tijdstip. We gebruikten geaggregeerde slots voor de minder urgente gevallen om het gebruik over de dagen te levelen.
3. **Plannen buiten piek-uren**: Deze methode richt zich op het operationele niveau en plant patiënten op basis van hun tijdsbestek de huidige bezettingsgraad. Patiënten met een langer tijdsbestek maken het mogelijk om de vraag over de dagen heen te levelen en de toegangstijd voor urgente gevallen te verlagen.

4. **Aanpassen van de personele inzet**: Elk deel van de dag is gepland met 5 laboranten met uitzondering van de dinsdag en donderdagmiddag (4 laboranten). Met deze interventie kunnen we het effect van het verminderen van het personele inzet analyseren nadat de variabiliteit in de vraag is gereduceerd.

Resultaten

De interventies kunnen de prestaties verbeteren, maar daarbij moet rekening gehouden worden met de trade-off tussen de verschillende KPI's. Door het verbeteren van het blokkenschema en plannen buiten piek-uren, verwachten we verbeteringen voor de toegangstijd (2 dagen), voor de same-day access ratio (48%), en patiënten die optijd geholpen worden (38%). Tot slot, als het management besluit dat de daling van de kosten aanzienlijk opwegen tegen een verhoogde toegangstijd en verlaagde same-day access ratio, kunnen de kosten worden verlaagd met circa 28.000 euro per jaar. Met de uitkomst van deze interventies laten we de toegevoegde waarde zien van plannen op basis van de verwachte vraag en het veranderen van de wijze van patiënten plannen.

Conclusies & Aanbevelingen

In dit onderzoek hebben we de factoren geïdentificeerd die de variabiliteit in de vraag beïnvloeden en knelpunten inzichtelijk gemaakt die een negatieve invloed hebben op de prestaties. Op basis van dit inzicht is het mogelijk om de variabiliteit te verminderen door het veranderen van het planningsproces van de radiologie-afdeling (back-end). Ook zou het van toegevoegde waarde kunnen zijn om de variabiliteit door de planning van de poliklinieken inzichtelijk te maken (front-end). Na het verminderen van de variabiliteit in de vraag, laten we zien dat de aanpassing van de personele bezetting vervolgens kan leiden tot een kostenreductie. Wij raden de echo unit aan om de nieuwe manieren van plannen in te voeren. Verder raden we aan om ook de planningspraktijken bij de andere modaliteiten nader te onderzoeken en te verbeteren. Tot slot, om de vraag in de toekomst nauwkeuriger te kunnen voorspellen, vereist dit een toekomstgerichte blik.

Preface

With great enthusiasm, I like to share my Master project with you. This is a result of my Master Industrial Engineering and Management and the execution of my thesis at Isala Zwolle. When I look back, my study time is characterised by long days at the university and a steep learning curve. Despite that, it was a time with lots of fun, pleasant coffee breaks and friendly people. After this, my working career starts in which I also hope to learn a lot and have the same lots of fun.

During my Bachelor, I became interested in optimising the dynamic processes of healthcare from a logistical point of view. When searching for a Master thesis, I went to Erwin and Ingrid to discuss the possibilities. Because of the ideal location and since Bernd could provide supervision for an interesting assignment, the choice for Isala was easy.

I want to use this opportunity to thank some people for their support during the last few months as well as the last few years. First of all, I thank Bernd for his support and being my supervisor. From the beginning, I realised that I could learn a lot from your insights and vision on healthcare. Your enjoyable anecdotes gave me more insight in the problems, and brought my research to a higher level. Furthermore, I thank Erwin and Ingrid for their supervision during my Master project as well as their support and enjoyable time during my entire Master. You both motivated me a lot at the start of my Master and were available to help me with the next steps after my Master. Erwin, you always motivated me and I learned a lot from you with respect to managing the project like using the helicopter view. Ingrid, our interesting conversations and your positive critical view helped me to improve my project. Furthermore, I want to thank staff from the radiology department for their input for this study. At last, I thank the Lean team of Isala for their interest in my project and enjoyable time at the office. Their friendliness and ideas had a positive effect on the project.

Enjoy reading!

Laura Hofman
Zwolle, September 2014

Content

1. Introduction

Diagnostic imaging techniques are important within every healthcare environment. Imaging is important in making the correct diagnosis, deciding on the appropriate treatment, and monitoring the effect of a treatment (WHO, 2014). For a successful follow-up, a sound and fast diagnosis is crucial. This research focuses on performance optimisation of the radiology department of the hospital Isala at Zwolle.

Section 1.1 describes the context of the research and gives a description of the hospital Isala at Zwolle. Section 1.2 focuses on the experienced problem within the radiology department of Isala. Based on this description, Section 1.3 describes the research approach.

1.1. Context

In the last decade, healthcare costs in the Netherlands have increased dramatically with almost 4 percent per year (Rijksoverheid, 2012). A major factor that influences the increasing healthcare costs is the rapid development of expensive medical equipment (CPB, 2011). In order to maintain costs, operations management techniques are promising and assumed to deliver enormous efficiency improvements in healthcare organisations (Hans, Wullink, van Houdenhoven, & Kazemier, 2006).

The number of treatments that rely on imaging techniques has substantially increased over the last 15 years. For example, the number of CT examinations tripled from 1996 to 2010, resulting in an increase of 7.8% per year (Barber, 2012). This rapid rise is driven by ongoing advances in technology that lead to an increase of the clinical application, the patient- and physician generated demand, and increased medical uncertainties (Smith, et al., 2012; Armao, Semelka, & Elias, 2011). The increasing popularity of diagnostic techniques and the rapidly developing technique make diagnostic equipment a capital-intensive area in terms of equipment as well as staffing costs. In order to limit the increase in equipment costs and maintain (or reduce) staffing costs, effective management of medical equipment is required.

The radiology department has a large array of medical equipment (modalities) to conduct research in the internal body and performs treatments like for example coronary angioplasty. Together with paramedics, radiologists support other specialties in diagnosing diseases. It is a supporting department and has diagnostic modalities divided over various rooms and locations, shared by many specialties. Shared resources are very common within hospitals because of the required technical infrastructure and highly specialised staff (Vissers & Beech, 2005). Because of the costly position, these resources are often characterised by scarcity. Well-known shared resources are the operating rooms (ORs), the intensive care unit, the wards, and diagnostic equipment (Gopakumar, et al., 2008). Sharing resources allows sharing costs but also results in strong dependencies between different specialties. For an optimal integral hospital performance, shared resources require effective management and alignment between departments.

Inadequate management of shared resources results in high unnecessary costs and decreases the service level for many stakeholders. The total demand of the shared resource is an aggregation of the demand pattern of different parties. Therefore, changes in the specific demand pattern of one party affect the availability of the resources of others. Without insight in the demand for each party, it is not possible to effectively manage the demand and plan capacity. Daily over- and underutilisation are a result since the real demand highly differs from the available capacity for the incoming demand. Regarding the radiology department, inadequate management results in unnecessary costs and reduces the service level for patients, requesting specialties, and staff members of the radiology department. Patients and their referring specialties face an uncertain process and access times for the imaging techniques, and staff faces a highly fluctuating workload resulting in many stressful situations.

The radiology department plays an important role in the patient flow through the hospital. If the radiologist detects an abnormality, treatment follows and aftercare takes place. For a successful follow-up, a sound and fast diagnosis is crucial. Especially for patients suffering from cancer early detection makes a real difference; treatment becomes less complex and is more likely to be effective (American Cancer Society, 2013; Cancer Research UK, 2009). Furthermore, diagnostic resources are central in the clinical pathways of many patients and long access times to diagnostic services directly disrupt the process flow through the entire hospital. Therefore, according to management of Isala, diagnostic resources should always be able to serve.

In order to guarantee timely access to care, government has established norms (*'Treeknormen'*) for the access time for several health services (NZA, 2013). For diagnostic services, the norm is that 80% of the patients should have been diagnosed within three weeks (Treeknorm.nl, n.d.). Because of the increasing transparency of healthcare to the wider public, healthcare insurers, gatekeepers of healthcare, and patients, also use the *Treeknormen*. These norms are one of the pillars for healthcare insurers during the purchasing process of healthcare. A suboptimal score can result in financial penalties or withholding a contract. Furthermore, gatekeepers of care, like general practitioners (GPs), use these norms to refer patients. Together with the increasing self-conscious choice of patients, a focus on timely access to healthcare becomes increasingly important. Furthermore, reducing the access time can increase the overall production level and reduce waiting lists and accompanied costs.

In this study, we focus on the radiology department of Isala Zwolle. The department faces a large variability in requests from different specialties while the available capacity is static over time. This results in capacity management problems and negatively affects the service level and costs. Isala is a non-academic hospital serving top clinical care. In 1998 Isala klinieken is established by the merger of two hospitals in Zwolle; the Sophia hospital and the Weezenlanden hospital. In 2009, Isala started the building of a new hospital at the Sophia location and opened his doors in August 2013. The hospital has approximately 5,577 employees (3,657 FTE), 341 medical specialists (314 FTE), 20 operating rooms, and 776 beds. With the available capacity, they produced 454,400 DTCs (diagnose treatment combination) and had a yearly revenue of 454 million euro in the year 2012 (Isala, 2013).

Improving the radiology department of Isala Zwolle has a high relevance. The department has a crucial and costly position within the hospital, shows many opportunities for improvement, and the performance affects many stakeholders. Furthermore, still a few studies focus on capacity management of the radiology department, which further increases the relevance of this study.

1.2. Problem description

In order to effectively use diagnostic resources, there should be a match between the available capacity and the incoming demand. The available capacity at the radiology department consists of 1) diagnostic modalities and 2) staff scheduled at each modality. The diagnostic modalities are characterised by a static availability and staff is characterised by a dynamic availability because of the possibility of flexible deployment. The demand consists of the incoming diagnostic requests of different specialties from different departments. This demand varies each hour, each day, and each week. Currently, there is no match between the incoming requests and the available capacity resulting in over- and underutilisation problems. Furthermore, inappropriate scheduling of the radiology department affects other departments and negatively affects the integral length of stay of patients in the hospital. More insight in the factors that influence the variability of patient arrivals enables the radiology department to forecast the demand.

Capacity management at the radiology department is currently based on performance indicators that only incorporate the average utilisation of the capacity. On average, there is sufficient capacity. However, because of the large variability in the demand, frequently moments occur in which the service level is suboptimal. The currently used performance indicators do not represent these moments. In order to be able to forecast demand and schedule sufficient capacity at each time of the year, more insight is required in the variability and its predicting factors. With this insight, planners can better adapt the capacity to the demand or reduce the fluctuations in the demand so that the demand better fits the capacity. If it is possible to reduce the systematic variability in the demand, the service level of the radiology department can increase and the number of modalities can possibly be reduced. The remaining random variability can be covered by flexible deployment. An inoperative modality is disappointing. However, an inoperative modality accommodated with staff is avoidable loss.

The radiology department has dedicated planners at the front desk. The planners spend their time with day-to-day operations and solving upcoming problems. There is no insight in the future demand and variability of the requests for the upcoming time horizon. Emergencies and patients with complications requiring further research disturb a smooth process flow because of a lack of forecasting. Without insight in the future demand, efficient planning based on forecasted demand and using resources efficiently is difficult. Therefore, capacity problems are most of the times solved by increasing capacity (e.g. increasing opening hours or increasing staff). This is not always the right solution when the goal is to reduce or to maintain costs. Decisions on a tactical level can result in a more efficient use of resources by for example efficient block scheduling or adapting working hours. These decisions should be updated periodically in order to react on variations.

The complex part of generating insights and forecasting future demand of healthcare services lies in the highly dynamic and unique character of the patients' demand. This requires a dynamic approach that has the ability to change processes to meet changing needs (Story, 2012). Haraden & Resar (2007) divide the variability in the demand into natural variation; variation from the randomness of the disease, and artificial variation; variation introduced from personal preferences and human decision-making. The effect of artificial variation far exceeds the effect of natural variation and is highly predictable. This gives the opportunity to forecast the major part of the demand.

By generating insight in the variability in demand and its predicting factors, the radiology department is better able to anticipate on future demand and schedule their staff. Consequently, this can result into a better hospital-wide performance and lower costs due to a smoother diagnostic track. Fine-tuning capacity and demand also positively influences the service level for patients, and referring specialists. The quality of care increases, the access time decreases, and the experienced workload decreases.

1.3. Research approach

1.3.1. Research objective

Generating insight in the factors that affect the variability on the utilisation of the capacity enables the radiology department to make accurate forecasts. Based on these forecasts, the radiology department is can better able to plan and control the processes. Therefore, the goal of this research is:

To reduce the variability of the utilisation of the radiology department by
a) generating insight in the factors affecting the variability and
b) analysing interventions to increase the match between demand and supply.

The utilisation of the radiology department concerns the utilisation of two capacities; staff as well as the examination room of the modalities. Therefore, the goal is to reduce the variability in staff utilisation and equipment utilisation.

1.3.2. Research questions

1. *What theories provide insight in the factors affecting the variability of the utilisation and what methods are suitable to improve the match between demand and supply?*

Chapter 2 gives an overview of the existing literature about capacity management and workload management. These theories give insight in the factors that affect the variability in the utilisation of the available capacities (staff and examination rooms). Furthermore, we describe interventions that can improve the match between demand and supply in a healthcare setting. Finally, we describe models that are used to evaluate interventions. With insight in the literature, we are able to identify the factors that affect the variability in the utilisation and evaluate suitable interventions for this specific setting.

2. *What is the current situation of the diagnostic process and what are the factors that affect the variability and operational performance of the radiology department?*

Chapter 3 describes the demand characteristics, the primary process, the planning and control mechanisms, and the current performance. We define suitable KPIs and operationalise the desired situation. Based on observations on the floor and an extensive data analysis, we assess the current performance in order to get insight in the factors that predict the variability in demand and to identify the bottlenecks that affect operational performance. This enables to identify the opportunities for improvement and define suitable interventions. We further demarcate the scope to the modality with the highest opportunity for improvement. Data sources for this research are the scheduling system Ultragenda (January 2010 to Dec 2013, n = 693,683) (Ultragenda, 2014) and the information system Cognos (January 2013 to March 2014, n = 236,381) (IBM, 2014).

3. *What interventions are suitable to improve the current performance of the radiology department?*

Based on the identified bottlenecks and useful interventions from the literature, Chapter 4 formulates the interventions for the specific situation at the radiology department. With detailed insight in the specific interventions, the radiology department gets insight in the ways to improve the operational performance. The interventions are designed for the modality of focus. However, insight in the effect of these interventions is also valuable for other modalities with comparable problems.

4. How can we model the processes at the radiology department?

In order to be able to measure the effect of several interventions on the performance, we require a validated and verified model of the current situation. Chapter 4 describes the interventions in detail, describes the conceptual model, and verifies and validates the programmed model.

5. What are the expected outcomes of the interventions with respect to the performance?

With insight in the bottlenecks, interventions that are suitable to improve the performance and a validated model, Chapter 5 gives the results of the simulated interventions. We evaluate the influence of each intervention on the KPIs and compare this with score in the current situation. These interventions are analysed using the simulation software Tecnomatrix Plant Simulation (version 10.1).

6. How can we implement the supposed interventions?

Chapter 6 gives implementation strategies for the suggested interventions. With a well-defined implementation strategy, the interventions are more likely to be implemented successfully. As in Chapter 4 and 5, this chapter only focuses on the modality with the highest opportunity for improvement.

Finally, this report formulates the conclusions, discusses the results and research approach, and gives recommendations for the radiology department. Figure 1 visualises the structure of this report.

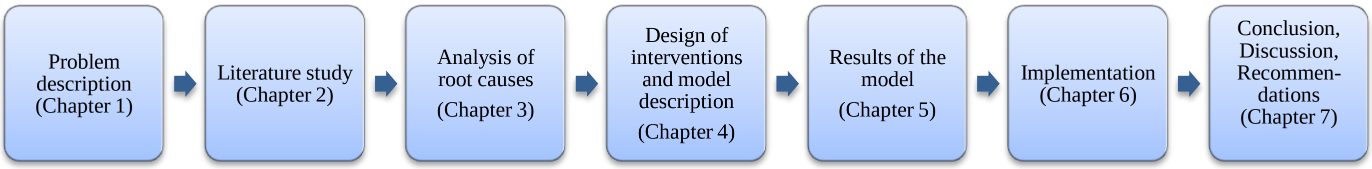

Figure 1 – *Structure of the report*

1.3.3. Scope

Three different aspects of the research area demarcate the scope of this research. First, we focus on the managerial area of resource capacity management at a tactical level as we focus on an efficient utilisation of available resources and on acceptable access times of the modalities. Resource planning on a tactical level has a medium-long planning horizon to take into account seasonal variability and is therefore more uncertain than in the short-term. Furthermore, the tactical planning has more flexibility and is less detailed than the operational planning in order to serve the incoming demand (Hans, van Houdenhoven, & Hulshof, 2011).

With this insight, we approach the problem by adaptations on the supply side (flexible deployment) and adaptations on the demand side (reducing the variability in the demand). This research focuses on the radiology of the hospital Isala. The radiology department has nine different modalities at eight locations. In order to increase the depth of the analysis, we demarcate the scope after a thorough description of the current situation and benchmarking the different modalities. Concluding, this research focuses on tactical decision making of resource capacity management at the radiology department.

2. Literature

This chapter reviews the existing literature in order to get insight in the factors that affect the variability in the utilisation of the available capacities and to get insight in a suitable solution approach. Section 2.1 introduces the general idea of capacity management. Thereafter, Section 2.2 describes how staffing and scheduling methods can affect the available capacity and incoming demand. Section 2.3 gives an overview of specific approaches we can use to improve the performance. Finally, Section 2.4 describes the usability of a simulation model in order to measure the effects of several experiments.

The emergency department (ED), operation rooms (ORs), and outpatient clinics are well-researched areas. Optimising the operational performance at these areas is performed using many tools and approaches like integer programming, modelling, and simulation (Gupta & Denton, 2009; Paul, George & Lin, 2006). However, the literature on process optimisation at the radiology department is scarce (Brasted, 2008). Schutz & Kolisch (2013) model a Markov decision problem of the radiology department to maximise profit without taking into account the service level. Another study shows the effect of adapting the capacity on the waiting times and utilisation level at the radiology department (Johnston, et al., 2009). The literature that focuses on the radiology department does not provide clear information on the predictors of the variability in demand as well as on process optimisation. Many tools and approaches of optimising the ED, OR, or outpatient clinics are useful to gather insight on improving the radiology department. Furthermore, the ORs are comparable to the radiology department because a) both are shared resources b), both are associated with high costs, and c) both resources are scarce (Gopakumar, et al., 2008). Therefore, this chapter focuses on studies from the ED, OR, and outpatient clinics.

2.1. Capacity management

Several studies have shown that the available money is never enough to meet all demand for healthcare services. Therefore, efficient resource allocation is required to obtain the best outcomes with that money (Gross, 2004). Capacity management concerns finding the balance between the demand of an operation and the ability to satisfy the demand with capacity. Furthermore, it is an activity that profoundly affects the efficiency and effectiveness of operations. Inefficient capacity management results in high unit costs (under-utilisation of resource) or in a low service level (over-utilisation of resource) (Slack, Chambers, & Johnston, 2007). Efficient capacity planning requires aggregated data at a medium-long planning horizon and requires insight of the degree of uncertainty (Hans, van Houdenhoven, & Hulshof, 2011). Especially this amount of uncertainty determines how much capacity the organisation should plan (Slack, Chambers, & Johnston, 2007).

A key driver for inefficient capacity management that is often overlooked is the existence of variability (Litvak, Green Vaswani, Long, & Prenney, 2010). Variability itself is not the root cause. However, when the capacity does not match the variable demand we see periodic overcrowding and underutilisation (Institute for healthcare optimization, 2012). Therefore, both reducing the variability as well as adapting the capacity is useful. Managing variability is also important in order to maintain adequate and affordable nurse staffing levels (Jayawardhana, Welton, & Lindrooth, 2011) and the amount of variability is assumed to be a factor of avoidable deaths (Healthleaders, 2011).

There are two types of variability: artificial variability and natural variability. Artificial variability (*potentially controllable*) is introduced by human decision making like scheduling practices of elective patients (Litvak, Green Vaswani, Long, & Prenney, 2010). Natural variability (*uncontrollable*) is caused by the variation from the randomness of the disease such as the admission of emergency patients. The natural variation can affect flow, but the artificial variation far outweighs the natural variation. When the artificial variability is minimised, a hospital must have sufficient resources for the remaining patient-driven peaks in demand (Haraden & Resar, 2011). In order to minimise the artificial variability, we should generate insight in the predictors of this variability. First of all, many hospitals face periodic patterns like midweek highs, weekend lows, and lag components of 1 and 7 days caused by moving patients to the next work shift (Moore, Strum, Vargas, & Thomson, 2008). In addition, Litvak, et al. (2010) notice that the scheduling practices of scheduled patients is a major predictor. For example, office hours of specific specialties or holidays of specialists at the outpatient departments can influence the demand pattern of subsequent departments. Furthermore, the temperature is a predicting factor. For instance, the prevalence of lung diseases negatively correlates with the temperature (Marcilio, Hajat, & Gouveia, 2013). When forecasting and planning future capacity, the major predicting factors of the arrival rate should be taken into account. Time-series models can be used to forecast future demand based on the historical arrival rates and an estimation of the effect of the predicting factors (Marcilio, Hajat, & Gouveia, 2013).

Capacity management concerns matching demand and supply has two counteracting objectives of getting the highest service level as well as acquiring the lowest unit costs. Patients require a reliable and low access time and the organisation strives for a high utilisation of capacity (Garfinkel & Thompson, 2012). In order to manage the utilisation of capacity as well as the service level for specific patient types many studies use block schedules (also defined as Master Schedule) (Beliën, 2007; Blake & Donald, 2002). A block schedule is defined as a schedule that specifies the number and type of rooms, the opening hours, and the specialty that has priority at each room (Cardoen, Demeulemeester, & Beliën, 2010). Furthermore, we can approach the match between demand and supply by using the three approaches of Slack, et al. (2007). The three approaches give insight in the controllable factors to optimise the match between demand and supply. The three approaches are:

1. **Level capacity plan** – capacity is kept constant, the operation tolerates the under use of the capacity or its inability to serve all demand.
2. **Chase demand plan** – capacity is frequently adjusted to match the demand at any point in time. Interventions to adjust capacity are a) using overtime, b) varying the size of the workforce, c) using part-time staff, or d) subcontracting.
3. **Managing demand** – demand is influenced or changed in order to match with the available capacity at any point in time.

2.2. Staffing and scheduling

Efficient and effective allocation of resources is a great challenge faced by many health care managers. The available resources represent a large portion of the budget, and can be potential bottlenecks in the process flow. In manufacturing, staffing and scheduling decisions are relatively simple compared to healthcare. Reasons are that the demand of healthcare is less predictable, crucial information is often not available (Carter, 2002), and there is a lack of communication between involved parties (Glouberman & Mintzberg, 2001). The general term for staffing, scheduling, and reallocating operations is workload management as illustrated in Figure 2 (Ozcan, 2009).

Staffing concerns decisions on the appropriate number of full-time employees (FTEs) for a particular unit that are made annually taking into account seasonal variations. Scheduling concerns both the supply side (scheduling resources) as well as the demand side (appointment scheduling) and concern tactical as well as offline operational decisions. The third component, reallocation of resources, concerns fine-tuning the previous decisions on a daily basis (operational decisions). Because of the scope of this research, we only describe the components staffing and scheduling. The workload management decisions on these different levels influence the productivity (output over input) and productivity related performance measures (Ozcan, 2009).

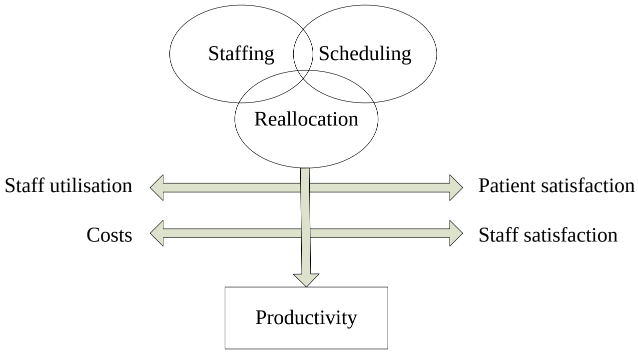

Figure 2 – *Workload management* (Ozcan, 2009)

Staffing

Historically, staffing levels were based on the average patient levels of the entire organisation. Although forecasts were used based on previous admissions and expected length of stay, the variation in demand had limited attention. Furthermore, the application to individual hospital units was limited leading to staffing inefficiencies. Ozcan (2009) focuses on three aspects in order to make staffing decisions: 1) patient acuity and classification systems, 2) methods for developing work standards and translations into FTE, 3) controversies between professional and industrial work standards.

An important aspect of staffing levels is the expected utilisation of employees (Page & McDougall, 1989). Often, many controllable and uncontrollable factors prevent the utilisation to be 100 percent. Furthermore, 100 percent is not a desired target utilisation as stated by Slack, Chambers, & Johnston (2007). Although noting the difficulties with determining utilisation targets, Page and McDougall (1989) give three possible methods: 1) review the historical levels of utilisation, 2) quantify the (un)avoidable delays and downtime and decide utilisation target on those delays, 3) calculate the utilisation target based on the utilisation per shift and set acceptable levels per shift. After setting the utilisation target, the next step is to calculate the work hours of 1 FTE based on a coverage factor (corrects for holidays, weekends, etc.) and calculate the number of required FTE.

Scheduling

Ozcan (2009) makes a distinction in staff scheduling, the most resource consuming area, and resource scheduling, one of the major revenue gathering areas in hospitals. Staff scheduling assigns the FTEs to the proper patients at the right times. Five important aspects to consider according to Ozcan (2009) are coverage, schedule quality, stability, flexibility, and costs. Important staff scheduling decisions are the length of a workweek (traditionally 5 days), the length of a workday (traditionally 8 hours), and the pattern of shifts. The pattern is either cyclical meaning that the schedule is created for the next couple of weeks/months ahead, or is flexible in which there is a core level of staff that can be varied by daily adjustments. Resource scheduling has the goal of matching demand with capacity so that resources are better utilised and access times are minimised (Gupta & Denton, Appointment scheduling in health care: challenges and opportunities, 2008). Cardoen, Demeulemeester, & Beliën (2010) divide resource scheduling into planning and scheduling. Planning concerns the process of adapting supply and demand, and scheduling concerns the sequence and time allocated to the activities of an operation.

2.3. Interventions

To improve the balance between demand and supply, several approaches are used. Examples are to decrease the service time, increase supply, or control the production level. Decreasing the service time or increasing supply results in a temporarily improvement because specialists refer patients more easily (a decreased entrance barrier). Controlling the production level on the other hand, implies changing behaviour of specialists and inherent medical decision-making (van den Vijsel, Engelfriet, & Westert, 2011). This is a long-term intervention and difficult to control in the scope of this research.

Another factor to improve the balance between demand and supply and increase the predictability of the demand, is to adapt the scheduling process. The literature on resource planning and scheduling is extensive and we only describe a small area that could be applicable to the radiology department. The radiology department has an inflow from elective and non-elective patients. However, literature addressing planning and scheduling issues of a combined patient mix of elective and non-elective patients is scarce. Also, the majority of the literature focuses on elective patient arrivals rather than non-elective patient arrivals (Cardoen, Demeulemeester, & Beliën, 2010). In this section, we focus on both planning and scheduling approaches for elective and non-elective patients. The literature shows the following possible approaches:

- **Balanced slots**: (Green, Savin, & Wang, 2006) analyse the problem of scheduling MRI magnets. They focus on the problem of serving waiting patients (emergencies and walk-ins) and outpatients. They show an optimal balance between empty slots (walk-in base) and scheduled slots under certain assumptions. However, this research, as well as other findings, does not come up with a general rule to balance these types of slots. Accordingly, the method of Green, et al. (2006) only maximises regular-hour utilisation while we both want to optimise regular-hour utilisation and patient fairness in terms access within the required time window.

- **Dedicated emergency room or dedicated blocks:** There are different degrees of urgency associated with the patient characteristics. Elective patients may be scheduled well in advance since there is no need for direct examination, while for emergency patients the speed of examination is critical to the patients' potential recovery. The schedule must take into account these arrivals in order to guarantee timely access. In the literature, two main methods are used for emergency scheduling: a) a dedicated emergency room, and b) dedicated time for emergencies. If there are enough emergencies, a dedicated emergency room can be profitable (Cayirli & Veral, 2003). In the research of Heng & Wright (2013) a dedicated emergency room is preferred since it decreases cancellations, overtime, and increases the probability for emergency patients served within the targeted time. In the simulation model of Wullink, et al. (2010), they found that the utilisation and amount of overtime of the ORs significantly improves when the blocks are spread over multiple rooms instead of using a dedicated OR. Accordingly, the amount of blocks to reserve for urgent cases depends on the trade-off between unused capacity due to excessive reservation and the number of cancellations for elective cases due to the arrival of urgent cases (Zonderland, et al., 2010). As we see, it depends on the input and desired outcome which intervention is more fruitful.

- **Integrated block sharing**: According to (Day, Garfinkel, & Thompson, 2012) block scheduling has two competitive objectives: a) providing specialists with predictable and reliable access times, and b) maintaining a high utilisation of capacity. The first can be obtained by assigning exclusive capacity (blocks) to specialists/specialties, and the second by not using blocks and just schedule on a walk-in base. However, assigning blocks to a specific group can result in a low utilisation because of unused time, and not using blocks would be undesirable for examinations that are not predictable and require short-term access (Dexter et al., 2003). Therefore, Day et al. (2012) suggest to use a integrated block sharing. The schedule assigns exclusive blocks to procedures with a predictable demand, and assigns shared blocks to procedures with a less predictable demand. By using a shared block for more specialties, risk-pooling emerges and capacity becomes more flexible.

- **Off-peak scheduling**: Rising (1973) is one of the earlier studies that forecasted the number of unscheduled patients and incorporated seasonality when addressing scheduling problems. "By scheduling more appointments during the periods of low walk-in demand, the appointment patients would smooth the load on physicians and facilities". This is comparable to the approach of Gupta & Denton (2009) and Cayirli & Gunes (2013) who suggest to reduce the variability in demand by filling off-peak hours with elective requests.

- **Sequencing rules**: Various sequencing rules for appointment scheduling are used: first come-first served (FCFS), longest case first (LCF), shortest case first (SCF), top down-bottom up, etc. (Ozcan, 2009). It highly depends on the schedule objectives and patient mix what sequencing rule is the most desirable.

- **Two patients in the first slot, no patients in the last slot**: One of the first papers concerning appointment scheduling was from Welch and Bailey (1952). The rule concerns scheduling two patients in the first time slot, then one patient in each following slot, and no patient in the last time slot. This allows for corrections for the variability in service times.

- **Separate scheduled and unscheduled patient flows**: The institute for healthcare optimization (IHO, 2014) suggests to separate the flow of scheduled and unscheduled patient flows. The main goals for the elective patient scheduling are maximising patient throughput, and minimising unnecessary waiting. Resources for unscheduled patients should be based on clinically driven maximum acceptable waiting times. However, according to Cayirli & Veral (2003) separating the patient flows on different resources is only profitable if there are enough unscheduled patients.

2.4. Simulation

In the literature models for resource planning can be broadly categorised as analytical or simulation based. The complex nature of healthcare processes makes it difficult to analyse processes with analytical models (Carter, 2002; VanBerkel & Blake, 2007). Simulation models on the other hand, can incorporate the complex flows with random arrival rates and random service times. The technique is used for analysing different settings, generally typed as 'what-if?' questions. Other advantages of a simulation model compared to an analytical model are that simulation models are easier to understand and justify to management (Shannon, 1998), enable us to estimate the performance under specific conditions, allows to control time (Law, 2007), allow modelling without risk (Johnston, et al., 2009). Disadvantages of a simulation model are that the set up is time-consuming, developing a simulation model requires specialised training, and is often expensive to develop (Law, 2007; Shannon, 1998).

Law (2007) defines simulation as "*the creation of a model that represents a system, and using this model to better understand the system it represents*". According to Shannon (1998), simulation is "*the* *process of designing a model of a real system and conducting experiments with this model for the purpose of understanding the behaviour of the system and/or evaluating various strategies for the operation of the system".* As stated by both, simulation aims to model the real-world. With this model, we can analyse several interventions and the reaction of the system. Law (2007) classifies simulation models based on three characteristics. First, the model is static or dynamic. A static model is a representation of a system at a specific time while a dynamic model incorporates changes over time. Second, the model is deterministic or stochastic. Stochastic models incorporate random variables while deterministic models have predictable components and do not have probabilistic components. Third, a model is discrete or continuous. The variables in a discrete model change when specific events occur while continuous models change with respect to time.

Evaluating interventions in the real system is also possible but might be too costly, disruptive to a system, or ethical impossible (Law, 2007). Other techniques such as dynamic programming or linear programming are used less often (Cayirli & Veral, 2003). Incorporating different classes of patients, different service times, and priority rules makes it difficult to find any optimum with mathematical programming and makes the model complex. Because of these flaws of analytical models and mathematical models, we use simulation as a means to evaluate different interventions. More information can be found in the book of Law (Law, 2007).

2.5. Conclusion

In this chapter we described the literature for this study in order to answer research question 1:

> *What theories provide insight in the factors affecting the variability of the utilisation and what methods are suitable to improve the match between demand and supply?*

Since the literature addressing the radiology department is scarce, we use literature that focuses on the OR, ED, and outpatient clinics to generate insight and to find feasible interventions. We use insights from capacity management since it concerns balancing the demand of an operation and the supply of the resource. In order to identify the root causes of the variability and its predictive factors, we should take into account the natural as well as the artificial variability (Litvak, Green Vaswani, Long, & Prenney, 2010). Predictive factors of the variability in demand can be the periodic patterns (hourly, daily, weekly, yearly pattern), a lag component after 1 or 7 days, scheduling practices for scheduled patients, and the temperature (Moore et al., 2008; Litvak et al., 2010, Marcilio et al., 2013). Identifying the predictive factors enables to more accurately forecast the demand and/or affect the demand, and better adapt capacity to the demand. Since in the current situation, the demand highly fluctuates as well as the capacity is not adapted to the demand, we use both the chased demand plan as well as the managing demand plan (Slack, Chambers, & Johnston, 2007).

The literature proposes several approaches to improve the fit between incoming requests and available capacity. The development of generally applicable approaches is limited since each study has a specific patient mix. Most of the studies focus on managing scheduled arrivals and ignore the unscheduled arrivals. In our study, we deal with unscheduled arrivals in combination with scheduled arrivals. We use the interventions in order to get insight in the effect of the intervention for specific patient types. We model the current situation of the radiology department and evaluate experiments using simulation. Simulation is appropriate since the processes are characterised by uncertainty and are complex to model. Examples are the changing opening hours and the distribution of the service time and arrival rate.

3. Context analysis

This chapter analyses the current situation and process of the radiology department in order to answer research question 2. The primary process is a black box that converts a certain input to an output influenced by the planning and control mechanisms. We analyse the inputs, primary processes and outputs to get insight in the predictive factors of the output, the bottlenecks, and to demarcate the scope. Section 3.1 describes the inputs in terms of the available capacities, the demand characteristics, and referring specialties. Section 3.2 describes the primary processes at the radiology department. Furthermore, Section 3.3 describes the planning and control framework (Hans, van Houdenhoven, & Hulshof, 2011) and Section 3.4 describes the output of the system and identifies the predictive factors for the variability in output. Section 3.5 describes the bottlenecks that negatively affect the performance, and Section 3.6 ends up with the modality with the highest opportunity for improvement. Finally, Section 3.7 ends up with a summary of the current situation.

3.1. Inputs

This section describes the inputs of the primary processes. We first describe the radiology department and the available capacities in terms of research modalities (3.1.1). Thereafter, we describe the patient mix for each modality (3.1.2), and finally we show the referrers of the radiology department (3.1.3).

3.1.1. The radiology department

The radiology department serves most of their patients from the main location Isala Zwolle (RIS). Other locations are the outpatient department at Zwolle (REDC) and the outpatient departments at Kampen (RKA) and Heerde (RHA). Most of their equipment is generic and located at the radiology department within RIS. The radiology department has dedicated equipment at orthopaedics (bucky), at the ED (CT and bucky), at Internal Medicine (IM) (x-ray screening) and at the operating rooms (OR) (x-ray screening). The orthopantogram (OPG), a panoramic x-ray scan for teeth and jaws, is outside the scope of this research since oral surgery performs the registration process instead of the radiology department. Table 1 gives an overview of the modalities at the different locations in 2014. See Appendix 1 for the functionalities of each modality.

Location Modality	RIS	REDC	RKA	RHA	Total
Bucky	5	2	1	1	9
Echography	5	2	1	1	9
CT	3				3
Dexa		1			1
Angiography	1				1
Mammography	2				2
MRI	3				3
x-ray screening	4				4
OPG	1				1

Table 1 - *Overview of modalities at each location*

The different modalities highly differ from each other requiring a different approach. For example, the angiography has a less predictable service time than the dexa, which is partly related to the high rate of unscheduled patients. Therefore, more fluctuation in the utilisation and a lower overall utilisation of the angiography is expected than at the dexa. The modalities are different based on the average service time of an examination, the distribution of the service time, and the patient mix (see Section 3.1.2). Table 2 gives an overview of the characteristics of each modality. The service time is the planned duration of the examination together with the preparation and registration time. No data is available of the actual duration of an examination.

Modality	Service time (minutes) (CV)	(min, max) (minutes)	Inpatients	Outpatients
Bucky	5.1 (0.26)	(5, 60)	14.7%	85.3%
Echography	22.8 (0.18)	(5, 60)	12.9%	87.1%
CT	19.5 (0.39)	(10, 50)	32.2%	67.8%
Dexa	20.5 (0.13)	(20, 40)	0.5%	99.5%
Angiography	30.0 (1.30)	(5, 120)	91.5%	8.5%
Mammography	15.7 (0.46)	(5, 60)	3.8%	96.2%
MRI	33.2 (0.40)	(10, 120)	18.3%	81.7%
X-ray screening (IM)	26.9 (0.66)	(10, 90)	38.6%	61.4%
X-ray screening (OR)	45.0 (0.16)	(5, 100)	61.2%	38.8%

Table 2 - *Average yearly production and distribution (Ultragenda: 2010-2013)*

Furthermore, we can classify each modality based on its function. This classification is useful for efficient capacity planning that fits the characteristics of a modality. A classification used by Geraedts (2005) is using the steering factors for planning capacity; is it the availability of the patient or the scarcity of capacity? The characteristics of modalities with a capacity function and an availability function are (Geraedts, 2005):

Capacity function:

- *Shortage of equipment*: small availability of equipment, waiting lists are a common practice.
- *Latent demand*: much unpredictable/invisible demand, adjustments affecting the waiting list influence incoming demand (supply-driven).
- *Development of medical equipment*: fast development, equipment is rapidly outdated.
- *Planning and scheduling are important*: appropriate capacity management is important to handle the latent demand with scarce resources.
- *Patient follows the money*: the available capacity and money decide where patients go (van Montfort, 2010).
- *Pull-system*: the capacity determines if a request is served (Hopp & Spearman, 2000).

Availability function:

- *Large availability of equipment*: capacity is always available and there are no waiting lists.
- *Easily to increase capacity*: easy operations without extensive conditions
- *Predictable throughput time:* a simple procedure with low variation in throughput time.
- *Money follows the patient:* patients decide where to go and when (van Montfort, 2010).
- *Push-system*: the demand decides when capacity should be deployed, insight of (forecasted) future demand is required (Hopp & Spearman, 2000).

Van Montfort (2010) uses a comparable classification and defines the availability function as demand-driven and the capacity function as supply-driven. Table 3 shows the modalities from the radiology department and classifies each modality based on current insight and interviews with staff. The modalities with a capacity function have a waiting time in contrast to the modalities with an availability function. Therefore, the planning horizon is longer requiring different planning methods.

Because a different planning approach is required for each modality, we demarcate the scope of this research to a specific modality after assessing the current performance of each modality.

Capacity function	Availability function
MRI	Bucky
Dexa	Echography
Mammography	CT
	Angiography
	X-ray screening

Table 3 - *Classification of modalities*

3.1.2. Patient mix

As stated before, the input of the primary process highly differs regarding the patient mix. Besides identifying the patient mix in order to assess the desired situation, identifying the patient mix helps to find the causes of the mismatch between demand and supply. For example, if the demand largely consists of inpatients, the analysis should focus on referrals from the different inpatient clinics instead of the outpatient centre. The patient mix consists of outpatients patients from the outpatient centre and inpatients from the clinics within Isala (see Table 2). Emergency patients are patients from the emergency department (ED) and inpatients requiring an examination at the same day. Currently, databases do not offer any urgency distinction and therefore we can only classify outpatients and inpatients.

According to Slack, et al. (2007), a distinction in scheduled and unscheduled patients is important in order to identify the artificial and natural variability. Scheduled patients are outpatients and scheduled inpatients. According to management, inpatients can be regarded as unscheduled patients as most of the inpatients require a scan on the same day which can only be influenced by online operational scheduling. Figure 3 shows the production pattern for the bucky which is also a representation of the other modalities. As stated by Slack, et al. (2007), Figure 3 shows that the variability is mainly caused by human decision making (scheduling practices, holidays) instead of the natural randomness.

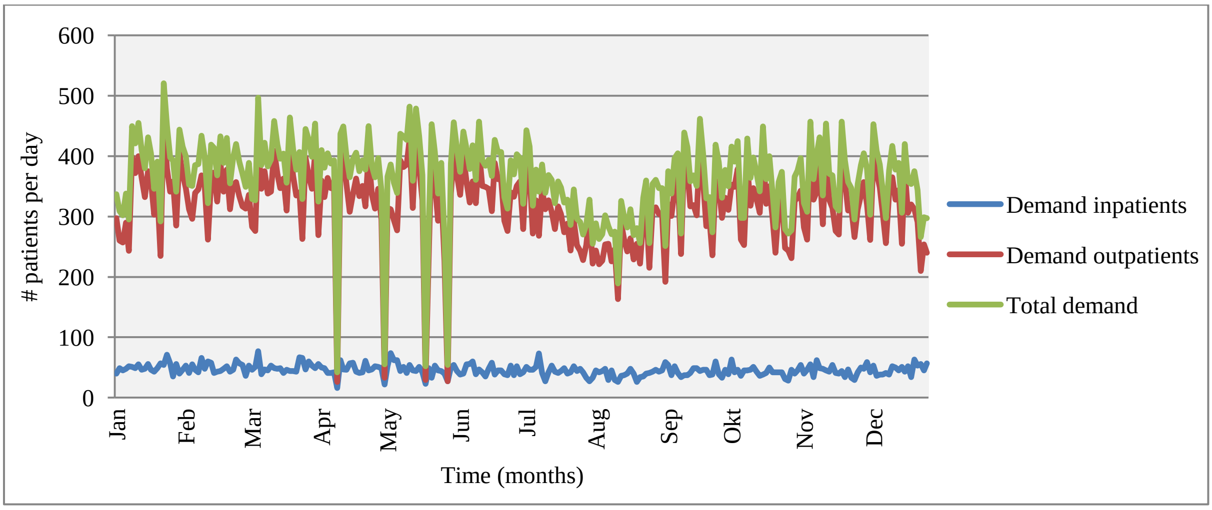

Figure 3 - *Artificial and natural variability of the production level of the bucky (Ultragenda: Jan 2012 – Dec 2012)*

3.1.3. Referrers

The referrals from of the radiology department come from the emergency department (ED), the outpatient department (REDC), and from the hospital wards (e.g. nursery, the operating rooms (OR), the intensive care (IC)). The inflow consists of requests for diagnostic research from different specialties. The inflow consists of 24% external referrals and 76% internal referrals. The general practitioners (GPs) are responsible for most of the external referrals and are not controllable by Isala. The internal specialties are better controllable by Isala. Management can discuss decision-making issues with the medical partnerships, but the medical partnerships are still responsible for a large part of their decision-making. Concerning the internal specialties, we can apply the 20/80 rule (Pareto principle). This means that 20% of the internal specialties refer 80% of the patients. Figure 4 shows the percentage of production for each internal specialty (controllable by Isala) and Appendix 2 presents the production in more detail for each specialty per modality.

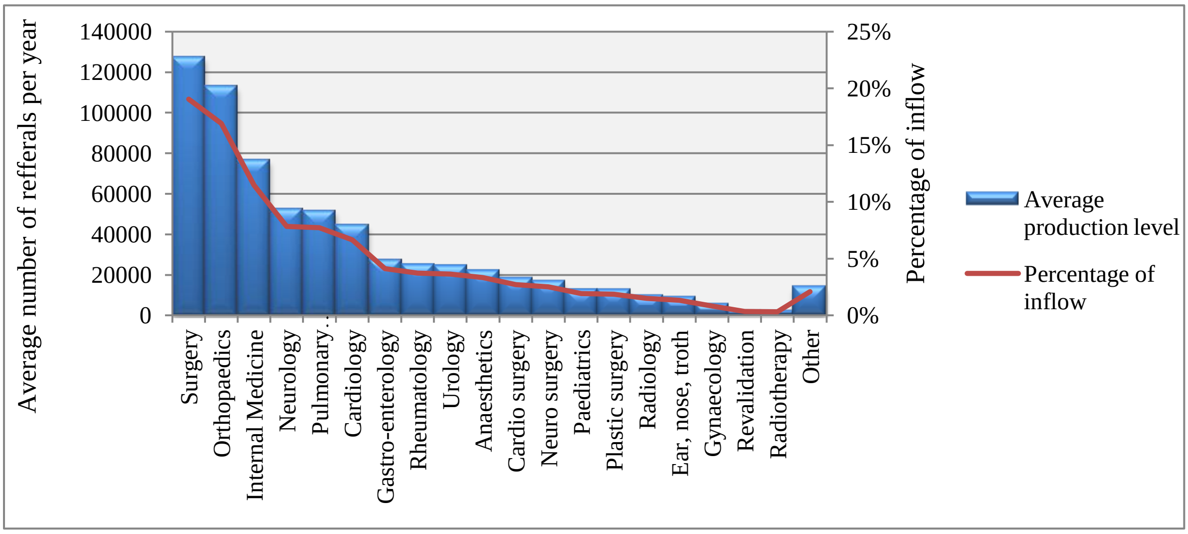

Figure 4 – *Yearly production of the radiology department (Ultragenda: 2010 – 2013)*

3.2. Primary process

Figure 5 shows the primary process for the different patient groups. The groups have different priorities for research but have a comparable primary process. In general, emergency patients have the highest priority and outpatients the lowest. However, it highly depends on the patient characteristics, urgency, and planners if the priority rule is strictly used (see next paragraph).

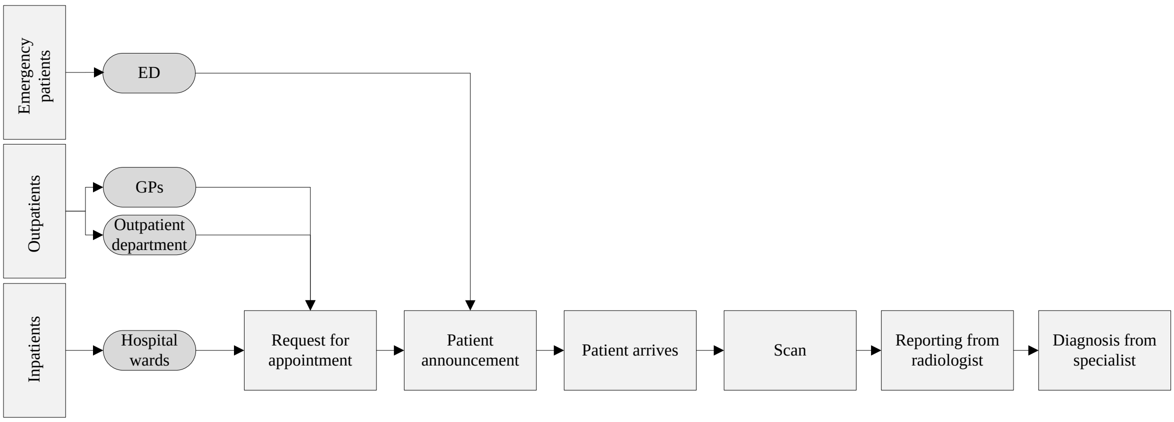

Figure 5 - *Overview primary process at the radiology department*

The first sub-process is the request for appointment. The planners at the front-desk of the radiology department plans the appointment for inpatients and outpatients on the first possible slot (FCFS) providing that the patient is available. Requests for outpatients are performed by the patient himself and requests for emergencies or inpatients are performed by the specialty. On the time of appointment, outpatients arrive at the desk and wait for the examination. Sometimes these patients get a higher priority than inpatients when they are already in the hospital and require an additional examination. Concerning the inpatients, the planners schedule an appointment time but this is not necessary the time that the patient can get access. The radiology department calls the referring department when they have a free slot so that the inpatient can arrive. This may negatively affect the entire hospital flow since the referring department cannot forecast the time that the nurse and porter need to be available for transferring the patient. This results in delays at the referring department as well as at the radiology department. Therefore, most of the times emergency patients have the highest priority, then outpatients requiring an additional examination, then inpatients, and then the other outpatients.

After the patient arrives, the technician invites the patient for the examination and performs the preparation (contrast fluid, positioning, etc.) and the examination follows. Afterwards, the sub-process reporting by the radiologist follows. The technician sends the findings to the radiologist who analyses the findings. Because of data constraints, we are not able to identify whether the radiologists are a potential bottleneck in the diagnostic process. Accordingly, the specialist receives the findings from the radiologist and gives the diagnosis to the patient. The time from request until diagnosis should be minimised in order to improve the outcome for the patient (American Cancer Society, 2013; Cancer Research UK, 2009) and reduce waiting costs for the hospital. Section 3.4 describes this performance in more detail.

3.3. Planning & Control

To give a more detailed description of the problem on different management levels, we use the healthcare planning and control framework of Hans, van Houdenhoven, & Hulshof (2011). The four-by-four framework incorporates four hierarchical levels and four managerial areas in order to help positioning problems and to demarcate the scope. The problem described in Chapter 1 focuses on the planning and scheduling of renewable diagnostic resources. Therefore, the scope of this research project demarcates to the area of resource and capacity planning. Table 4 represents the framework, and accordingly, we analyse each quadrant from the area resource capacity planning.

Area **Level**	Medical planning	Resource capacity planning	Materials planning	Financial planning
Strategic	Development of medical protocols	Case mix planning	Supply chain design	Investment plans
Tactical	Protocol selection	Block planning, admission planning	Supplier selection	Budget and cost allocation
Offline operational	Diagnosis of individual treatment	Appointment scheduling	Determining order sizes	Diagnosis related groups (DRG) billing
Online operational	Triage, diagnostic emergencies	Monitoring	Inventory replenishing	Billing complications

Table 4 - *Framework for hospital planning and control (Hans, van Houdenhoven, & Hulshof, 2011).*

Strategic level

The strategic level concerns decision making about case mix planning and capacity dimensioning. With the new hospital, the radiology department has slightly changed their capacity (equipment as well as staff) based on historical demand and forecasted future demand. In the new building of the hospital, the radiology department has 24 modalities. Most of the modalities are located at the radiology department. A bucky and CT are dedicated to the emergency room, one bucky is dedicated to orthopaedics, two x-ray screening modalities are dedicated to IM and two x-ray screening modalities are dedicated to the OR. Table 5 gives the mix of staff at the radiology department. Other strategic decisions mainly focus on the level of radiologists and purchasing new equipment.

Employees	# FTE
Administration	21.8
Radiologist	14.8
Pathological analyst	1.0
Technician	81.3
Operational manager	6.6
RVE manager	1.0

Table 5 - *Staff mix*

Tactical level

Staffing and partly scheduling are elements of capacity management at the tactical level (Ozcan, 2009) and depend on decisions at the strategic level. We describe the staffing decisions for technicians, since this is the largest group of employees and are the focus of this research. Thereafter, we describe the resource scheduling decisions.

For the more complex modalities (MRI, CT, angiography) the radiology department has specialised technicians allowed to work at these modalities. For the other modalities, the technicians are interchangeable and therefore flexible to schedule. The scheduling pattern is cyclical (Ozcan, 2009) and has a static character. The scheduling horizon for technicians is four weeks. The radiology department schedules each week the same number of technicians, which fluctuates based on the available number of staff. Therefore, it is highly supply-driven since the number of scheduled technicians depends on the available capacity rather than the forecasted demand. Appendix 3 gives the different shifts and working hours of technicians after the new building in August 2013.

Block schedules are the basis for capacity planning at the radiology department. With block schedules the radiology department reserves slots (time blocks) for specific patient groups, specialties or departments. Current management control at the tactical level is negligible. Therefore, the block schedule does not always fit actual demand resulting in underutilisation and increased access times. Changes in the block schedule are rare and based on insight of the operational manager rather than calculations or forecasts. Some operational managers discuss the future demand with a (small) part of the requesting parties in order to adapt the block schedule. However, there are no structured meeting to discuss future demand of each speciality. With these meetings, the radiology department could establish the required capacity for each group.

Operational level

At the operational level, operational managers reallocate staff between modalities (online operational level) and planners perform the appointment scheduling (offline operational level). Currently, there is no insight in the reallocation practices. Therefore, it is not possible to calculate the real utilisation of staff. Furthermore, there is no insight in the required number of technicians at each time at each modality disabling efficient reallocation. Appointment scheduling is performed at the front desk of the radiology department or at the desk of the MRI and CT. In general, the planners use the First-Come, First-Served (FCFS) rule and directly plan the requests. The system directly transfers this appointment to the work list of the assigned room. If a patient needs an appointment a long time ahead, planners store the request for a later moment. However, for each modality, there are different employees responsible for the appointment scheduling (planner or technician) resulting in different practices. According to the planners at the front desk, many problems occur because of the use of different rules (or no rules at all). Examples of these problems are that it is not clear when there are peaks of requests for patients requiring fast access and that request forms are incomplete.

3.4. Current performance

This section analyses the current performance and analyses the factors that cause the fluctuations. By identifying the controllable and non-controllable factors that cause the fluctuations, we are able to develop interventions.

3.4.1. Stakeholders analysis

In order to establish the current performance of the process and control mechanisms, we establish key performance indicators (KPIs). By quantifying the current and future performance, we can establish the effects of logistical decisions. Nevertheless, how do we define the performance? This depends on the point of view of the stakeholders. Figure 6 shows the different stakeholders of the radiology department. Stakeholders have their own interest and specific KPIs that are important to them. Since this research focuses on optimisation the logistical performance of the radiology department, we describe logistical KPIs for these four perspectives.

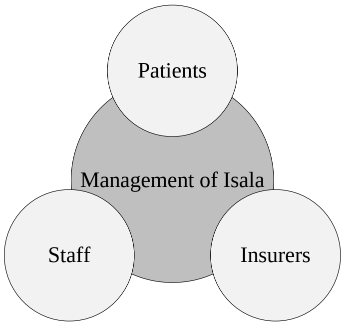

Figure 6 - *Stakeholders radiology*

Patient perspective

When patients and their GPs (the gatekeeper of healthcare) choose for a hospital, the access time plays a dominant role. An early access time implicates a fast diagnostic track. However, a low access time does not directly imply an early diagnosis. Therefore, the total length from request to result is important (throughput time). When looking at the access time, for patients there is a high difference between direct access and a waiting time. Scholtens (2009) has analysed the patient preferences regarding the planning processes of the CT scan and found that the most important aspect is same-day access. Table 6 shows the most important KPIs for the patient perspective in the scope of this research.

KPI	Definition
Access time	Time between request and time of appointment
Throughput time	Time between request and time of diagnosis
Waiting time	Time that patient waits at the waiting room
Same-day access	Proportion of patients getting the examination on the day of request

Table 6 – *KPIs from a patient perspective*

Insurer perspective

From the insurer's point of view, the production level is a leading factor during the negotiation with hospitals. Furthermore, the access time is an important pillar during the negotiation process and is a reflection of the quality of a hospital (Sint Maartenskliniek, 2011; Custers, Arah, Klazinga, 2009). Because of the increased attention on quality of care, the KPI access time becomes more important in the future (Zorgvisie, 2014). Table 7 shows the most important KPIs.

KPI	Definition
Access time	Time between request and time of appointment
Production level	Number of served patients per year

Table 7 – *KPIs from an insurer perspective*

Staff perspective

Based on observations at the radiology department, we can assume that the peaks in the workload determine staff satisfaction. During these peaks, staff has to serve a respectively higher demand with the same amount of staff. The radiology department currently measures the workload using the Sanders points system. The Sanders points system is a national registration system to represent the required time of radiologists for each specific intervention (De Nederlandse vereniging voor radiologie, 2008). If there is more variability in the workload (number of Sanders points per time unit), the peaks are higher. Therefore, we measure the variability in order assess the workload. Another factor that is important for staff and can be influenced with this research is the amount of overtime. More overtime results in a lower staff satisfaction.

KPI	Definition
Overtime	Worked time outside regular working hours
Workload	Variability in Sanders points

Table 8 – *KPIs from a staff's perspective*

Management perspective

In this research, we define the management perspective as the Board of Directors and management of the radiology department. We assume that the management perspective is based on the perspectives of patients, insurers, and staff. Therefore, most of the KPIs overlap and therefore we only present organisation specific KPIs. The first KPI is the utilisation of the rooms. A high utilisation of rooms results in low unit costs since it allows sharing capacity costs (rooms accommodated with technicians) over more units. Furthermore, the deviation of the realised time from the planned examination time is important. A higher deviation implies a higher variability in the demand or that the scheduled duration does not match with the real duration. Accordingly, this results in over- or underutilisation complications (for example high waiting times or high costs). Furthermore, the number of no-shows is important for efficient scheduling. With a high number of no-shows, the schedule can allow overbooking in order to fill available time resulting in a higher utilisation. Finally, one of the most important KPIs for the management perspective is staffing costs. Staffing costs represent a large portion of the hospital's budget and are therefore important to control.

KPI	Definition
Utilisation of rooms	Time that room is occupied divided by time that room is available
Planned versus realised examination time	Deviation of realised examination time from

	planned examination time.
No shows	Patients that do not show up for their appointment
Staffing costs	Yearly direct and indirect labour costs and premium

Table 9 – *KPIs from a management perspective*

3.4.2. Measurement constraints

Based on the four stakeholders we can identify twelve KPIs. For some KPIs not sufficient high-quality data is available. We could collect data by performing observations or by collecting data from the software of the modalities. However, collecting sufficient data would be too time consuming with respect to the additional value. Therefore, we do not measure some KPIs. Main causes for the data constraints are that the times are not measured or because the time is an approximation.

Time is not measured: Figure 7 shows the important times for the patient. The current information system does provide insight in the realised times that the patient arrives at the radiology department, the start time of the scan, and the time of diagnosis from the specialist. Therefore, we cannot measure the waiting time and the throughput time. Furthermore, the radiology department only has systems that show the shifts that staff is scheduled. There is a lack of insight in the realised working hours. Therefore, we are not able to measure overtime. At last, we are not able to measure the number of no-shows since data sources only show the realised examinations.

Time is an approximation: For the access time, we require insight in the time of the *request for appointment* and the time that the *patient arrives*. Both times are not available but we can approximate the times with available data. We approximate the *request for appointment* by looking at the date of the preceding appointment at the specialist. However, this can slightly misrepresent the actual access time. For example the actual access time can be longer if the specialists requests an examination on day i, sees the patient again on day i+1, while the examination is scheduled at day i+4. In addition, we use the scheduled appointment time to measure the time that the patient arrives. Furthermore, we measure the utilisation of rooms using the scheduled appointment durations because of a lack of insight in realised durations. The scheduled durations may differ from the actual durations. As well as for the workload, we can only measure the scheduled workload and not the realised workload. Finally, this means that we approximate the access time, the utilisation, and the workload. We should take in mind that this only enables to compare the scores relatively between modalities but do not represent the absolute score.

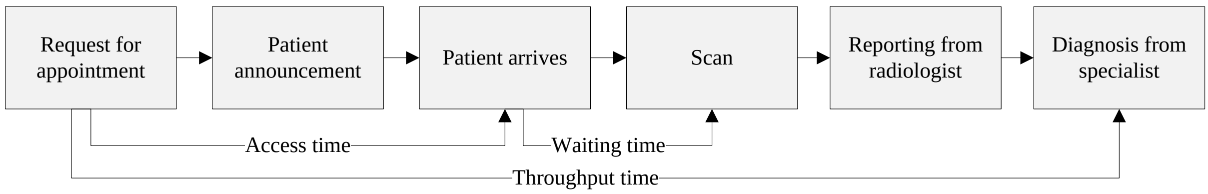

Figure 7 – *Process steps and durations*

3.4.3. Included KPIs

KPI 1: Access time

We can measure both the prospective access time as well as the retrospective access time. The prospective access time provides information concerning the future available appointment time (for example, the third available slot). The retrospective access time is the realised access time. Most of the times, this access time differs from the prospective access time since not each patients requires direct access. Because of data constraints, we only measure the retrospective access time in days. We measure the access time by only taking into account scheduled patients since unscheduled patients in general have no access time in days.

We use the date of the preceding appointment at the specialist and the scheduled appointment date to measure the access time. Therefore, we retrieved a new data set consisting of 7263 examinations with a preceding appointment at the specialist.

We define the access time as:

Access time = day of examination – day of request

KPI 2: Access-ratio

To analyse whether the access time changes over time, we determine the access ratio. The access ratio shows whether the available capacity fits the demand. If the ratio is larger than 1, the incoming demand is higher resulting in an increasing waiting list. If the ratio is smaller than 1, there is more capacity available than required for the demand of today resulting in a reduced waiting list or even a surplus of capacity. We define the access ratio as:

$$\text{Access ratio} = \frac{\#\,arrivals}{\#\,served\ patients}$$

KPI 3: Same-day access

Same-day access enables patients to see their own physician, it reduces the number of hospital visits (Wong, Watson, Young, & Regan, 2008), decreases the number of no-shows, reduces interruptions and telephone callbacks and reduces backlogs (Murray & Berwick, 2003). However, a high-same-day access ratio of scheduled patients reduces the available time for unscheduled patients. Therefore, the same-day access ratio for scheduled patients negatively correlates with the waiting time for unscheduled patients.

We measure the same-day access rate using data of Ultragenda. This data set contains the date of request but does not contain the patient type. Therefore, we are only able to measure the same-day access for all patient types. However, it would be more valuable to assess the same-day access rate for scheduled patients since the unscheduled patients usually get same-day access. Furthermore, we are not able to measure the correlation between the same-day access rate for scheduled patients and the waiting time for unscheduled patients.

We define the same-day access ratio as:

$$\textit{Same-day access ratio} = \frac{\#\, patients\ for\ which\ day\ of\ request = day\ of\ appointment}{total\ number\ of\ patients} * 100\%$$

KPI 4: Production level

The production level is a main focus of the radiology department and is an indicator for the revenues. We measure the average production level over the years 2010 to 2013 based on the number of realised examinations using the following formula:

$$\textit{Production level}_{2010\text{-}2014} = \textit{Average number of realised examination per year}$$

KPI 5: Workload

To calculate the workload the department uses Sanders points. Sanders points is a national registration system to represent the required time of radiologists for a specific intervention. One Sanders point equals one minute of work for a radiologist. The radiology department also uses the system to express the workload of technicians. However, the workload of a technician is not always the same as the workload of radiologists since both have different tasks. For example, on average, 45 Sanders points represent an MRI scan. The analysis of the examination by the radiologist can take 45 minutes, but executing the examination and assisting a patient by the technician can for example take 30 minutes. Furthermore, the Sanders points system is not directly applicable to compare the average score between modalities. For example, 30 Sanders points for a CT scan is not the same as 6 examinations of 5 Sanders points at the bucky. At the radiology department, the Sanders points are used to see the trend for each modality. Appendix 4 represents the trend over the years 2010-2013.

We measure the workload for each weekday, week and month. It is not possible to calculate the hourly workload because of data constrains. We measure the variability using the coefficient of variation (CV) instead of the standard deviation. The CV is the standard deviation divided by the mean, which enables to compare the variability regardless of the mean. We measure the workload as:

$$\textit{Workload} = \frac{\sigma\ (\#\, Sanders\ points\ per\ day\ per\ room)}{\mu(\#\, Sanders\ points\ per\ day\ per\ room)}$$

KPI 6: Utilisation level

To determine the time that the modality is used for patient care, we calculate the utilisation level of the rooms of each modality. The utilisation level is based on a workday from 8:00 PM to 17:00 AM. This means that we only measure the scheduled service time in this specific time frame of workdays. Therefore, the available time at a room equals (60*9=) 540 minutes. The databases do not provide information about realised service times.

Furthermore, each examination type at each modality has a standard scheduled duration. However, in reality there are still large differences within a specific examination type. The within deviation can be explained by the different patient characteristics (urgency, age, weight, etc.) or by randomness in the scheduling practices. Appendix 5 gives an example of the different scheduled durations for an MRI of the knee. We incorporate these differences by calculating the utilisation level as:

$$Utilisation = \frac{sum\ of\ scheduled\ service\ time}{sum\ of\ available\ time} * 100\%$$

With this KPI we are able to identify whether the planning results in a robust schedule. If the ratio is too high, the operational waiting time for patients increases, the flexibility of the schedule decreases, and overtime increases. If the ratio is too low, the unit costs per patient are high and the waiting list increases. So, we should find an optimal utilisation level to have an acceptable outcome with respect to the competing KPIs. Figure 8 shows the positive correlation between utilisation rate and waiting time based on the Pollaczek-Khintchine formula (Pollaczek, 1930). The expected waiting time increases if the utilisation rate increases or if there is more variability in the service time. The Pollaczek-Khintchine formula is stated as:

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

EW_q = expected waiting time
μ = expected service time
ρ = utilisation rate ($\frac{\lambda}{\mu}$)
CV_s^2 = squared CV of service time

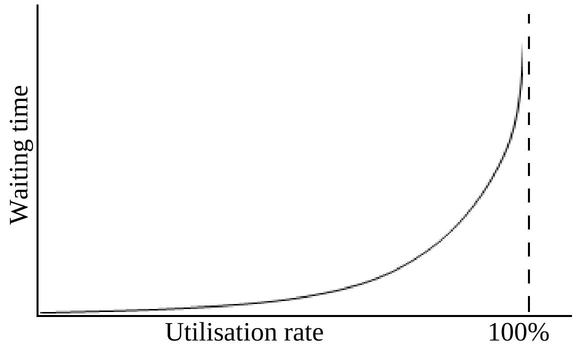

Figure 8 – *Relation utilisation and waiting time*

KPI 7: Staffing costs

We only focus on staffing costs since in the scope of this research we can only directly influence staffing costs and not, for example, costs for disposables. In addition, we focus on the staffing costs of technicians since this is the largest staffing cost centre of the radiology department (Kostprijsmodel, 2013). We define the staffing costs as:

$$Staffing\ costs = \sum labour\ costs\ dedicated\ to\ technicians\ (per\ year)$$

3.4.4. Measurement current performance

This section performs a zero-measurement to identify the bottlenecks and to determine the modality that shows the most opportunities for improvement. For the calculations, we use data recorded in the system of the radiology department and hospital wide data systems (Cognos and Ultragenda). This contains data of the old building (registration before August 2013) and the registration from the new building (registration from August 2013). In order to identify if production levels are comparable before and after the new building, we perform a Student's t-test assuming equal variances. Comparing the total data set we do not see a statistical difference before and after August 2013 (t(df=182) = -0.04, P-value = 0.97). Also, when we look at a specific modality, for example the bucky, we do not see a statistical difference (t(df=201) = -1.49, P-value = 0.14). As proposed by Litvak, et al. (2010), we measure both the average performance and the variability of the performance.

In the current situation, the only KPI that the radiology department uses is the utilisation level. Therefore, the process is organised in order to achieve the highest utilisation level, which can negatively affect other KPIs. Furthermore, the radiology department has no norms for the KPI(s). As stated in Section 3.1, each modality has different requirements, which disables to directly compare the KPIs with each other. We deal with this problem by comparing the modalities taking into account whether the modality has an availability function or a capacity function.

KPI 1: Access time

Figure 9 shows the average and median retrospective access time of 90% of the requests of each modality. We measure 90% of the requests since sometimes specialists request an image to be performed over several weeks/months (for example, a follow-up consult). We correct for these high access times by not taking into account the highest 10% access times for each modality. Each modality has a positively skewed distribution (see Figure 9: the average is always higher than the median). Furthermore, looking at the median diminishes the impact of the extreme high access times. Therefore, the median is a better representation for most of the requests.

Based on the median access time, we see that the echo and CT perform the worst of the availability - modalities and the dexa scores the worst of the capacity-modalities. Especially for the dexa, the score is high with respect to the patient mix (99.5% scheduled arrivals). This can imply that there is a shortage of capacity or that a waiting list is acceptable (then the utilisation for the dexa should be high), or that the scheduling practices are inefficient resulting in a waiting list.

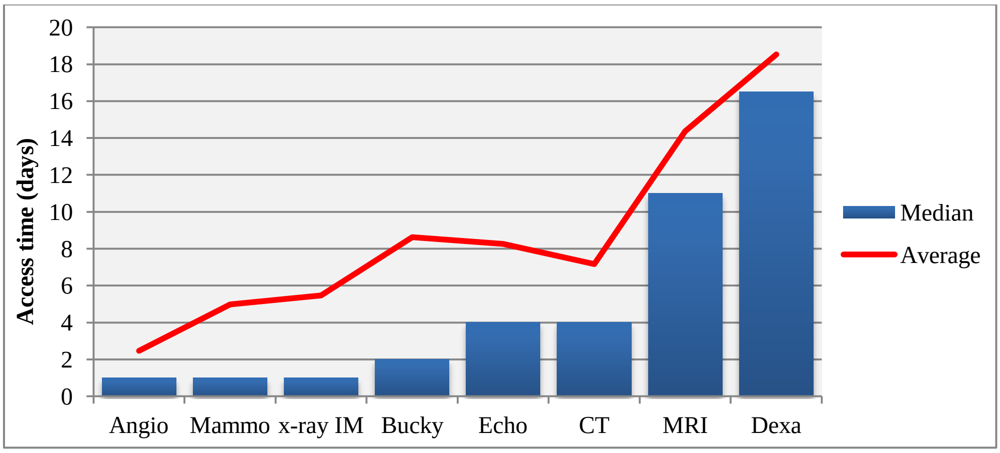

Figure 9 - *KPI access time (Cognos: n = 238,402)*

Table 10 shows the CV of access time. If the CV is higher, there is more variability. Since the access time is positively skewed (more observations on the right of the median) the CV is larger than 1.

Much variability in the access time implicates that the artificial variability is high and that the capacity is not adapted to the variability or that the natural variability is high. The modalities with the highest CV are the CT, echo, and mammo. The natural variability can explain the relative high CV for the CT. However, for the echo and mammo the high CV can better be explained by the high artificial variability. Section 3.3 shows that at the tactical level, the radiology department uses block schedules. These block schedule are not updated frequently for each modality and therefore, do not always fit the incoming demand. This is a possible cause of for the high CV for the echo and mammo.

Modality	CV
Angio	2.40
Mammo	2.61
x-ray IM	1.14
Bucky	2.38
Echo	2.93
CT	3.11
MRI	1.14
Dexa	2.09

Table 10 - *CV of access time*

KPI 2: Access-ratio

The access ratio is the ratio of arriving patients to served patients. Figure 10 shows the access ratio for the bucky (most stable access ratio) and the x-ray at the IM (most variable access ratio). When there is much variability, the capacity does not fit the demand and does not serve patients at the right time.

This results in waiting lists. The bucky has a very stable pattern, and therefore, there is a good fit between available capacity and incoming demand.

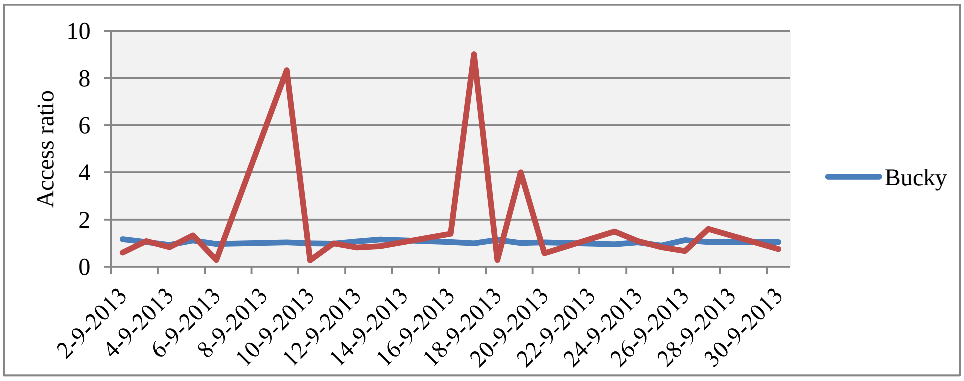

Figure 10 – *KPI access ratio (Cognos, September 2013)*

Table 12 shows the mean and standard deviation of the access-ratio. The dexa has a mean below one. This means that on average there is more capacity than demand. The MRI (μ = 1.16) and x-ray (μ = 1.52) at the IM show that many times the average is above one. This can have several causes: a shortage of capacity, a backlog, a highly variable demand with a large forecasting error, or that the scheduling mechanism does not work efficient (depending on the variability). The MRI has a relatively low variability. Therefore, in general the capacity is available when required. The high mean access ratio can imply a shortage of capacity or a backlog from the movement to the new building. The x-ray at the IM (stdev > 1) shows more variability. This can be a result of either the highly variable demand or an inefficient forecasting and planning of capacity. For this KPI, the modalities with much variability and an access-ratio that highly deviate from one have the most opportunity for improvement (dexa and x-ray at the IM).

KPI 3: Same-day access

Figure 11 shows the ratio of patients served at the day at which also the specialist requests the examination. The highest same-day access ratio is for the modality angiography and the lowest for the dexa. Based on interviews, we can remark that this is due to the proportion of unscheduled patients. The angiography has the highest proportion urgent patients and the dexa has the lowest proportion of urgent patients. After the angiography, the x-ray IM has the highest proportion inpatients. However, we see that these patients show a low same-day access rate. Furthermore, it is remarkable that the bucky has a relative high same-day access rate based on the unscheduled arrival rate (14.7%) and compared with the unscheduled rate of the echo (12.9%).

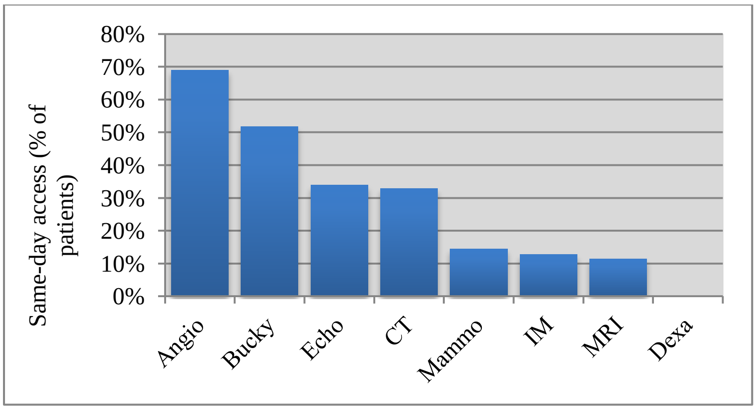

Figure 11 – *Average same-day access rate (source:*

KPI 4: Production level

Table 11 shows the average production levels over the years 2010 to 2013. The bucky produces most of the examinations and the dexa the least. When deciding on the modality with the most opportunity for improvement, we weigh this by the impact of improving the process. This partly bases on the production level. If the production is high, adapting the process has influence on many patients. Furthermore, we weigh the impact of improving the process by analysing the financial impact (see KPI 7).

Modality	Average yearly production (# served patients)
Bucky	121381
Echography	30153
CT	22233
Dexa	1923
Angiography	2510
Mammography	6247
MRI	13142
X-ray screening (IM)	2569

Table 11 – *Production level 2010 - 2013*

KPI 5: Workload

Figure 12 presents the workload over the weekdays using boxplots. When the box is larger, the variation (CV) within a weekday is higher. When the difference of the medians (line within box) is larger, the variation (CV) between weekdays is higher. The workload measures the total number of Sanders points and does not relate this to the number of scheduled staff since this is static over the weekdays, weeks, and months. An exception is the increase at the x-ray IM at Tuesdays when the level is 1,5 FTE instead of 1 FTE. This is not in relation to the high increase at the Tuesday. The other exception is the dexa who have no staff at Fridays. However, this modality still shows many variability. We do not correct for these days in the figure, but correct for this in Table 12.

The y-axis is not equal since the graph does not allow comparing averages but allows comparing relative variation. The dexa shows the largest variation (CV) within a weekday. Other modalities that show much variation between weekdays are the dexa, x-ray IM and mammography. Angiography, echography, CT, MRI, and x-ray OR show outliers above median. The evening appointments at specific days explain these outliers.

Appendix 6 shows the weekly and monthly workload patterns. These patterns show a remarkable seasonal pattern for the bucky, echography, dexa and mammography. The demand drops down during the holidays and peaks right before and after holidays. The other modalities have a more random pattern since these modalities have on average a higher urgency for patients.

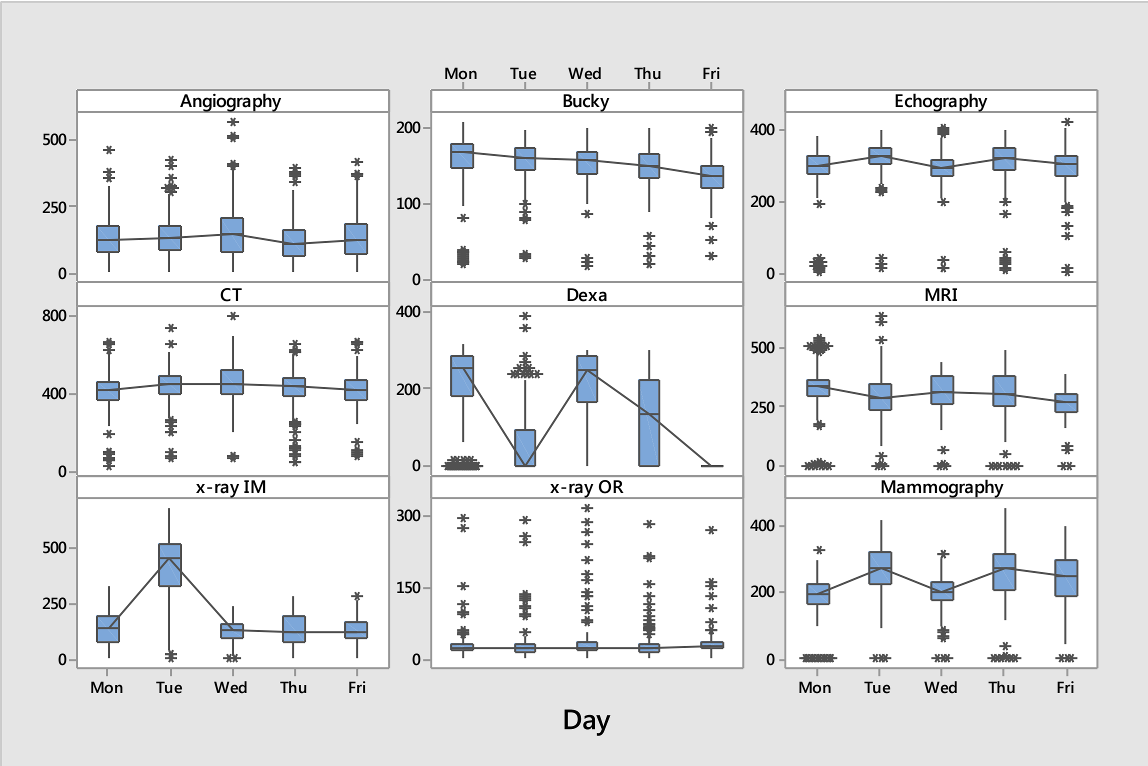

Figure 12 - *Variability of workload over the days (source: Cognos, n=1043 days)*

KPI 6: Utilisation level

Figure 13 and Figure 14 show the hourly and daily utilisation pattern of two modalities that show the difference in variability between a modality with a high variable pattern (echo) and a modality with a low variable pattern (MRI). As stated before, there is positive relation between the access time and utilisation level. Maintaining a low access time, results in a relative lower utilisation level. Therefore, it is acceptable that the utilisation level of modalities with a clear availability function is lower than that of the modalities with a clear capacity function.

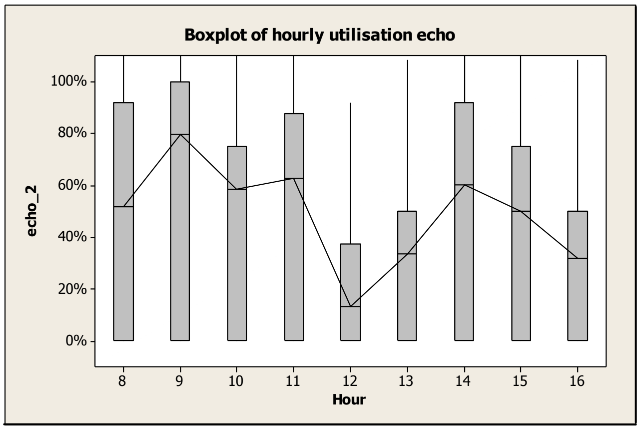

Figure 14 - *Utilisation per hour (echo)*

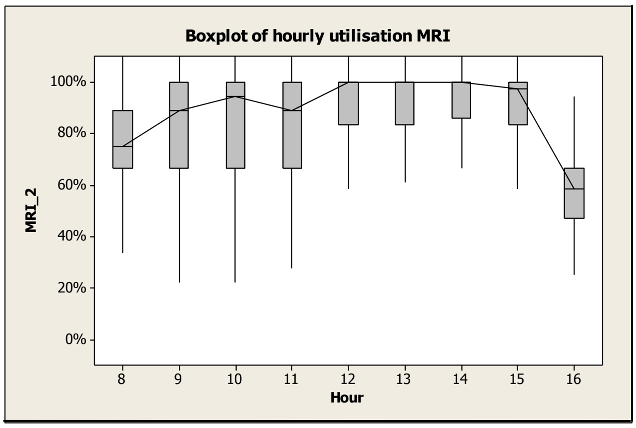

Figure 13 - *Utilisation per hour (MRI)*

We calculate the utilisation levels per hour, per day, and per week (see Figure 15). The MRI has the highest utilisation level followed by the CT. For the MRI, this is also expected with a high access time. Regarding the CT, the utilisation level is quite high with respect to the amount of unscheduled patients. The x-ray IM has the lowest utilisation level followed by the dexa. For the x-ray IM this is in line with the low access time. When the access time is low, the radiology department has a short planning horizon to schedule the incoming demand. Therefore, the utilisation is expected to be lower when the access time is low. However, for the dexa it is remarkable that the modality has a low utilisation and a high access time. Looking at the amount of scheduled arrivals, this implies that the scheduling practices are inefficient and have a high opportunity for improvement.

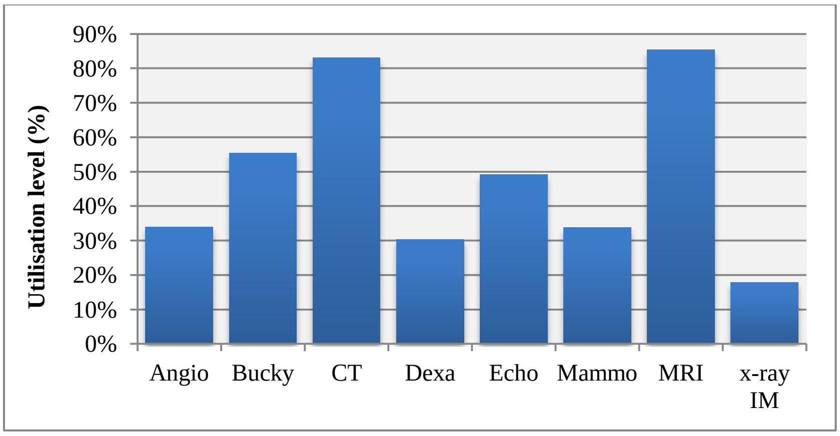

Figure 15 – *KPI utilisation level (average of hourly, daily, and weekly utilisation)*

Table 12 shows more detailed data of the utilisation. The bucky and echo show the highest overall variability in the utilisation, which addresses the high experienced workload. Looking at the hourly, daily and weekly variability, we see most of the variability in the hourly pattern (angio: $\sigma = 0.42$; bucky: $\sigma = 0.40$; echo: $\sigma = 0.39$). This are modalities with an availability function so the demand is less predictable which results in a higher variability. The demand is less predictable because of relative high rate of unscheduled arrivals. However, also a large part of the hourly, daily and weekly variability is artificial. Based on observations and meetings with the stakeholders, we now identify the main predictors of the variability in the utilisation.

For the hourly utilisation, we see for most of the modalities the typical pattern of Figure 14 . The peaks are around 9AM, 11AM, and 2PM. A predictor for these peaks are the visits of specialists to the patients at the wards (generating peaks of unscheduled arrivals). Most of the time, the specialist directly wants an examination. Therefore, the time of request of unscheduled patients and the visits of specialists are major predictors of the variability. Furthermore, we see the lowest utilisation around noon. At this time, many radiologists are on break and therefore the radiology department does not schedule many patients. As stated in Section 3.2, many outpatients who are already in the hospital requiring an additional examination get priority. Therefore, the time of request of scheduled patients is also a predictor. For the daily pattern, we notice that the office hours of specialists are a predictor. For example, the office hours of rheumatologists are a major predictor for the demand at the echo. We are not able to measure this correlation since we have no insight in the office hours of the outpatient clinics. This would be valuable since many patients are outpatients and referred from the outpatient clinics. Furthermore, the discharge moment in the week is important for the daily variability. At Fridays, many specialists want to discharge the patients in order to reduce the workload during the weekends. Therefore, we see for many modalities a peak of inpatient requests at the Friday (as well as at the end of each day). Looking at the weekly patterns, we see a clear seasonal pattern for most of the modalities with peaks before and after each recognised holiday.

KPI 7: Staffing costs

Figure 16 shows the yearly staffing costs dedicated per modality. Most of the costs are from the bucky and thereafter the echo. These costs are high because of the high number of modalities (both 9 modalities) that have at least one technician per room per day. While the number of rooms of the bucky and echo is equal, the staffing levels at the bucky are much higher.

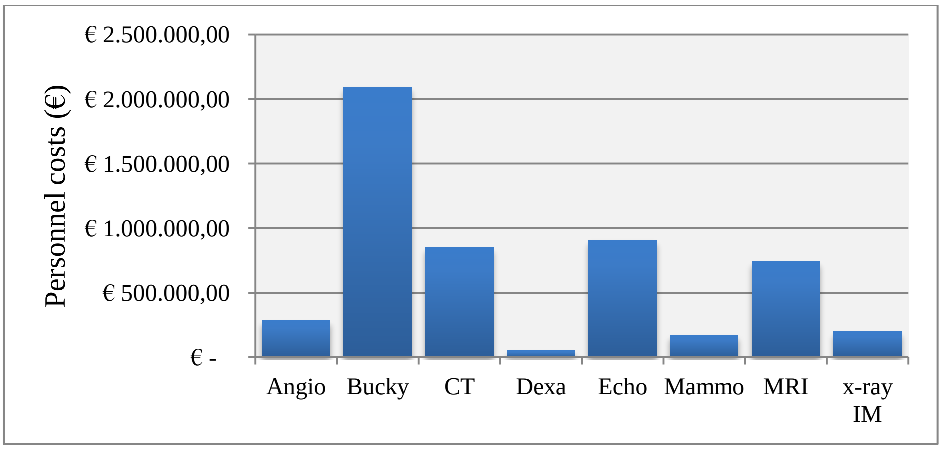

Figure 16 – *KPI staffing costs*

3.4.5. Overview

In this section, Table 12 gives an overview of the current performance at the radiology department. In order to identify the modality with the highest opportunity for improvement and the most impact, we compare the process indicators (1, 2, 3, 5, and 6) with the production level and staffing costs. Finally, we focus on the modalities with the highest opportunity for improvement based on the process indicators weighted for the production level and staffing costs.

	Angio	Bucky	CT	Echo	MRI	Mammo	IM	Dexa
KPI 1: access time (median)	1	2	4	4	11	1	1	16
KPI 1: access time (CV)	2.40	2.38	3.11	2.93	1.14	2.61	1.14	2.09
KPI 2: access ratio (μ)	0.98	0.96	1.00	1.03	1.16	1.05	1.52	0.62
KPI 2: access ratio (σ)	0.66	0.19	0.32	0.55	1.00	0.88	1.82	1.04
KPI 3: same-day access	69%	52%	33%	34%	11%	14%	13%	0%
KPI 4: production level	2510	121381	22233	30153	13142	6247	2569	1923
KPI 5: workload (σ)	0.24	0.88	0.22	0.80	0.14	0.13	0.12	0.37
KPI 6: utilisation level (μ)	34%	55%	83%	49%	85%	74%	18%	43%
KPI 6: utilisation level (σ)	0.27	0.35	0.24	0.26	0.18	0.15	0.11	0.25
KPI 7: staffing costs	€ 283.011	€ 2.094.281	€ 849.033	€ 905.635	€ 741.489	€ 169.807	€ 198.108	€ 50.942

Table 12 – *Overview performance*

3.5. Bottlenecks

Section 3.4 performed the zero-measurement and described the factors that affect this performance. We described the factors that affect the overall performance as well as the specific predictors that affect the variability of the utilisation based on meetings with the operational managers, observations at the floor, and a detailed analysis. We now summarise the bottlenecks that affect the performance for the entire radiology department.

1. **Data registration**
   1.1. *Realised service time not available:* The databases do not record the realised service times. Recording these times is valuable in order to determine the required appointment time for each examination and patient type. Furthermore, with insight in the realised service times we can measure the realised utilisation. This enables to better control and optimise the operational performance (e.g. decrease waiting times and decrease workload).
   1.2. *Request form incomplete:* In the current situation, planners use the FCFS rule and schedule each patient in the first available slot. When the request form contains the date of the second-consult, the planner takes this into account and postpones the appointment. However, most of the times essential information misses on the request form resulting in the FCFS. This negatively affects the access time for patients requiring fast access (since each patient gets fast access). Furthermore, it results in a high experienced workload and a high utilisation since the FCFS approach does not affect the peaks in the number of requests. Recording the date of request and the date the follow-up consult at the specialist increases the planning horizon, and enables to smooth the incoming variability in requests. We refer to this time frame as the time window of the patient (time second consult – time of request). This time window enables to schedule patients based on the time in which they require an examination, rather than scheduling each patient FCFS.
   1.3. *No-shows, refusals, backlog, and cancellations not recorded:* The current databases do not measure the number of no-shows, refusals, and backlogs. With this information, the radiology department is better able to schedule capacity based on the expected utilisation levels. This can improve the utilisation level and therefore reduce the access time for scheduled arrivals.
   1.4. *Waiting time not measured:* The current systems do not measure waiting times. When the radiology department does not measure the waiting time, it can also not control waiting times.
   1.5. *No insight in outpatient schedule:* As stated by Slack (2007), to increase this fit, we can adapt the capacity or adapt the demand. Many requests originate from outpatients referred by the outpatient clinics. Therefore, insight in the outpatients schedules could give many insights in the required capacity at each moment. Furthermore, with this information it could be possible to level the demand by switching blocks in the outpatient schedule.
   1.6. *Realised staffing levels:* The databases do not show information about the realised staffing levels at each hour of the day at each modality. Therefore, it is not possible to measure the realised workload, to control the workload and to effectively reallocate staff between modalities. This negatively impacts the experienced workload at each modality.

2. **Performance measurement**
   2.1 *Missing norms*: Each month the radiology department measures the internal performance. However, there are no clear norms and therefore, it is not possible to identify the suboptimal performance and control the performance. Also in our study, we benchmark different KPIs. Since the norms are missing and the different modalities are not comparable, we rank the modalities based on the type of modality and patient mix.

2.2 *Performance measurement focused on utilisation*: In the current situation the radiology department only measures and controls the utilisation level based on the scheduled service times. This only gives the planners and operational managers the incentive to optimise the utilisation level. This negatively affects the waiting time and workload.

3. Appointment scheduling

3.1. Sequencing rule: As stated before, the FCFS rule is not a suitable priority rule when serving different patient types with different requirements. It disables timely access for patients that need timely access and results in a fluctuating workload and unnecessary costs.

3.2. Appointment time inpatients: Inpatients get an appointment time, but this appointment time does not represent the expected time of service. The radiology department calls the requesting department in order to send the patient. This time can highly deviate from the scheduled appointment time. This affects the length of stay of patients through the entire hospital and affects the waiting time at the radiology department.

4. Communication

4.1. Phone calls: the phone calls at the front desk and at each modality distort the primary process. Many phone calls concern missing information on the request forms.

4.2. Lack of communication between departments: The radiology department and their requesting specialists have different objectives and different insights. Not sharing information can result in an inefficient system (for example when specialists always want direct access for inpatients) and increase waiting times affecting the entire hospital flow.

5. Forecasting & scheduling

5.1. No insight in arrival pattern: Unscheduled arrivals are, according to the technicians of the radiology department, the main cause of the disrupted patient flow and highly unpredictable. However, when measuring the artificial variability and the natural variability, we see that most of the variability is caused by outpatients and that the variability of patients that are characterised as unscheduled are highly influenced by human decision making. Without insight in the arrival pattern of unscheduled and scheduled patients, the schedule cannot provide sufficient capacity at the right time. This results in varying access times (negatively impacts the integral patient flow) and a fluctuating utilisation (high costs/high workload). Furthermore, empty slots as well as overbooked slots emerge resulting in waiting times for patients and different patient scheduling practices of the planners.

5.2. Block schedule not data-driven: Another factor that negatively impacts the quality of the block schedule is that operational managers create a block schedule differently from each other. It depends on the operational manager how much the schedule is based on data or on personal insight. Therefore, the department should share insight on how to create block schedules taking into account the specific patient mix and characteristics of the modality.

6. Staffing

6.1. Staffing level per room: For each modality there is a predetermined ratio for number of technicians per room. This is for example two technicians per bucky room and one technician at the echo room. However, sometimes the bucky operates very well with one technician at a room. We recommend to further inspect decision making on these staffing levels to improve the realised experienced workload.

3.6. Demarcation of scope

Section 3.5 has summarised the bottlenecks based on performance measurement, brainstorm sessions with stakeholders, and observations at the radiology department. We cannot identify the worst performing modality only based on the performance measures. Therefore, we should take into account the characteristics of the modality and the characteristics of the patient mix. Taking into account these factors, we argued at each KPI which modalities score suboptimal. The modalities that have opportunity for improvement, regarding their operational performance, are the dexa, echography, CT, x-ray at the IM. We have discussed these findings with management, after which management decided that this research is to further focus on the echography. Arguments for this choice are the high total staffing costs and high hourly variability in demand resulting in a high experienced workload.

In the current situation at the echo, the following KPIs have an opportunity for improvement. Furthermore, we give the general bottlenecks for these KPIs. Chapter 4 describes the bottlenecks and predictive factors for the variability in more detail for the echo.

- **Access time**: the echography cannot always guarantee timely access to each specialty for elective patients. The available capacity (in terms of slots) does not match with the demand and does not provide capacity at the right time.
- **Waiting time**: technicians feel that unscheduled arrivals highly disturb the process resulting in waiting times for patients. However, Figure 3 shows that most of the variability is artificial submitted by scheduled arrivals instead of unscheduled arrivals. In many situations (Murray & Berwick, 2003), as well as for this situation, the problem is that most of the capacity is assigned to outpatients. There is little or no capacity reserved for unscheduled arrivals which disables access for unscheduled arrivals.
- **Utilisation of rooms**: the daily utilisation level of the echo is 64%. Looking at the rate of elective patients (87%), it is in our opinion possible to improve the utilisation level. However, the real utilisation level differs from the measured (scheduled) utilisation level. The causes are that we cannot measure real service times (utilisation is based on appointment times because of data constraint), and we do not have insight in the use of the empty slots. According to staff, most of these slots are utilised. Therefore, we expect the realised utilisation level to be higher than the measured utilisation level but still at a low level.
- **Experienced workload**: the technicians at the radiology department experience a high workload because of the high variability in demand per hour and per day. To reduce the experienced workload we aim to reduce the variability in demand.

3.7. Conclusion

In this chapter we have answered research question 2:

> *What is the current situation of the diagnostic process and what are the factors that affect the variability and operational performance of the radiology department?*

We have described the inputs of the primary process, the primary process, the planning and control mechanisms that influence the primary process, and the outputs from the process based on seven KPIs. Based on the output of the system, we analysed the general bottlenecks that affect the performance of the radiology department. The main bottlenecks are that the radiology department does not forecast demand on a regular base. Decisions on the tactical level are static and do not take into account variation of demand over time. The radiology department uses block schedules to schedule patients at specific slots. However, without periodically updating these schedules based on communication with the requesting parties, the aim to effectively allocate capacity with a block schedule is destroyed. Furthermore, most of the patients are outpatients and therefore insight in the block schedules of the outpatient clinics is useful. Because of data constraints, this is not possible. Insight in these schedules is a major factor to improve the patient flow through the entire hospital.

One of the major bottlenecks is the radiology department is not able to accurately forecast demand since there is no insight in the factors that affect the demand pattern over time. In this Chapter we have identified the major predictors for the demand pattern for scheduled as well as unscheduled arrivals. The predictors we have identified are: the day, hour and week of request (especially for the availability modalities since the time of request is more comparable to the time of examination than of modalities with a clear capacity function), the time of visits from the specialists at the clinics, the discharge moment, the breaks of technicians, and we assume that the schedules of the outpatient clinics are major predictors (we cannot analyse this).

We demarcate the scope to the modality echography. Regarding the variability in access time, the same-day access rate, and the variability in demand, the echography has a high opportunity for improvement. Also the dexa, CT and x-ray screening modality at the IM have a high opportunity for improvement. However, based on the current performance in relation to the staffing costs and production level, and based on recommendations from management, we focus on the echography.

4. Solution approach

In this chapter, we further focus on the echography. This chapter describes interventions based on the literature to improve the performance and to answer research question 3. Furthermore, we examine the effect of the interventions by designing a simulation model. Therefore, we first describe the system behaviour and elements of the real-world system that we include in the simulation model.

Section 4.1 first describes the interventions that have potential to improve the current situation. Then, we describe the objective (Section 4.2), data collection (Section 4.3), content of the model (Section 4.4), the programmed model (Section 4.5), and the verification and validation of the model (Section 4.6). Finally, Section 4.7 ends with a conclusion. During the description of this chapter, we make assumptions. Appendix 7 collects the assumptions in the assumption list.

4.1. Potential interventions

This section focuses on interventions to improve the performance by affecting the specific bottlenecks of the echography (See Section 3.5). Table 13 shows each intervention and which KPIs are influenced with the intervention.

Control demand	Capacity planning	**Emergency echo** (Heng & Wright, 2013)	Optimises the waiting time and experienced workload
		Optimise slot allocation *(Day, Garfinkel, & Thompson, 2012; Wullink, et al., 2010)*	Optimises the access time, waiting time, utilisation, experienced workload
	Patient scheduling	**Off-peak scheduling** *(Denton, 2009; Cayirli & Gunes, 2013)*	Optimises the access time, utilisation, experienced workload
Control capacity	Staff scheduling	**Match number of technicians**	Optimises the utilisation

Table 13 – *Proposed interventions*

Intervention 1 - Emergency echo
In the current situation, the radiology department has on average five dedicated emergency slots per day. However, on average there are twelve emergency arrivals per day. Without extensive calculations, we can see that the demand is much higher than the available capacity. A shortage of emergency slots results in waiting times for emergency patients and can explain why technicians see emergency patients as main disturbers. These waiting times emerge for emergency patients when they should wait for an empty slot or dedicated slot for emergencies. Furthermore, if it is a highly urgent emergency patient, it can also affect the waiting time of scheduled arrivals. In addition, a shortage of emergency slots can negatively affect the workload of technicians since the current schedule does not take into account the predictive factors for unscheduled patients. For example, more emergency patients are expected at Fridays since specialists want to discharge patients before the weekend.

By using one dedicated echo room at each day of the week each hour of the day, we have a capacity of (9*60 =) 540 minutes per day for emergency patients. Also during lunchtime, the echo room should be staffed in order to be able to serve emergencies. On average, the echography schedules 23 minutes for emergency patients resulting in a capacity of 24 blocks at the emergency echo room per day.

The required number of blocks depends on the day of the week. Based on a Student's T-test (see Appendix 8) we see that the arrival rate is significantly different between each weekday and Friday (P-value < 0.05). Therefore, we calculate the required blocks for the weekdays Monday to Thursday and the required blocks for the Fridays. The daily emergency arrival rate has the best fit with the Poisson distribution. Figure 17 shows that the echography requires 15 emergency slots for the Monday to Thursday and 18 slots at the Fridays to have sufficient capacity for 90% of the days. With a capacity of 24 slots each day, we have a surplus of emergency slots.

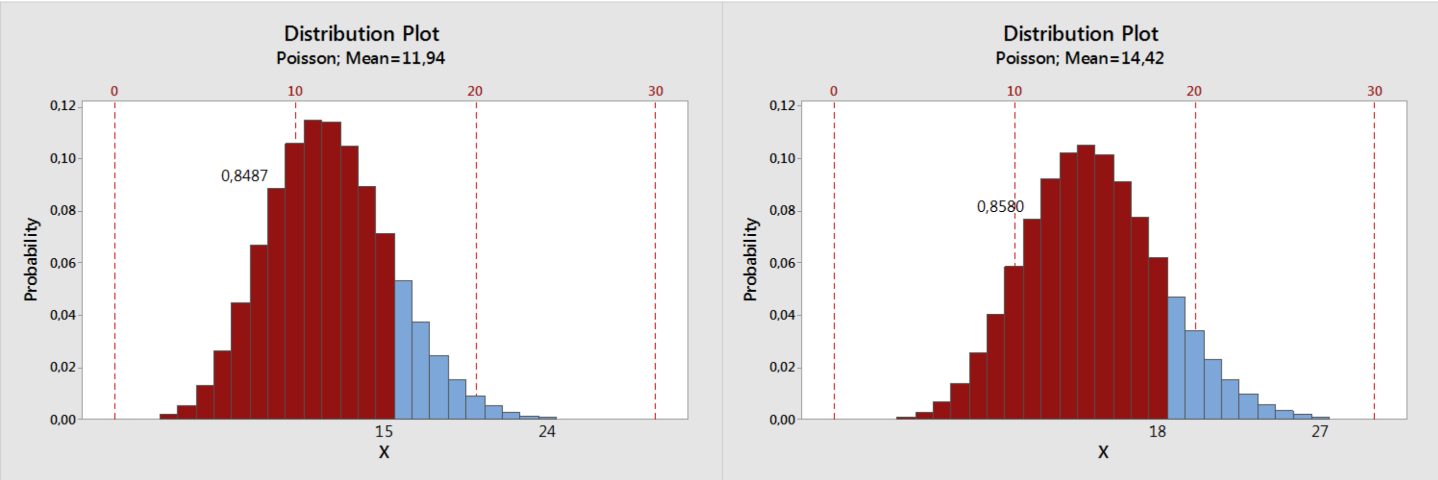

Figure 17 – *Required capacity for each weekday*

Since inpatients also require fast access at the echo and because of the risk-pooling effect, we can use the dedicated echo room for emergency patients and inpatients. Based on the same calculation given before, we can measure the required number of slots for emergency patients and inpatients together. The required number of slots for emergency patients and inpatients together at the Monday to Thursday is 24 and at the Friday the required number of slots is 29. This results in a shortage of slots at the Friday when using a dedicated room for inpatients as well as emergency patients. Therefore, we schedule (29-24=) 5 slots at the other echo's for unscheduled patients.

In the simulation model we implement this by reserving one echo room (V-E1) for unscheduled patients at each day and each hour. In the model, it is not possible to serve scheduled patients in this slot and it is not possible to serve emergency patients and inpatients in another echo room (we do not model the exceptions). Furthermore, we create a block schedule for the other echo rooms (E-1 to E-4) based on intervention 2. Therefore, intervention 1 is a combination of a dedicated echo room and an optimised block schedule for scheduled arrivals.

Intervention 2 – Optimise slot allocation

In Chapter 3 we have seen that the echography has a relative high access time and a highly variable access time compared to other availability modalities. Especially the highly varying access time negatively affects the reliability of the access time to specialists. Furthermore, the utilisation level also highly fluctuates over time resulting unnecessary staffing costs and a high experienced workload. One of the main bottlenecks of these problems is that the block schedule does not reserve sufficient capacity for each examination type when required. This results in an inefficient block schedule that rather can be seen as a disturber of the primary process than as being supportive to the process.

We see that the available capacity has approximately the same pattern as the required capacity (Figure 18). However, to establish the mismatches, we look into more detail. Figure 18 also gives an example of the examination type echo mammae for which there is an obvious mismatch between the required slots per weekday and the available slots. Appendix 9 shows the fit between demand and capacity for the other examination types.

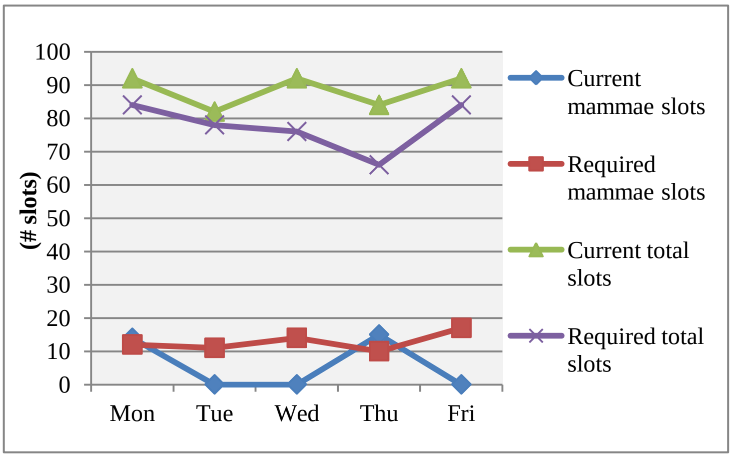

Figure 18 – *Available slots versus required slots*

A block schedule has the goal of providing specialists with a predictable and reliable access time as well as maintaining a high utilisation (Day, Garfinkel, & Thompson, 2012). Assigning exclusive blocks results in a reliable access time (can negatively affect the utilisation) and not assigning blocks (free-access) increases the utilisation (can negatively affect the access time). Therefore, we should find the right balance between reserving slots and free slots. We suggest to use dedicated slots for the examination and patient types with a higher urgency in order to provide a short access time if required and to use generic slots for the other examinations. In this study, we generate a static block schedule taking into account the hourly and daily arrival rates and patterns. However, by using a flexible schedule for each time horizon (like a quarter) the schedule better fits the demand resulting in a better performance. Because of a lack of time, we evaluate one static block schedule.

On average, the echo has 73 requests per day and 88 slots to serve patients. So, on average there are sufficient slots. In order to have enough slots for 90% of the days, we should first identify the arrival distribution. Appendix 10 shows that the arrival distribution has the best fit with the normal distribution (AD: 0.330; P-value: 0.512) and that we require 94 slots on de Monday to Thursday and 96 slots at the Fridays in order to serve each patient at the day of request. Based on these findings, we see that the current capacity cannot serve same-day access for each patient in 90% of the days. However, same-day access is not required for the less urgent cases. By postponing those appointments, the current capacity is sufficient to serve the demand.

As stated before, the aim of this intervention is to reserve sufficient capacity for the urgent examinations at the required time and to use generic slots for the other types. Therefore, we suggest to reserve capacity for emergency patients, inpatients, and urgent outpatients. The emergency patients and inpatients are quite comparable and both require more time than outpatients do. We aggregate the demand of emergency patients and inpatients in order to achieve risk-pooling. Risk-pooling suggests that the variability in demand reduces when aggregating demand across different groups. As demand aggregates, it becomes more likely that a high demand from one customer will offset the low demand of others. This enables to reduce the safety stock and therefore reduces the average required capacity.

The first step is to determine the average demand per weekday and demand pattern for unscheduled patients (See Section 4.3 for the data). The next step is to assign the required slots per weekday to the highest peaks at the day. Thereafter, we look at the scheduled arrivals. We sort the examination types based on the urgency. We retrieve the urgency by looking at the average time window of the examination type (See Section 4.3). Furthermore, we use integrated blocks for examination types with a high urgency but a less predictable demand (Day, Garfinkel, & Thompson, 2012). Then, we calculate the required slots per weekday, identify the pattern, and assign the slots on the same way as described before. For the next step, we look at the correlation between specific examination types. Based on statistical tests, we see that the echo mammae significantly correlates with the echo punction ($r = 0.83$), echo biopsy ($r = 0.33$), and echo armpit ($r = 0.96$). Research for mammae patients consists of a mammography and echo of the mammae. If abnormalities are detected, additional research follows starting with a punction, then a biopsy, and finally an echo armpit. Therefore, the echo mammae is a predictor for the demand of the other three examination types and we take into account this relation when assigning slots to a specific time.

For this intervention, we only adapt the block schedule and do not change the staffing levels and opening hours. Therefore, we fill the block schedule with generic slots to serve the remaining outpatients as well as to serve as a buffer for each request. In addition, these generic slots smooth the utilisation and improve timely access. The new block schedule has less slot types, less dedicated slots, shows a better fit with the demand, and is more flexible (See Appendix 11 for the new schedule after the first iteration). In the simulation model, we first create a new schedule. Then, we increase the dedicated slots with 20% and 40% and then decrease the dedicated slots with 20% and 40% resulting in five schedules. We can summarise this intervention in a heuristic:

1. **Sort** examination types on increasing urgency
2. Determine the **average demand** and **demand pattern** for unscheduled and scheduled patients
3. Define **slot types**
4. **Assign number of slots** to unscheduled patients and scheduled patients based on:
    - The average demand
    - The demand pattern
    - Demand predictors (time of visit from specialist, discharge moment, breaks of technicians, correlation of echo mammae with echo punction, echo biopsy, and echo armpit).
5. Fill remaining capacity with **generic slots**
6. Calculate the **ratio scheduled/unscheduled (R)**
7. **Create new schedules**:
    a) Increase R with 20% and go to step 4 (2 times)
    b) Decrease R with 20% and go to step 4 (2 times)
8. **Decide** on the best performing schedule with respect to the expected output.

Intervention 3 – Off-peak scheduling

In the current situation, the FCFS rule is used which schedules each patient arrival at the first slot. However, we can delay some appointments to optimise the access time for the urgent patients, which does not negatively affect the desired access time for the other patients. Furthermore, scheduling FCFS means that the variability in the incoming requests is not changed. This results in a variable utilisation of the modalities and a fluctuating workload for staff. With this intervention, each arriving request is scheduled at the day at which the current number of scheduled patients is the lowest. This day should be within the time window (see Section 4.3).

Figure 19 gives an example of off-peak scheduling to smooth the utilisation over the weekdays. We show for each request the planning horizon (1 day = should be examined at or before Tuesday). The first graph shows how the five requests (arriving at Monday) are scheduled resulting in fluctuating utilisation. The other graph shows that we can smooth the incoming requests by scheduling the request at the day with the lowest current utilisation (within time window). Furthermore, with off-peak scheduling we are better able to serve the patients within their time window. For example, request number 3 has access within its time window with off-peak scheduling but not with FCFS.

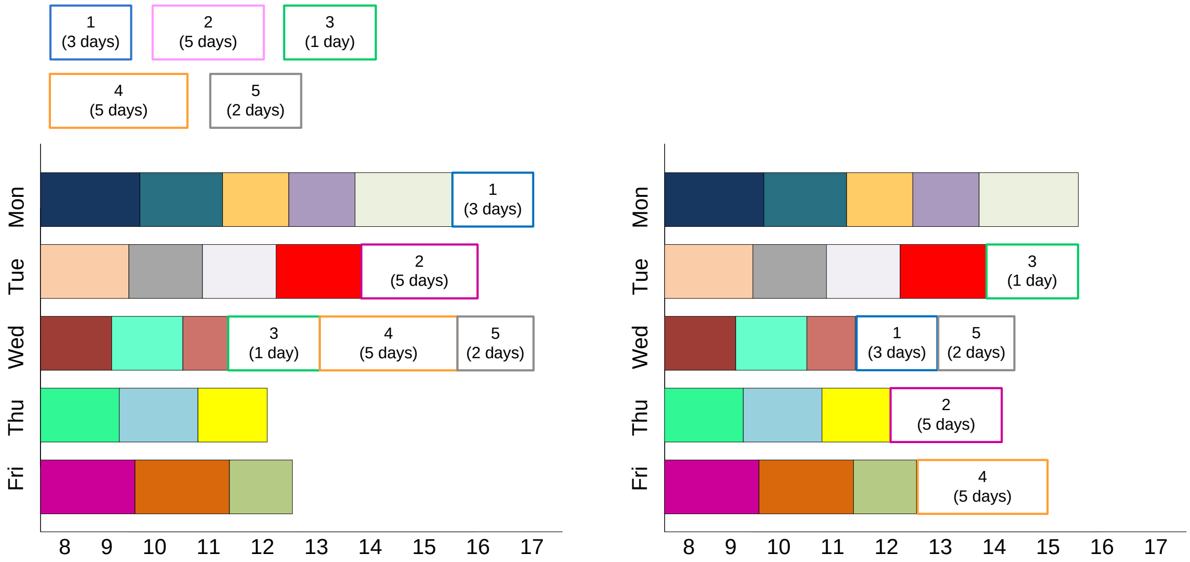

Figure 19 – *Example of FCFS scheduling and off-peak scheduling*

Intervention 4 – Staff scheduling

In the current situation, the Mondays, Wednesdays and Fridays are equipped with 5 technicians. The Tuesdays and Thursdays are equipped with 4.5 technicians (1 FTE less in the afternoon). This combination results in a total of 4,579.668 euro for 81.25 FTE resulting in 56.366 euro per FTE.

As we see in Figure 18, the demand on the Wednesdays is lower than the demand on Tuesdays. However, on the Tuesdays the echo rooms are equipped with 4.5 technicians while on the Wednesdays the rooms are equipped with 5 technicians. Therefore, we want to analyse the effect of reducing the number of technicians with 0.5 FTE at Wednesday in the morning. We choose the morning since in the afternoon more unscheduled patients arrive because of the visits of doctors and in the morning relatively more scheduled patients arrive (we can better control this flow). Furthermore, it is interesting to simulate the effect of further reducing the capacity at Thursdays since this is the least busy day. Adapting the staffing level at this day has the least negative impact on the same-day access.

4.2. Objective

Based on the problem description and definition of the scope, the objectives of the simulation are that:

- The model gives insight in the performance indicators access time, room utilisation, experienced workload of technicians, waiting time for elective patients, waiting time for emergency patients, required number of technicians, and staffing costs before and after the intervention.
- The model gives a reliable representation of the patient flow and scheduling practices at the echography.
- The model incorporates the variability in demand per patient type and per hour, per day, and per week.
- The model must be easy to use and therefore only incorporate the required level of detail.

4.3. Data collection

To specify model parameters and input probability distributions of the system, we require information about the input. In order to improve the performance, we can adapt these parameters. The parameters are based on the literature review of Cayirli and Veral (2003) and we only include the relevant parameters in the scope of this study. The simulation does only include regular working hours (8.00AM – 5.00PM) since then most of the staff is scheduled and most of the patients are served.

4.3.1. Capacity

For the processes at the echo, two types of capacities are required: staff and echo rooms. We first describe the roles and modelling process of staff and then describe the echo rooms.

Staff

There are different types of staff for the planning, control, and execution of the primary process. We include the technicians in our simulation model. Technicians perform the examinations, sends a report of the findings to the radiologist, listen to the voicemail for emergency requests, and schedule emergencies and punctures. If a technician has time and sits at the desk, the technician listens to the voicemail and schedules the emergency patients. We assume that when a technician has more than 10 minutes spare time, the technician performs the emergency requests. Furthermore, the service time by the technician and radiologist may differ slightly per employee. Since there is no information of the technicians who are on duty, *we assume that there is no significant difference in examination time between employees.*

The model does not incorporate radiologists since we do not have insight in the times that radiologists review the examinations and send the findings to the requesting specialist. Therefore, radiologists can be a potential bottleneck and delay the diagnostic process. There are two radiologists dedicated to the echo. One radiologist analyses the mammograms, the echo mammae and echo ampit. The other radiologist analyses the emergency requests and the other examinations. For the examinations of echo mammae, echo armpit, and emergency requests the technician needs to discuss the findings directly after the examination with the radiologist. *We assume that no other scans are directly discussed with the radiologist.* Radiologists are located in a nearby room of the echo. If the radiologist is not on his place while the technician wants to discuss the findings, this may cause a delay for the technician and patients waiting for an examination.

Furthermore, the model does not incorporate the planners, since the planners are not distorting the process in the current situation and are therefore not of importance.

Examination and waiting rooms

The echography has five examination rooms (E-1; E-2; E-3; E-4; E-5) and two waiting rooms. Each echo is equipped with the same scanning techniques. However, the size of the rooms slightly differs. Therefore, most of the inpatients are scheduled at the larger rooms (E-2 and E-3) which are better accessible with a bed. We do not incorporate these small differences since inpatients can be served at each room.

Before the examination, patients wait in the dedicated waiting room that is adjacent to the echo room at which the patient is scheduled. However, in practice technicians pick the patient from the other waiting room if there is no waiting patient in the dedicated waiting room. Therefore, we do not incorporate the different waiting rooms.

4.3.2. Patient attributes

Classification and prioritising

The current model incorporates three different patient types with different priorities: elective outpatients (OP), elective inpatients (IP), and emergency patients (EP). The highest priority for appointment scheduling is for emergency patients and the lowest for elective patients. Patients of the same class get priority based on the First Come First Served (FCFS) principle. Furthermore, EPs consist of highly urgent patients to patients who can wait for, for example, eight hours. *We assume that emergency patients require access on the same day they arrive in the system.*

Arrival rates

The arrival rate during weekdays for each patient type depends on the time of request, whether the day is a national holiday, and the block schedule of the outpatient clinic. One of the major predictors of the demand is the outpatient schedule. Based on the type of specialty and its referring rate, we could forecast the arrival rates at the echo as well as the type of examination. With the current systems, we cannot get insight in these schedules. However, by measuring the time of request we can approach the arrival rate and the type of requests from the outpatient schedules. We first determine the arrival rate for each patient type (OP, IP, and EP). Thereafter, we identify the examination type of each patient arrival.

The arrival process is time dependent varying per hour, per day and per week. Each weekday has the same busy hours, and almost each week shows the same busy days. Busy hours are especially from 9AM to 11 AM, and after lunch. Causes are the visitation process and the start-up of the OR. The daily pattern highly depends on the block schedule of the outpatient department. For example, the Tuesdays and Thursdays are busy days because then blocks for mamma care are scheduled at the outpatient department. For mamma care the goal is to have a diagnostic track of 1 day. Therefore, the echo gets many semi-urgent requests on the Tuesdays and Thursdays. Looking at the weekly pattern, the arrival rate shows a typical cyclical pattern with lows in the holiday weeks. Concerning the arrival process, we take into account the following assumptions:

- *We assume that the state changes each hour, so the arrival interval is one hour.*
- *We assume that the average number of patients varies per hour (h), per weekday (d) and per week (w). Therefore, we express the average number of arrivals per hour with* $\square_{\square,\square,\square}$.
- *We assume that there is no relation between the week and the arrival rate per weekday. Therefore, every week the busy weekdays are the same.*
- *We assume that there is no relation between the weekday and the arrival rate per hour. Therefore, every weekday the busy hours are the same.*
- *In the simulation model, national holidays and maintenance of equipment are not included since this has a negligible overall impact.*

Since the arrival rate depends on the hour, weekday, week, and patient type, we generate arrival parameters taking into account the specific time factor (h, d, w) and patient types (OP, IP, and EP). The time interval is one hour, since the state changes each hour. We introduce the following parameters:

$\lambda_{h,d,w}$	The average number of patients arriving in hour *h*, weekday *d*, and week *w*.
α_h^{OP}	The average number of OPs arriving in hour *h*.
α_h^{IP}	The average number of IPs arriving in hour *h*.
α_h^{EP}	The average number of EPs arriving in hour *h*.
β_d^{OP}	The day factor representing the fluctuations per weekday for OPs.
β_d^{IP}	The day factor representing the fluctuations per weekday for IPs.
β_d^{EP}	The day factor representing the fluctuations per weekday for EPs.
γ_w^{OP}	The week factor representing the fluctuations per week for OPs.
γ_w^{IP}	The week factor representing the fluctuations per week for IPs.
γ_w^{EP}	The week factor representing the fluctuations per week for EPs.

With h = 8,...,16, d = 1,...,5, w = 1,...,52

We can calculate the arrival rates $\lambda_{h,d,w}$ with the following formula:

$$\lambda_{h,d,w} = \sum \begin{cases} \alpha_h^{OP} * \beta_d^{OP} * \gamma_w^{OP} \\ \alpha_h^{IP} * \beta_d^{IP} * \gamma_w^{IP} \\ \alpha_h^{EP} * \beta_d^{EP} * \gamma_w^{EP} \end{cases}$$

In order to calculate the values for α, β, and γ we use historical data of the year 2013 with 18878 observations. We now describe how we calculate the different parameters for some patient types. Appendix 12 gives an overview of the data we calculated and used as input data.

First, we calculate and plot the arrival rate per hour (α). We see a clear difference between the arrival rates per hour for each patient type (see Appendix 12). Therefore, we should calculate for each hour and for each patient type the access rate. This finally results in (9 hours in a day * 3 patient types =) 27 hourly rates.

Second, we calculate the day factor (β). After plotting the daily arrival rates, we see obvious differences for the OPs and IPs, but small differences between the weekdays for EPs (see Table 14).

Day	# emergencies per day
Mon	12.40
Tue	11.55
Wed	11.37
Thu	12.43
Fri	14.42

Table 14 – *Arrival rates per day for EPs*

In order to determine whether the differences for EPs are statistically significant, we use the Student's T-test. A two-tailed t-test confirms with a P-value ≤ 0.05 that there is a statistical difference between each weekday and the Friday (see Appendix 7). An explanation for this is that specialists want to discharge inpatients before the weekend. Therefore, specialists request an examination for an emergency patient in order to be able to also decide on the discharge at the same day. There is no statistical difference between the other weekdays. Therefore, we identify for the EPs a distribution for the Monday to Thursday and a distribution for the Fridays. For the EPs and OPs we identify the distribution for each day. We use Minitab to fit the distributions for each patient type. For some days there is no distribution with a good fit based on the P-value. Then, we look at the AD value and choose the distribution with the highest AD value. For the EP arrivals, the Poisson distribution was the best fit for each day (highest AD, highest P-value). For the other arrivals, the normal distribution was the best fit (see Appendix 10 for an example of the distribution identification with Minitab).

For calculating the day factor, we first measure the average daily arrival rate for each patient type. Accordingly, the specific day factor for a weekday is the relative difference between specific daily arrival rate and the average daily arrival rate. For example, if on average 15 IPs arrive per day and on Wednesday 17 IPs arrive, the day factor is (17/15=) 1.13. Table 15 gives the day factors.

Day	EP	IP	OP
Monday	1.06	0.84	1.12
Tuesday	0.92	1.12	0.86
Wednesday	0.74	1.01	0.98
Thursday	1.05	0.94	1.07
Friday	1.23	1.09	0.96

Table 15 – *Day factors*

Third, we measure the week factors (γ) that mimic the seasonal effect. In Chapter 3 we already identified that there is no clear difference in the arrival rate of patients before and after the new hospital. Appendix 12 also shows the weekly arrival rate of patients arriving in the months January to August in order to show the differences between 2013 and 2014. Also in the weekly pattern, we do not see a large difference. Since there are no clear differences in the weekly pattern before and after the new hospital, we can use the data of 2013. The calculations for the week factor are the same as for the day factor. Figure 20 presents the week factor of OP arrivals and Appendix 12 shows the table of each week factor for each patient type.

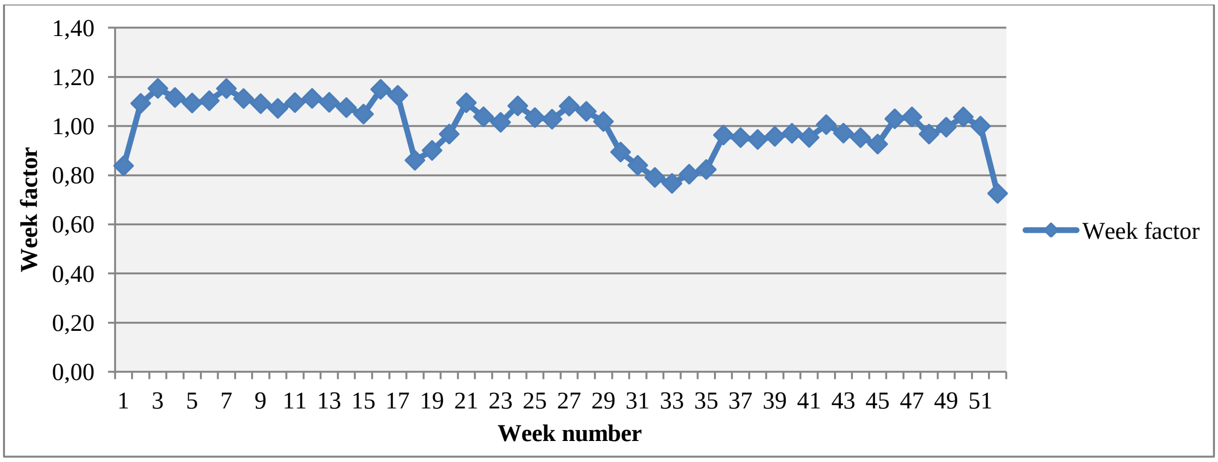

Figure 20 – *Week factor OPs*

Besides we determine the arrival rate based on patient type, we can identify the arrival rate for the specific examination type. In the current situation, the echography performs 37 examination types. In order to better be able to analyse the demand pattern, we aggregate some examination types. For example, we aggregated the demand of echo arm left and echo arm right to one type. Furthermore, we aggregated the demand of the examination types with a low prevalence (together <10% of the total demand) which are mentioned *echo other*. Based on this aggregation we end up with 13 examination types. We describe these examination types in the following paragraph. The type of examination that arrives varies each hour and each day since it depends on the schedule of the outpatient clinics. See Appendix 9 for the daily variability and Appendix 10 for the hourly variability of the major examination types. We assume that the weekly variability in the arrival rate per examination type is negligible and has little impact on the model results. We calculate an empirical distribution of examination types based on historical data.

Appendix 12 gives the empirical distributions of each examination type per hour and per weekday. The empirical distribution is based on historical data. We use these empirical distributions in our simulation model not to generate the number of patient arrivals but to identify the incoming patient arrivals as described before.

Service times

Because of the scope of this research and limited data availability, we only measure the service time for the 'scan' process. The service time (in minutes) differs for each patient according to a discrete probability distribution since the values can take on only stochastic values. *We assume that the service time depends on the type of examination, patient type (O, I, or E), and the need for a radiologist. We assume that the service time is not dependent on the radiologist on duty and not dependent on the perceived workload*. According to staff members there are small differences between the analyses of different radiologists. Because of the small effect, we do not take into account these effects.

The only data that is available concerning service times is the *scheduled* duration of an examination. We perform a small observation of different examinations to identify the empirical distribution. Only for echo mammae, echo upper abdomen, and echo abdomen there are enough observations showing the same empirical distribution. For each observed examination type, the average real duration is approximately 5 minutes shorter than scheduled. Table 16 shows the scheduled duration of the observed examination types and the real duration of the observed examination types. Since there is no extensive data available of the other examinations, *we assume that each examination is on average 5 minutes shorter than the scheduled duration.* The observed examination types show the same pattern in the probability distribution. *This results in the assumption that each examination type has the same empirical distribution of the service time with different parameters.*

Examination type	**Scheduled duration** (average deviation from actual duration)	**Actual duration** (min, max)
Echo upper abdomen	25 minutes (4 minutes)	21 minutes (17; 25)
Echo abdomen	25 minutes (4 minutes)	21 minutes (16; 25)
Echo mammae	20 minutes (6 minutes)	15 minutes (13; 18)
Echo arms	20 minutes (4 minutes)	16 minutes (13; 21)
Echo legs	20 minutes (6 minutes)	14 minutes (12; 18)
Echo kidneys	20 minutes (7 minutes)	13 minutes (12;18)

Table 16 - *Scheduled versus actual duration echo*

Comparing the inpatients to the outpatients, inpatients have on average a higher duration time since these patients require more time during the positioning on the table. Comparing emergency patients to outpatients, emergency patients have a wider range (but same average). For these patients it is sometimes not clear how many images are sufficient, therefore, there is a higher chance that the scheduled appointment duration does not match with the real duration.

Some examination types and patient types require direct review from the radiologist. These examinations are echo mamma, and examinations for inpatients and emergencies. For the other examinations, the radiologist reviews the examination in the time frame between processes ‘scan’ and ‘second consult’.

Time window

As stated in Section 3.5, it should be useful to schedule patients based on their time window. This time window (time between request and examination) represents the urgency of the examination for the patient type. A short time horizon means that the specialist requires an examination of the patient on a short term. For each examination type we can identify a time window which can be used when scheduling capacity in the block schedule. In order to identify the distribution we plotted for each examination type the access time for the patient. The Weibull distribution shows the best fit with the real data. Thereafter, we plot for each examination type the arrival rate distribution and estimate the parameters. Table 17 shows the parameters of each examination type and Figure 21 gives an example of a distribution plot of the examination type echo kidneys in order to identify the type of distribution.

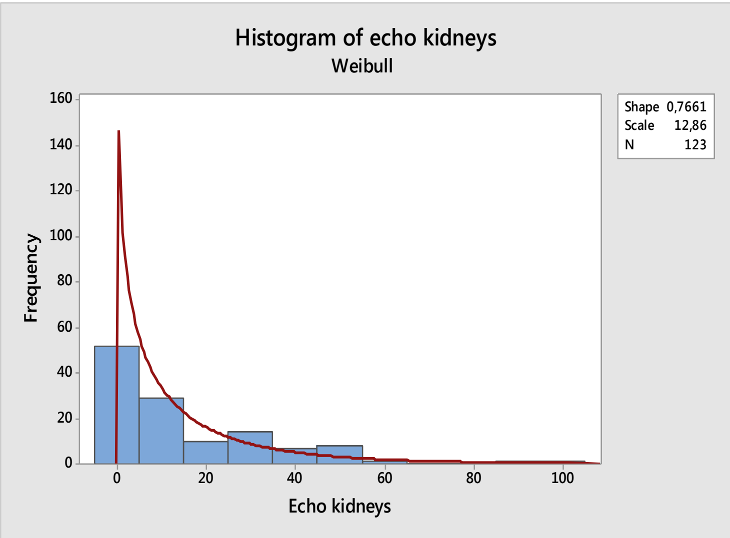

Figure 21 - *Distribution identification and parameter estimation echo kidneys*

Examination type	Shape	Scale
Echo abdomen	0.66	3.36
Echo arm	0.95	3.62
Echo legs	0.58	3.39
Echo biopsy	1.32	2.91
Echo upper abdomen	0.74	18.33
Echo neck	1.39	4.46
Echo jodium	1.06	5.95
Echo groin	1.15	1.91
Echo mammae	0.9	3.58
Echo kidneys	0.77	12.86
Echo armpit	1.27	1.52
Echo punction	1.24	2.35
Echo shoulder	1.33	2.55

Table 17 – *Parameter estimation examination types*

No-shows & refusals

In the data it is not visible how many patients do not show up for their appointment. These patients are removed from the schedule. And when the radiology department schedules requests for a specific day, these requests are all finished at the same day. Based on expert opinion, *we assume that the amount of no-shows is negligible and that there are no refusals.*

Block scheduling

The block schedule of the echo consists of time slots that are reserved for specific examination types or patient types at a specific time. A block schedule concerns decision making on the tactical level since the block schedule reserves capacity for the next weeks. the operational level, planners fill these slots with patients. Each slot has a predetermined set of patients who are suitable. For example, a biopsy slot is only accessible for requests for a biopsy. Appendix 13 shows the different slots and patient types who are suitable for each slot type.

Appointment scheduling
The planners at the front desk of the radiology department perform the scheduling process of the echo. An exception for this is that technicians schedule the requests for punctions. Offline scheduling is based on the available time in the block schedule. Each patient gets an appointment time based on the sequencing and priority rule. Online scheduling concerns scheduling the emergency patients and inpatients between the scheduled elective patients.

Sequencing and priority rule
The sequencing rule that echo currently uses is that each elective patient that requires an appointment gets the first possible appointment time that is available in the block schedule (first-come, first-served: FCFS). The priority rule is that if emergency patients, inpatients, and outpatients wait for access to an echo room, the emergency patient gets access to the first available room. Thereafter, inpatients have the highest priority and the least priority is assigned to elective outpatients. The radiology department uses this rule since emergency patients are assumed to require direct access and inpatients require fast access since for these patients echo can be the bottleneck in their patient flow.

4.3.3. Output

The output measures are:

- Primary output measures
  - Average access time scheduled arrivals (days)
  - Waiting time for unscheduled patients (minutes)
  - Experienced workload
  - Average room utilisation
  - Same-day access ratio
  - Patients served within their time window
  - Yearly production level
  - Yearly staffing costs

- Secondary output measures:*
  - Access ratio for EPs, IPs, and for OPs per examination type
  - Scheduled/unscheduled ratio

** We use the secondary output measures to change the schedule*

4.4. Content of model

This section describes the different steps of the simulation model. As described before, the simulation model consists of the processes that take place after the first consult at the specialist (intake) until the second consult (diagnosis). Figure 22 shows the frame of the process flow. The figure incorporates the first consult and follow-up consult at the specialist to give a complete overview of the adjacent processes. We do not describe these steps since this is out of the scope of this research.

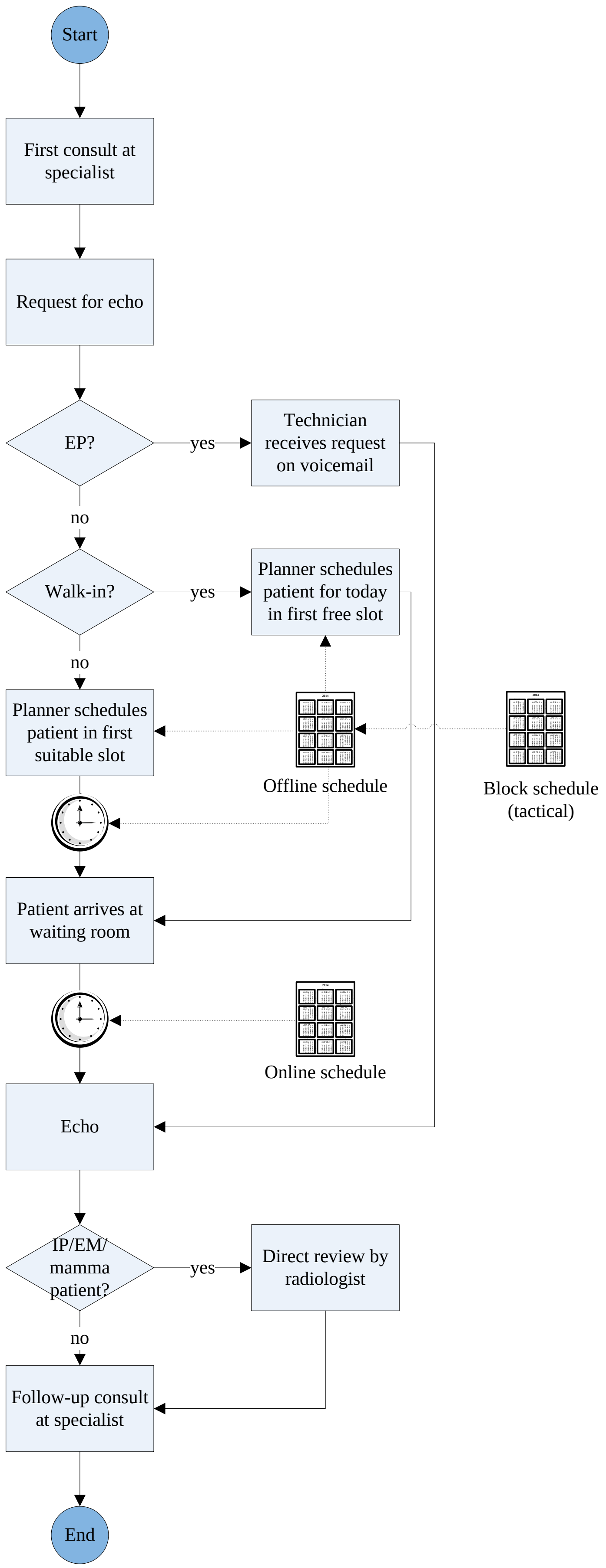

Figure 22 – *Process flow at echo*

We can identify the following processes and decision rules that we take into account in the simulation:

- **Request arrival**
  - The request from the specialist arrives at the radiology department.
  - Identify the patient type
  - Initialise the ID number, the examination type of the request based on the empirical distribution, the service time, and the time window.
  - Adapt the service time if the request needs to be discussed with the radiologist directly after the examination. Direct review is required for the echo mammae, and examinations for inpatients and emergency patients.
  - If it concerns a request for an emergency patient, the patient characteristics are recorded and the patient is served at the first slot suitable slot (dedicated to emergency patients or the first empty slot).
  - Send patients to the waiting list.

- **Scheduling**
  - Waiting list: assigns appointment times and keeps patients who wait till their appointment time is reached.
    - If it is an emergency patient, perform the online appointment system, else, start with the offline appointment scheduling and then the online appointment scheduling.
      - Offline appointment scheduling: Look at the tactical schedule and identify when this patient type and examination type can be scheduled. Schedule patient at first available and suitable slot and determine the appointment time.
      - Online appointment scheduling:
        <ins>Emergency patients:</ins> If there is a free slot or a slot dedicated to emergency patients, send the emergency patient to the waiting room.
        <ins>Inpatients/outpatients:</ins> If the appointment time is reached, send patient from the scheduling buffer to the waiting room.

- **Examination**
  - Waiting room
    - Sort patients from high to low based on the priority rule for patient types. This means that emergency patients have the highest priority, then inpatients, and outpatients have the lowest priority.
    - If a server is available, move the first patient from waiting room to scan.
    - Measure the waiting time.

  - Scan
    - Perform examination with assigned examination time. The examination time consists of the preparation (reading patient files, picking up the patient-elevator, etc.), making the required images, reporting the findings.
    - Measure the access time and update the performance measures.

- **Second consult**
  - The patient leaves system.

4.5. Programmed model

In this section, we translate the conceptual model into a programmed simulation model using Plant Simulation (version 10.1). Plant Simulation is a discrete-event simulation tool, which means that specific events trigger other events. We now give an overview of the global structure of the programmed model, the type of simulation, the required run length and warm-up period, and verify and validate the model.

4.5.1. Global structure

In Figure 23 we show the programmed simulation model in Plant Simulation. The model consists of a frame (*Radiology)* that collects the input data and records the output data and of a frame (*PatientFlow)* that simulates the primary processes of the echography. When running the model, movable units (green patients in the model) move through the primary process and the simulation model collects data. For example, if a patient leaves the waiting room, the waiting time is recorded (event-based). When the run length (days) has elapsed, the model runs the next experiment and changes the experimental factors. Finally, one table file collects the data of each run in order to be able to compare outcome between the experiments.

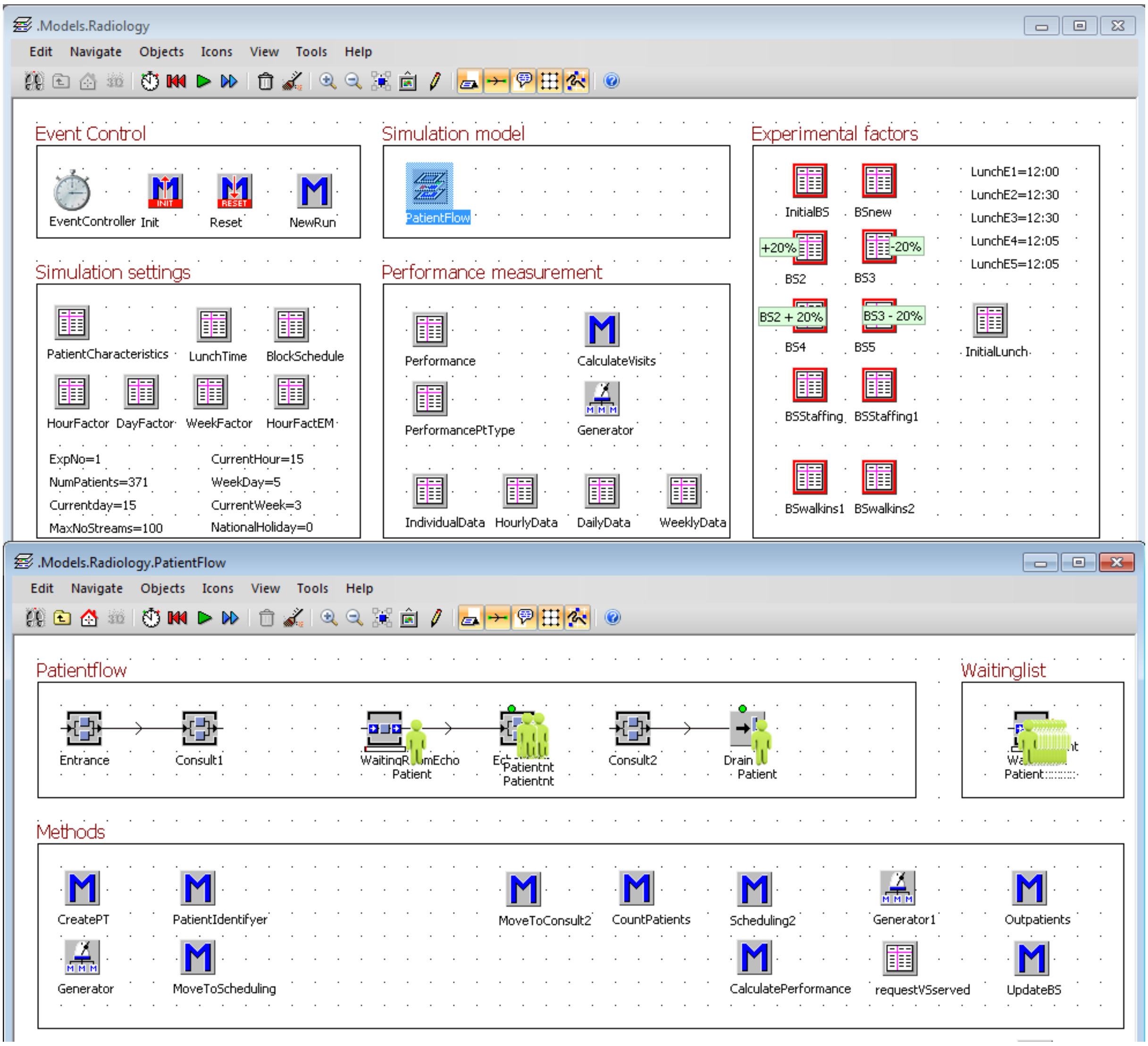

Figure 23 – *Overview of simulation model*

We now shortly describe the frame *PatientFlow* in order to get insight in how we modelled the steps.

The basis for the process flow is the physical flow of patients from the first consult to the second consult. The consecutive steps are the entrance, first consult at the specialist, the waiting list, the waiting room, the echo room, and the second consult.

At the first station *Entrance* the method *Create Patient* is called. This method creates patients (MUs) based on the predetermined hourly arrival rate, the day factor and the week factor and moves the MUs to the station *Consult1*. At *Consult1* the method *PatientIdentifyer* assings an ID number, patient type, examination type, service time, and time window to the MUs. Unscheduled patients go to *WaitingroomEcho* and at this time, the waiting time starts. Scheduled patients go to the station *WaitingList* and the access time starts. The method *Outpatient* identifies the next available slot and moves the first patient that fits in the slot based on the examination type. When patients arrive at the *EchoRoom*, the waiting time and access time are recorded. When patients leave the system after the *Consult2*, the method *CountPatients* measures for each individual the KPIs and saves this in a table within the main frame.

4.5.2. Type of simulation

In this simulation study we use random samples from a distribution function to generate estimates. These results can highly differ from the true characteristics of the model because of high variances. Therefore, we should use statistical techniques to get a valid model with enough data within an acceptable runtime. In order to determine which techniques are useful to validate the programmed model with respect to the output, we should determine the type of simulation.

Simulations can be typed as terminating and non-terminating simulations (Law, 2007). A terminating simulation has a natural event that specifies the run-length (e.g. office closes at 6 PM). Non-terminating simulations do not have a natural event that stops a run and has steady state performance measures (e.g. average waiting time over a year). Non-terminating models are used to assess the system behaviour in the long term.

In our study we deal with both types. The day-to-day processes are terminating since staff and rooms are available for a specified time period. However, we also deal with a non-terminating model since we measure long-term performance measures which are not controlled by a natural event. To get reliable results for the long-term, we should determine the run-length.

Furthermore, each simulation starts with initial conditions. The performance of the system depends on these conditions (transient system behaviour) or does not depend on these conditions (steady state behaviour). The model in this study starts with an empty system with no patients on the waiting list, no patients served resulting in a low initial utilisation. To identify the steady state performance, we should identify the warm-up period and delete the first observations (Law, 2007).

4.5.3. Run length

A method to determine the run length of the simulation is to use the confidence interval method (Law, 2007). This is a convergence method and implies that we measure the cumulative mean after each replication. If the absolute difference of the cumulative mean is less than 0.02 of the preceding cumulative mean, we have the required run length. This should be represented with a reasonably flat graph since the variability in the mean diminishes over time. We use the KPI utilisation since this KPI is highly influenced by the initial situation. For example, in the beginning of the simulation the utilisation is much lower because of the small waiting list. If the waiting list increases, there is a higher chance that the dedicated slots can be filled resulting in a higher utilisation level. Based on this method and using the KPI utilisation, we should have a run length of 115 days. However, a year consists of 258 working days. We decide to increase the run length to 258 days to incorporate the seasonal pattern of one year.

4.5.4. Warm-up

We use the graphical method of Welch to determine the warm-up period. By deleting this warm-up period, the data is representative for steady state behaviour. We plot the moving average during one run and identify the point in time after which the moving average is reasonably stable. Based on the plot of the utilisation level in Figure 24, we see that the warm-up period is 15 workdays (3 weeks).

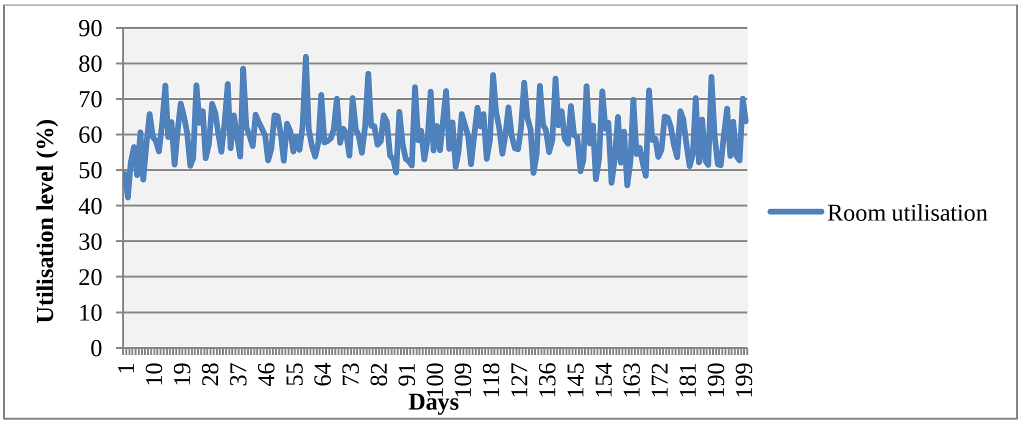

Figure 24 – *Warm-up period*

4.6. Verification & validation

Simulation models aim to represent a real system. In order to be able to generate reliable results, we should verify and validate the model (Figure 25). Verification concerns determining whether input data and assumptions are correctly translated into the computer program. Validation is the process of determining whether the programmed model is an accurate representation of the real system (related to the particular objectives for the study) and closely resembles output data (Law, 2007). For specific techniques to verify and validate a simulation model see the book of Law (2007).

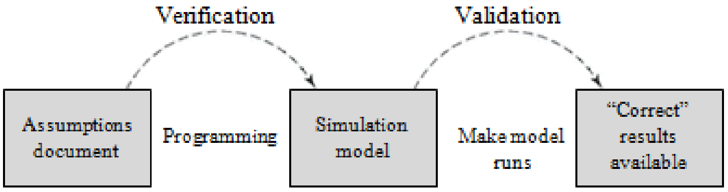

Figure 25 – *Verification and validation (Law, 2007)*

4.6.1. Verification

The first technique according to Law (2007) is to **debug** the model. We programmed the model by using several sub-programmes in order to easily find the location of errors. In the initial phase, the model was highly simplified in order to have a model that can run. Debugging the different sub-programmes was an iterative process during the programming phase.

Another technique is to **let more than one person review the model**. Based on close collaboration and meetings with stakeholders, the program is assessed in order to check whether statements are correctly translated. During these meetings, we have made new assumptions and programmed the assumptions in the simulation model. One of the assumptions that has changed is that in the initial assumptions document slots are kept empty if there is no waiting patient for this slot type resulting in idle time for the echo room. However, in the current situation idle time is reduced by 'sometimes' filling these empty slots with other patient types. In order to estimate when planners fill the slots or keep the slots empty, we assume that planners fill these empty slots with inpatients and emergency patients. After the verification, the model runs and does not show any bugs. Finally, consensus is achieved among group members about what should be included or excluded.

The last technique we used is **watching the animation** of the simulation model. One difference between the model and reality is that the treatment of emergencies visually differs. In reality, emergencies arrive at the ED and the technician goes to the ED to serve the patient at the dedicated echo at the ED. In the simulation model, the technician does not physically move to the dedicated echo. This does not impact the performance since the technician still works for the echo room and the KPIs also incorporate emergency patients. Another difference is that the service time for emergency patients is slightly higher which is partly due to the walk of the technician. We took into account this increased service time. By leaving the echo room, the experienced workload can be higher. We do not take this into account since we assume that it does not significantly impact the experienced workload. Also, during the animation we noticed that some patient symbols changed during the process. We were able to solve this problem.

The analysis shows that the current model does not perfectly translate the real process into a simulation model. However, the model does not show bugs, is able to run and consensus is achieved by stakeholders. Based on the goal of this research and level of detail, the model is correctly translated. The next step is to validate the output of the simulation model.

4.6.2. Validation

Law (2007) proposed qualitative as well as quantitative techniques for increasing the validity of the simulation model. We shortly describe the qualitative and quantitative validation process.

Qualitative validation

We retrieved data sets from the data systems Cognos and Ultragenda. Currently, these sources give information about the scheduled appointment duration of all patients from January 2010 to December 2013. Regarding the production levels, we noticed small differences. We performed a two-tailed t-test of the production levels in 2013 with H0: $\mu 1 = \mu 2$. It shows that there is no significant difference between the two sets ($t(364) = -0.9736$, P-value > 0.05). Unfortunately, this data only shows the scheduled service time. With the available data we are not able to get insight in the realised service times and utilisation levels. Therefore, we observed the primary process and performed time registrations to validate if the scheduled durations are representative for the realised durations. Based on statistical tests, we can assume that the scheduled durations are comparable to the total required time for a patient (preparation time + service time + dialogue with radiologist).

Also with this data we do not get insight in the difference between scheduled start time and realised start time in order to calculate the waiting time. Another pitfall is that the databases do not record the requesting department but only the requesting specialty. The radiology department has agreements with specific departments among the accessibility of patients (e.g. patients from the acute care department require an echo within 12 hours). Currently we are not able to measure this performance. The last annotation concerning the quality of the data is that it does not show the arrival times of emergency patients. It is therefore only possible to calculate the arrival times of scheduled patients.

Concerning the access time, we retrieved data from previous appointments of patients. Based on several assumptions, we are able to approach the access time. The reliability of the access time is not very high but gives a good approximation. Finally, with this data we are able to quantitatively validate the production level, utilisation, workload, and access time for each patient type at each time. We are not able to validate the waiting time.

In the simulation model patients enter the system at the start of each hour according to a non-stationary Poisson process. In the real system patient arrivals are distributed over the hour. This difference does not have influence on the final results since each patient first moves to the waiting list and then moves to the echo according to the scheduling rule. A way to distribute the arrivals is to apply thinning (Law, 2007). Since thinning does not impact the final results and increases the computation time, we continue with the simplified arrival process.

Quantitative techniques

The quantitative techniques that are proposed by Law (2007) are to validate components of the model and to validate the output of the overall model. We first validate specific components and thereafter validate the overall output.

An important aspect of the model is the number of arrivals during each time interval. We calculated a daily arrival rate, a day factor and a week factor to simulate the arrival pattern during the year. We now calculate for each month the total number of OPs and show the pattern of the daily arrivals of OPs since this is the largest group and has the most influence on the simulation results. We see that there are no obvious differences between the monthly production. A Student's t-test confirms that there is no significant difference ($t(22) = 0.05$, P-value = 0.48).

Figure 26 gives the daily arrival pattern. We see that the pattern is comparable but that the simulated demand has more variability. Therefore, we compare the variance and analyse whether the difference in variability are significant. Based on an ANOVA analysis we calculate the variance: $\sigma^2_{simulation} = 18.6$ and $\sigma^2_{real\text{-}world} = 21.4$. The F-test shows that there is no significant difference in the variance ($F(11) = 1{,}15 < F(critical) = 2{,}82$).

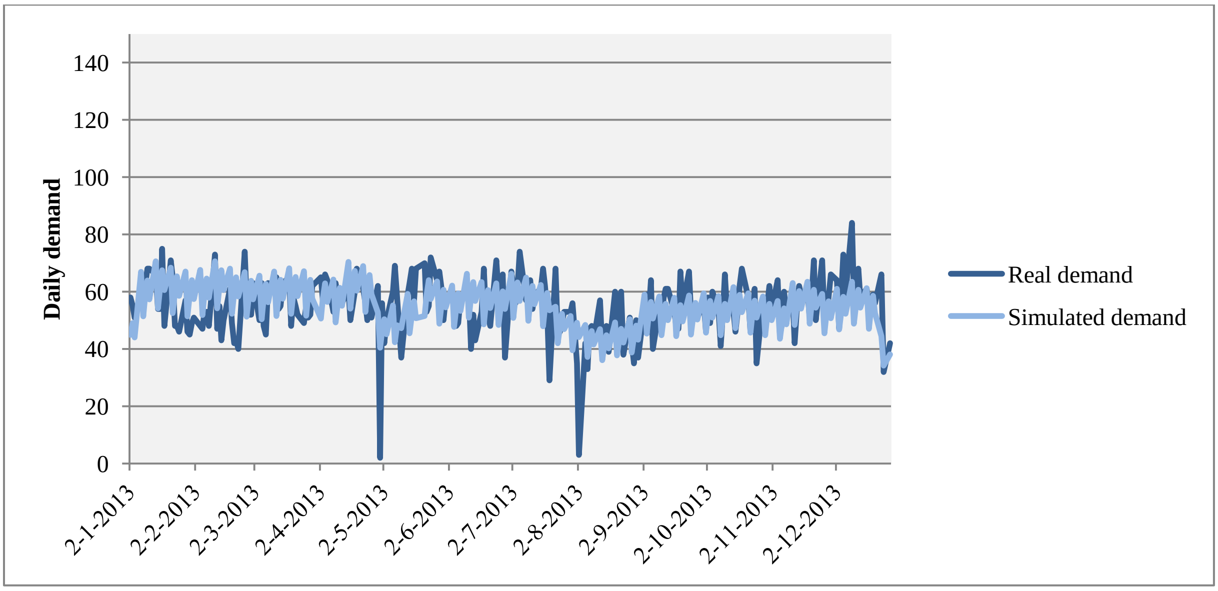

Figure 26 – *Daily demand pattern OPs*

The next factor we measure is the utilisation level since we noticed during the simulation that the utilisation level of the simulation differs from the real-world situation. The utilisation level for the real-world situation is 64.2% and for the simulation model is 60.3% (difference = 3.9%). Based on a Student's T-test with t(272) = 4.9 and t(critical) = 2.0 we notice that the difference is significant. We can clarify this difference since in the simulation model we measure the realised duration based on the approximated service time and in the real-world situation we measured the scheduled utilisation (because of a lack of insight in realised durations). The utilisation is based on the incoming demand and the available capacity. Since the model uses the same staffing levels and has a comparable demand pattern (see Figure 26), we see that the pattern of the utilisation is comparable. Only the magnitude of the measured utilisation of the real situation and the simulation model slightly differs.

Another important factor is that we calculated the probability for each examination type. Most of the patients are outpatients and therefore we focus on the arrival rate of outpatients for each examination type. We see in Figure 27 that the simulated demand per examination type is comparable to the real demand per examination type. The echo other (covering small examination types) shows a difference. This difference is due to the difference in grouping. In our simulation study, we combined the echo leg and echo upper leg. However, in the real situation, these are two distinct examination types.

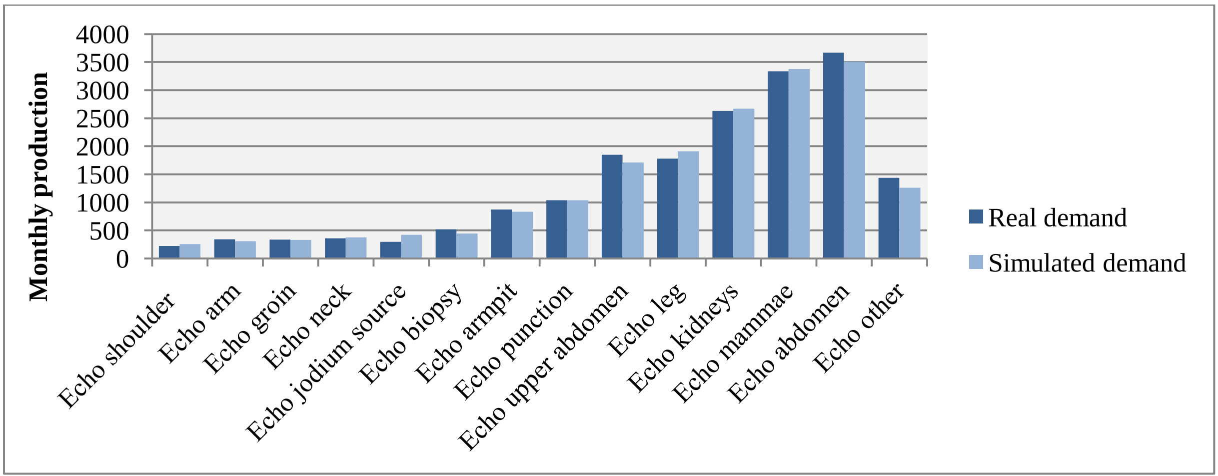

Figure 27 – *Real and simulated yearly demand for each per examination type*

Regarding the overall production level, the real production level of the year 2013 was 18561 examinations and in our simulation model this was 18256 examinations. So the real difference is 305. Since we do not have sufficient data of the yearly production with the same settings, we calculate the difference between the daily production level. Based on a confidence interval of the difference in the daily production [-0.99; 2.90] we see that there is no significant difference in production since the zero is in the interval.

The validation shows that there are small differences between the simulated situation and the real situation. For three out of the four output measures the model is valid. This is based on the measures average demand of OPs per month, the variability of the demand of OPs per month, and the total yearly production level. Only for the measure utilisation level, the model is not valid since the simulation model shows a significant lower utilisation level. By adding an assumption, we attempt to increase the fit between the real and simulated utilisation level.

4.7. Conclusion

This chapter answers the research questions 3 and 4:

What interventions are suitable to improve the current performance of the radiology department?

How can we model the processes at the radiology department?

Based on insight of the literature, we have designed four interventions to improve the specific situation of the echography. In the current situation, the department does not forecast the arrival rate and arrival pattern of emergency patients resulting in capacity problems for this patient type. Therefore, the first intervention is to use an emergency echo. Furthermore, the department does not forecast the arrival rates and patterns of outpatients based on data. Therefore, the capacity is not available when required resulting in a higher and less predictable access time, and utilisation problems. This results in the second intervention: optimising the block schedule. In the current situation the radiology schedules patients using the FCFS sequencing rule which does not enable to smooth the fluctuating arrival rate resulting in a high experienced workload as well as utilisation problems. This results in the third intervention: using off-peak scheduling. Finally, if it is possible reduce the variability with these interventions, we want to evaluate if we can reduce the number of staff.

Furthermore, this chapter has described the elements of the simulation model in order to get insight in the input of the model and the output of the model. In order to get reliable results of the simulation model, we have verified and validated the model assumptions and the output of the model by comparing the operations and output in the real-world with the assumptions and output of the model. Based on the verification and validation, we can assume that the model is a realistic representation of the real-world.

5. Experimental results

This chapter describes the results of our simulation study after programming the interventions and running the simulation model. Section 5.1 describes the performance of the initial design. Section 5.2 describes the performance of the different experiments compared to the initial design. Accordingly, Section 5.3 describes the decision on the best performing experiment. Finally, Section 5.4 summarises this chapter. The experiments are based on the four interventions (see Chapter 4 for details):

1. Dedicated echo room for unscheduled arrivals
2. Optimising the block schedule
3. Off-peak scheduling
4. Adapting the staffing level

5.1. Results initial design

In order to be able to identify which experiments have a better performance than the current performance, Table 18 shows the current performance. As stated in Section 4.3.3 we use the following KPIs:

Access time:	average number of days for scheduled patients
Waiting time:	average number of minutes for unscheduled patients
Experienced workload:	average experienced workload per day (%)
Utilisation:	average utilisation level per day (%)
Same-day access ratio:	average same-day access ratio per day (%)
Served within time window:	average rate of patients served within time window (tw) per day (%)
Production level:	yearly number of incoming requests
Staffing costs:	yearly staffing costs (€)

In the initial situation, the number of appointment slots on Monday to Friday is respectively 105, 94, 106, 94, and 106. Each weekday the echo rooms are equipped with 5 technicians, except for the Tuesday and Thursday afternoons (4 technicians from noon). The afternoons have a lower staffing level since during the mornings more slots are required for sober examinations. In the initial situation 88% of the slots are dedicated to scheduled arrivals resulting in an average of 12.4 slots per day for unscheduled arrivals.

KPI	Initial design	KPI	Initial design
Access time (days)	77.2	Same-day access ratio (%)	35.2
Waiting time (min)	73.2	Served within tw (%)	52.5
Experienced workload (%)	91.9	Production level (n)	18256
Utilisation (%)	60.3	Staffing costs (€)	270,557

Table 18 – *Initial performance of the model*

5.2. Experiments

Two of the proposed interventions address capacity planning, one intervention addresses patient scheduling, and one intervention addresses staff scheduling. These interventions focus on the tactical level as well as on the operational level. With the interventions in this research we aim to connect the tactical and operational level by first optimising the block schedule (capacity planning) and then optimising the way we schedule patients to this block schedule. Experiment 1 to 6 experiment with a new block schedule, Experiment 7 experiments with a new patient scheduling method based on the new block schedule we prefer, and experiments 8 and 9 experiment with adapting the staffing level based on the preferred block schedule and scheduling method.

Experiment 1

For this experiment we dedicate one echo room to unscheduled arrivals. In the current situation, there are too few slots for emergencies and emergencies are felt as disruptive to the primary system. Using a dedicated room for unscheduled arrivals increases the number of slots and separates the flow between unscheduled and scheduled arrivals. This enables the planners to completely fill the other four echo rooms with scheduled arrivals. As stated in Section 4.1, the block schedules of the other four echo rooms are scheduled by applying the heuristic and approach of intervention 2. For this experiment, 79.3% of the slots are dedicated to scheduled arrivals (1/5 of the rooms).

Table 19 gives the results of experiment 1 and the initial design. Compared to the initial design, each performance measure improves. This is partly due to the dedicated echo room and partly due the better block schedule for unscheduled patients at the remaining four echo rooms. In order to identify the specific effect of the improved block schedule, we now perform experiments 2 to 6.

KPI	Initial design	Exp 1	KPI	Initial design	Exp 1
Access time (days)	77.2	46.4	Same-day access ratio (%)	35.2	40.0
Waiting time (min)	73.2	41.9	Served within time window (%)	52.5	56.1
Experienced workload (%)	91.9	80.5	Production level (n)	18256	18362
Utilisation (%)	60.3	66.0	Staffing costs (€)	270,557	270,557

Table 19 -*Results of experiment 1*

Experiments 2 to 6

Dedicating one echo solely to unscheduled arrivals can result in a low utilisation. Furthermore, it can negatively affect the waiting time at peak hours since there is just one echo room available. With experiments 2 to 6 we use dedicated slots for unscheduled arrivals. This enables to reserve slots at peak times which can reduce the waiting time.

For the optimised block schedule we analyse 5 experiments. Experiment 2 dedicated capacity to each patient type based on the average demand. Based on the average demand, we assign 85.1% of the slots to scheduled arrivals (on average 16.6 unscheduled slots per day). The access time of scheduled arrivals and the waiting time for unscheduled arrivals are correlated with each other. However, we want to achieve a low access time and a low waiting time. Therefore, the experiments analyses the effect of increasing and decreasing the number of slots assigned to scheduled patients. Experiment 2 starts with an allocation based on the average required slots per examination type. Thereafter, we decrease the number of slots for scheduled patients in experiment 3 with 20% (81.2% unscheduled) and in experiment 4 we further decrease with 20% (77.8% unscheduled). Then, based on the situation of experiment 2, in experiment 5 we increase the slots for scheduled patients with 20% (88.6% unscheduled), and in experiment 6 we further increase with 20% (90.6% unscheduled).

The experiments with a decreased number of scheduled slots show a decreasing waiting time for unscheduled arrivals. However, the decrease is small in relation to the increase of the access time. Furthermore, the utilisation level decreases and the same-day access rate for scheduled arrivals strongly decreases. Furthermore, we can explain that the production level of experiment 3 is slightly lower than experiment 2 since there are more slots for unscheduled arrivals available than required on average. For experiment 5 and 6 we see the expected opposite effect. The elasticity of the waiting time in relation to the number of slots for unscheduled patients strongly increases at experiment 6.

The initial utilisation was 60.3%. With these interventions the utilisation level increases to a maximum of 67.1% at experiment 6. Based on a Student's T-test, we see that the difference for each experiment compared to the initial design is significant (t(df=182) > -13.2, P-value < 0.05). So, the experiments positively impact the utilisation level but the effect is still small. Reasons that the utilisation level is still low (compared to the other modalities) can be explained by the artificial variability that we are not able to predict with this research, the high natural variability of requests, the high capacity level, or the high deviation of realised and simulated service times. Experiments 8 and 9 adapts the capacity level and analyse the additional effect of adapting capacity on the utilisation level.

	Initial design	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6
Access time (days)	77.2	6.7	12.6	29.4	4.4	3.2
Waiting time (min)	73.2	64.5	58.9	58.3	86.6	191.0
Experienced workload (%)	91.9	84.3	82.4	79.1	87.9	82.2
Utilisation (%)	60.3	66.1	65.1	64.2	66.2	67.1
Same-day access ratio (%)	35.2	76.6	59.4	43.4	85.1	90.5
Served within time window (%)	52.5	79.1	71.0	59.2	84.5	85.1
Production level (n)	18256	18362	18342	18394	18380	18319
Staffing costs (€)	270,557	270,557	270,557	270,557	270,557	270,557

Table 20 – *Results of experiments 2 to 6*

In order to identify the best experiment for capacity planning, we compare the performance of the initial experiment and experiments 1 to 6. In the current situation, there are no norms for (most of) the KPIs and only the KPI utilisation is measured. The echo unit only has agreements with the ED and the AOA. Emergency patients from the ED require access within one hour and emergency patients from the AOA require access within one day. In our opinion, the last norm is high when patients are characterised as emergencies. The access time is about 3 days in the current situation. Since there is enough capacity to serve the incoming capacity at each weekday, an access time within one day is preferred. Furthermore, the goal of the experiments is to achieve the highest utilisation level, the highest same-day access ratio, the highest ratio of patients served within their time window, and the highest production level (staffing costs are equal).

Trade-off access time and waiting time

We now assess the trade-off between reducing the access time and reducing the waiting time. Furthermore, the waiting time and utilisation are negatively correlated. We do not further analyse this trade-off because of the minimal difference of the utilisation level over the six experiments.

Figure 28 shows the dependent relation between the waiting time for unscheduled arrivals and the access time for scheduled arrivals. Experiment 1 has the best score for the waiting time (worse score for the access time) and experiment 6 has the best score for the access time (worst score for the waiting time). The lower left corner of Figure 28 shows the experiments with a relative low access time and relative low waiting time (Exp 2 and Exp 3). It depends on management which experiment (a better access time or a better waiting time) is preferred. We use the settings of experiment 2 for experiments 7 to 9. The waiting times between the experiments 2 and 3 do not differ much but the access time is much better with experiment 2. Furthermore, the other KPIs score better for Experiment 2 or the difference is negligible.

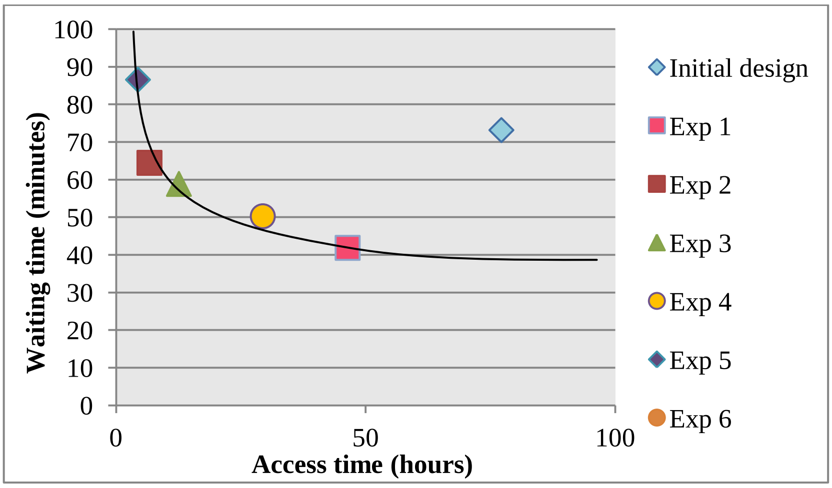

Figure 28 – *Trade-off between waiting time and access time*

Experiment 7

With this experiment we improve the patient scheduling process by scheduling based on the targeted time window and current daily utilisation levels. The arriving request is not scheduled at the first available slot (FCFS) but at a day with the current lowest utilisation level within the targeted time window. Since the experiment is based on the block schedule of experiment 2, the percentage of dedicated slots to unscheduled arrivals is 88% (16.6 unscheduled slots per day).

Off-peak scheduling has a positive impact on the average access time, waiting time, the same-day access ratio, and the ratio of patients served within the targeted time window compared to experiment 2. The difference between access times is small. However, when comparing the distributions of the access time between the distribution of experiment 7 (min = 0.1 days, max = 90.1 days) has a wider spread than experiment 2 (min = 0.2 days, max = 46.8 days). This enables the scheduled arrivals with a short time window to be scheduled on time, which results in a longer time for arrivals that can wait. The utilisation level is not increased. In this study, the utilisation level can now only be affected by adapting the capacity to demand.

KPI	Initial design	Exp 2	Exp 7	KPI	Initial design	Exp 2	Exp 7
Access time (days)	77.2	6.7	5.8	Same-day access ratio (%)	35.2	76.6	83.6
Waiting time (min)	73.2	64.5	61.2	Served within tw (%)	52.5	79.6	90.2
Experienced workload (%)	91.9	84.3	85.1	Production level (n)	18256	18362	18359
Utilisation (%)	60.3	66.1	66.0	Staffing costs (€)	270,557	270,557	270,557

Table 21 – *Results experiment 7*

Experiments 8 and 9

Experiments 8 and 9 are based on the block schedule of experiment 2 and the patient scheduling method of experiment 7. In the current situation, the echo has scheduled five technicians at Mondays, Wednesdays, and Fridays and 4.5 technicians at the Tuesdays and Thursdays (see Section 4.1). As we have seen, the demand at the Tuesdays is even higher than at the Wednesdays. Therefore, experiment 8 is a configuration in which we reduce the staffing level with 0.5 at the Wednesday. For experiment

9, we further reduce the staffing level with 0.5 at the least busy day (Thursday). Adapting the staffing level at Thursday has the least negative effect on the same-day access

Decreasing the staffing levels positively affects the utilisation level and staffing costs. However, the intervention negatively impact the access time, the experienced workload, same-day access ratio, patients served within the time window, and production level. The production level of experiment 9 is the lowest production level and the utilisation level is the highest of all experiments. By decreasing the staffing level, timely access becomes challenging. Regarding the utilisation level, experiment 9 seems to show that the utilisation level is at its maximum. Further increasing the utilisation level is not desirable because of the negative impact on the access time. In our opinion, a utilisation level of approximately 70% is desirable for the echo since it is a modality with an availability function.

KPI	Initial design	Exp 2	Exp 8	Exp 9
Access time (days)	77.2	6.7	9.1	38.1
Waiting time (min)	73.2	64.5	63.6	63.3
Experienced workload (%)	91.9	84.3	85.1	87.3
Utilisation (%)	60.3	66.1	69.4	71.8
Same-day access ratio (%)	35.2	76.6	60.5	32.1
Served within tw (%)	52.5	79.1	82.4	77.2
Production level (n)	18256	18362	18334	18304
Staffing costs (€)	270,557	270,557	242,374	214,191

Table 22 – *Results experiment 8 and 9*

Table 23 gives an overview of the results of each experiment. In order to estimate the individual effect of each intervention, we compare different experiments. Comparing experiment 1 and 2 allows estimating the effect of intervention 1 (dedicated echo room). Intervention 1 has the most impact on the waiting time. Furthermore, comparing experiment 2 with the initial experiment allows to estimate the effect of intervention 2 (optimising the block schedule). Intervention 2 has a positive impact on each KPI and especially improves the access time. By comparing experiment 2 with experiment 7, we can estimate the effect of intervention 3 (off-peak scheduling). Intervention 3 especially increases the ratio of patients served within the time window. Finally, by comparing 8 and 9 with experiment 2 enables to estimate the effect of intervention 4 (adapting the staffing level). Intervention 4 has a negligible effect on most of the KPIs but positively affects the staffing costs.

	Experiment									
KPI	Initial	1	2	3	4	5	6	7	8	9
Access time (days)	77.2	46.4	6.7	12.6	29.4	4.4	3.2	5.8	9.1	38.1
Waiting time (min)	73.2	41.9	64.5	58.9	58.3	86.6	191.0	61.2	63.6	67.3
Experienced workload (%)	91.9	80.5	84.3	82.4	79.1	87.9	82.2	85.1	85.1	87.3
Utilisation (%)	60.3	66.0	66.1	65.1	64.2	66.2	67.1	66.0	69.4	71.8
Same-day access ratio (%)	35.2	40.0	76.6	59.4	43.4	85.1	90.5	83.6	60.5	32.1
Served within tm (%)	52.5	56.1	79.1	71.0	59.2	84.5	85.1	90.2	82.4	77.2
Production level (n)	18256	18362	18362	18342	18394	18380	18319	18359	18334	18304
Staffing costs (€)	270, 557	270, 557	270, 557	270, 557	270, 557	270, 557	270, 557	270, 557	242, 374	214, 191

Table 23 – *Overview of results*

5.3. Conclusion

In this chapter we have analysed four interventions by analysing nine experiments in order to answer research questions 4 and 5. Most of the times if an experiment scores the best on one KPI, the experiment has a very worse score on another KPI (negatively correlated). By assessing the trade-off between different KPIs, management can decide on the best setting. Since there are no norms for each KPI, we cannot decide on the experiment that scores sufficient on the KPIs.

Comparing different experiments enables to assess the individual effect of each intervention. Based on these comparisons, we see that the interventions can improve the waiting time, access time, patients served within the time window, and costs. Based on the description of the trade-off between waiting time and access time we suggest to use the block schedule of experiment 2. Furthermore, using off-peak scheduling further slightly increases the performance. Finally, when management decides that a decrease of costs of approximately 28,000 euro per year outweigh an increase in access time (3.3 days) and a decrease in the same-day access rate (23.1%), we suggest to implement the settings of experiment 8.

With the proposed interventions, more experiments are possible. However, this becomes too intensive for the goal of this study. With these experiments we show the effect of scheduling capacity based on the forecasted demand taking into account the specific requirements of the request. This gives the radiology department insight in the factors to improve the match between demand and supply. Furthermore, we have analysed one static schedule that is used for a complete year. We strongly recommend to update the schedule periodically to also incorporate the seasonal patterns.

6. Implementation

This research proposes valuable interventions to improve the performance of the echography. However, not all interventions are yet implemented. In the current situation the echo already predicts and schedules the number of slots for a punction and biopsy by looking at the expected number of request for an echo mammae. Furthermore, based on suggestions from this research, the number of emergency slots has increased. To achieve implementation of the interventions and to achieve long-term and short-term improvements for the entire radiology department, we propose the next steps:

Create urgency

The main focus of the radiology department is to focus on the daily processes and to achieve a high utilisation level. Sharing the results of this study and discussing the implications with the operational managers creates urgency of looking forward instead of behind. Furthermore, in the current situation the only used KPI is the utilisation level. Therefore, there is no urgency to optimise the block schedule and use off-peak scheduling. By using more KPIs, there is a higher urgency for the operational managers to adapt their planning and scheduling methods and positively affect the performance.

Give attention to individual ideas

During the observations and discussions with staff, we noticed that many staff members of the radiology department have insight in the problems and are able to improve these problems. Identifying the strengths of each individual and increasing the freedom to develop these strengths increases the staff satisfaction and can support continuous improvement.

Organise a tactical planning meeting

Each month, the operational managers of the radiology department together with the main referring departments/specialties should organise a tactical planning meeting. During this meeting each stakeholder discusses its performance, future developments, and the requirements towards the radiology department. This gives the radiology department insight in the required capacity, and the referring departments insight in the challenges of the radiology department.

Train the operational managers

The operational managers are responsible for creating the block schedule. They should be trained to generate effective block schedules based on historical data and specific requirements. Analysing historical data is not a daily business for the operational managers. Therefore, training the operational managers with Excel and developing a good block schedule would be valuable.

Continuous performance measurement

By measuring the performance of several KPIs and discussing these findings periodically, the attitude towards change can be improved. This means not only measuring the utilisation, but also specific KPIs for modalities with a capacity function or an availability function. Furthermore, this allows the department to plan the future and correct for issues of the history.

Continuous improvement

After implementing the proposed interventions, we suggest to further identify opportunities for improvements. The proposed interventions address major problems, however, there are still other issues disrupting the patient flow. Furthermore, the input (e.g. patient types, examination types, capacities) as well as the process can differ in the future which requires a new approach.

7. Conclusion, Discussion & Recommendations

This chapter reflects on the problem and the way we achieved the goal. Section 7.1 describes the main conclusions of this research, Section 7.2 discusses the approach and results of this research, and Section 7.3 ends with recommendations for the radiology department and for future research.

7.1. Conclusion

The main goal of this research is:

To reduce the variability of the utilisation of the radiology department by
a) generating insight in the factors affecting the variability and
b) analyse interventions to increase the match between demand and supply.

The radiology department is equipped with eight different types of modalities. To generate insight in the factors that affect the variability in the performance, we have demarcated the scope to a specific modality at the main location of Isala. Based on an extensive benchmark, observations and meetings with stakeholders, we have generated insight in the performance of the radiology department. This insight is required in order to establish the variability and to identify the factors that affect the variability. The variability in the performance is an effect of a highly fluctuating demand and a static capacity over time. This research addresses the variability in demand for echo requests per hour, per day, and per week. Predictors for the variability are the time the doctors visit inpatients (9AM, 11AM), the discharge moment (after 2PM), the breaks of technicians (noon), the number of echo mammae requests, and the time of discharge (Fridays, before weekend). Furthermore, we expect that the outpatient schedules are major predictors. For example, there are many patients at the Monday and Thursday because of office hours for mammae patients. Since we have no insight in the outpatient schedule, we cannot assess the entire effect of the outpatient schedule on the demand at the radiology department.

Furthermore, the goal of this research is to increase the match between demand and supply. Therefore, we use the analysis of the current situation in order to identify the major bottlenecks that affect the performance. By removing these bottlenecks, we can improve the performance. The main bottlenecks are: a shortage of emergency slots because of a lack of insight in the emergency arrival pattern, an incorrect or incorrect used block schedule, no insight in the targeted time window of patients resulting in the suboptimal FCFS scheduling rule. The underlying problem for these specific bottlenecks is that in the current culture of the radiology department (and probably a larger part of the hospital) the main focus is on the daily operation. Staff of the radiology department believes that forecasting the demand is not possible because of the high fluctuations in demand. Removing these bottlenecks can improve the performance in terms of access time, waiting time, utilisation level, workload, and costs.

We have simulated the effect of four interventions: a dedicated echo room for unscheduled arrivals, optimising the block schedule, off-peak scheduling, and adapting the staffing level. The interventions can improve the performance, but we need to take into account the trade-off between different KPIs. By improving the block schedule and using off-peak scheduling, we expect major improvements for the access time (2 days), same-day access ratio (48%), and patients served within their time window (38%). Finally, if management decides that the decrease in costs significantly outweigh the increased access time and decreased same-day access, costs can reduce with approximately 28,000 euro per year.

7.2. Discussion

With this research, we address the tactical and operational level of resource capacity planning. We provided Isala insight in the benefits of forecasting demand and analysing patterns in order to be able to manage the processes in an effective way. In the current situation, there are some developments and strategies to improve the performance of the radiology department. However, these strategies only take into account a small part of the total demand (e.g. only adapt schedule for mammae-care patients), are only based historical data or on gut feeling, and only address the utilisation level. In our research, we suggest interventions to improve the operational a well as tactical level of scheduling and address the utilisation level as well as other important KPIs. This provides the radiology department a way to improve their current processes. Furthermore, the Lean department within Isala is interested in this research and is inspired by the approach. Therefore, this research is of additional value to approach comparable problems within the hospital.

Based on the literature review, we see that the literature addressing capacity management issues at the radiology department is scarce. With our research we expand the current literature by improving both the utilisation level as well as service related KPIs like the access time. Another factor of this research that is valuable for the literature as well as for the domain healthcare is that this research shows the benefits of forecasting demand. Forecasting the demand improves the ability to adapt the demand pattern and to further fine-tune capacity. The external validity of this research with regard to the effect of the interventions depends on the input characteristics and process characteristics of another setting. In our study, we do not recommend to use an emergency echo since the demand for unscheduled patients is too small. However, when the number of unscheduled arrivals is higher, it can be valuable to use a dedicated echo for these patients. Based on the current state of literature of capacity planning at the radiology, we expect that many radiology departments that use a block schedule can improve the performance by optimising their block schedule and using off-peak scheduling. However, when a radiology department does not use block schedules (e.g. free access), we cannot guarantee the external validity. Therefore, it highly depends on the comparability of the setting in terms of inputs, process and planning and control mechanisms whether this research can be generalised to other settings.

In retrospect, we would perform some things differently. First, it would be better to measure both the date of the first consult as well as the date of the second consult to identify the time window of patients. In the current situation we have only measured the date of the time between first consult and visit at the radiology department. Measuring the time until the second consult increases the time window and further improves the ability to smooth the variability of demand. Second, it would be better to perform more measurements of the realised service times for each examination type. Due to time constraints we have not increase the number of measurements. By including more observers from the radiology department, we could achieve more measurements in the same time. Third, it would be valuable to approach the problem by also taking into account scheduling practices at the referring departments. Analysing the scheduling practices and requirements of the department with the highest demand would generate valuable information within the time of this research.

Other points that affect the internal validity are the benchmark method, the high number of assumptions concerning the simulation model, and the way we identified the best performing experiment. By including more KPIs, other modalities could be the modality of focus. Furthermore, the way we identified the best performing experiment is based on norms and the amount of improvement compared to the initial situation. With other norms, other experiments could become the most powerful.

7.3. Recommendations

This section describes the recommendations for Isala. Section 7.3.1 gives recommendations based on the findings of this research for the entire radiology department, Section 7.3.2 gives the specific recommendations for the echo, and Section 7.3.3 describes recommendations for future research.

7.3.1. Generic recommendations from research

1. Define KPIs and norms

We suggest to not only measure the utilisation level, but also to incorporate the proposed KPIs in this study in order to establish the current performance. Furthermore, the norm of each KPI needs to be established in order to make a judgment on the performance.

2. Assess outcome of current way of scheduling

For each unit of the radiology department we suggest to assess the current way of capacity planning and the identify the effect of using this approach. Furthermore, each unit should reflect the outcome of their planning approach with respect to the desired situation of the specific unit. For example, open access, a dedicated emergency room, or aggregating slots can be useful in some settings.

3. Forecast demand

In this study we have shown the additional effect of forecasting future demand and scheduling capacity based on the forecasted demand. This can increase the fit between incoming requests and available capacity for the request. Therefore, the operational managers should use historical data and discuss the desired situation with the requesting specialties.

4. Adapt appointment times

The appointment times for many examinations does not match with the required time and is not adapted over the last time. To have sufficient time for the examination, we recommend to adapt the appointment times based on realised data. Therefore, the unit can either continuously record the realised service times or measure the realised times during at least one week. We recommend to continuously record the realised time in to also have realistic appointment times in the future. An example is to record the data of the imaging equipment.

5. Collect required date of result on request form

To further improve off-peak scheduling and smooth the incoming flow of requests, we recommend to collect the date of the second consult (diagnosis) on the request form. In the current situation, some specialists write this date on the request form. However, this date should always be available.

7.3.2. Specific recommendations from research

1. Implement new block schedule and scheduling rule

Based on the positive results of the optimised way of creating a block schedule and scheduling patients, we strongly recommend to implement the new approach. This positively affects the performance of the radiology department as well as the performance of their referring departments.

2. Forecast demand based on predictors

The conclusion has summarised the predictors for the variability in demand for the echography. A specific predictor for the echo is for example the number of echo mammae that predict the echo punction, biopsy, and armpit. During the scheduling process, the operational manager should not reserve capacity for the echo punction, biopsy and armpit before reserving slots for echo mammae.

3. Aggregate slots

Aggregating demand enables risk-pooling which reduces the required slack and increases the availability of capacity. We recommend to use slots for examinations with a low prevalence and high variability, slots dedicated to both echo punction and echo biopsy, and slots dedicated to both inpatients and emergencies.

4. Only reserve for urgent patients

In the current situation, the schedule also reserves slots for less urgent patients (like echo kidneys). However, reserving slots is only useful for urgent cases to guarantee timely access. For the other patient types and examination types we suggest to use generic slots which can increase to utilisation.

5. Front-desk schedules punctions

In the current situation, the echography receives the requests for a punction and schedules the request. This requires many time and therefore we recommend to let the front-desk schedule punctions. With a clear instruction, the front-desk can increase the available time of technicians to patients.

7.3.3. Future research

1. Research at the other modalities

In this study, the main focus is on the echo because of the highest opportunity for improvement. However, we also identified other modalities with a low overall performance. Based on our benchmark, we suggest to improve the balance between demand and supply at the Dexa and CT.

2. Develop workload tool

During this research, fine-tuning capacity between modalities was not possible. There is no insight in the real staffing level as well as the experienced workload at each modality. This disables effective reallocation. We recommend to perform research on a tool that presents at each modality the workload of each modality.

3. Research on outpatient schedule

The outpatient schedule is a major predictor of the flow from outpatients in the entire hospital. During this project, we were not able to get insight in the schedules because of data constraints. We strongly recommend to adapt the data sources in order to generate insight in the outpatient clinic schedules and to analyse the effect of the schedules on the patient flows.

4. Apply research to other areas

Since less literature focuses on capacity management at the radiology department, we suggest to apply this research at other radiology departments. Furthermore, we expect that not only the current literature is limited, but also the practical application of capacity management at this area is limited.

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Appendices

Appendix 1 – Description of modalities

Bucky - The bucky is a modality using x-rays to visualise the internal structures of a patient. X-rays are produced by an x-ray tube and is a form of electromagnetic radiation. During a procedure, x-rays are sent through the body and captured behind the patient by a detector. A proportion of the x-rays is absorbed and can have negative effects depending on the dose. Bone tissue absorbs more x-ray than soft tissue and gives more contrast in the image. Therefore, the bucky is often used to diagnose bones or dense tissue (WHO, 2014).

Echography - The echography uses ultrasound, high-frequency sound waves, to provide cross-sectional images of the body. The modality has a transducer that produces sound waves and captures the returning waves which are represented at dots on the screen. Ultrasound is a very safe procedure with minimal known adverse events (WHO, 2014).

CT - Computed tomography (CT) is an imaging modality that uses x-ray photons. The scanner is an x-ray tube to pass x-rays through the body and detects the x-rays to create a two or three dimensional image. The additional value of a CT compared to the bucky is that it creates cross-sectional slices of the body. Sometimes contrast fluid is used to distinguish structures of a similar density. The CT utilises a high dose of x-ray compared to the bucky and therefore there is a higher risk on complications (WHO, 2014).

Dexa - Dual-energy x-ray absorptiometry (Dexa) or bone density scanning, is an enhanced form of x-ray technology to measure the bone loss. Dexa is most often performed on the lower spine and hips and is used to diagnose osteoporosis (RadiologyInfo, 2013).

Angiography - Angiography is used for the visualisation of blood vessels (in particular: the arteries, veins, and heart chambers). Contrast fluid is injected into the blood vessels in order to detect the vessels using x-rays. The x-ray dose of angiography is higher than the dose from the bucky. Therefore, there is a higher risk on complications (WHO, 2014).

Mammography - Mammography is an imaging technique that uses a low dose of x-rays for imaging of breast tissue. Mammography utilises standardised views to detect breast lesions or for the detection of early breast cancer. Each breast is examined separately and compressed against the film to obtain the best visualisation. Pain sometimes occurs but furthermore, it is a safe procedure (WHO, 2014).

MRI - Magnetic resonance imaging (MRI) is a medical imaging technique used to visualise detailed internal structures using magnetic radiation. MRI provides three dimensional views of the body organs with good soft tissue contrast. Therefore, it is possible to visualise for example the brain, spine, and muscles. MRI is a generally safe procedure and there is no radiation exposure. Injuries may be caused on patients with metallic implants (WHO, 2014).

X-ray screening - is comparable to the bucky modality. The modality makes a film composed by different images in order to identify movements in the body (Healthcare Imaging Services, n.d.)

Appendix 2 – Production per modality per specialty

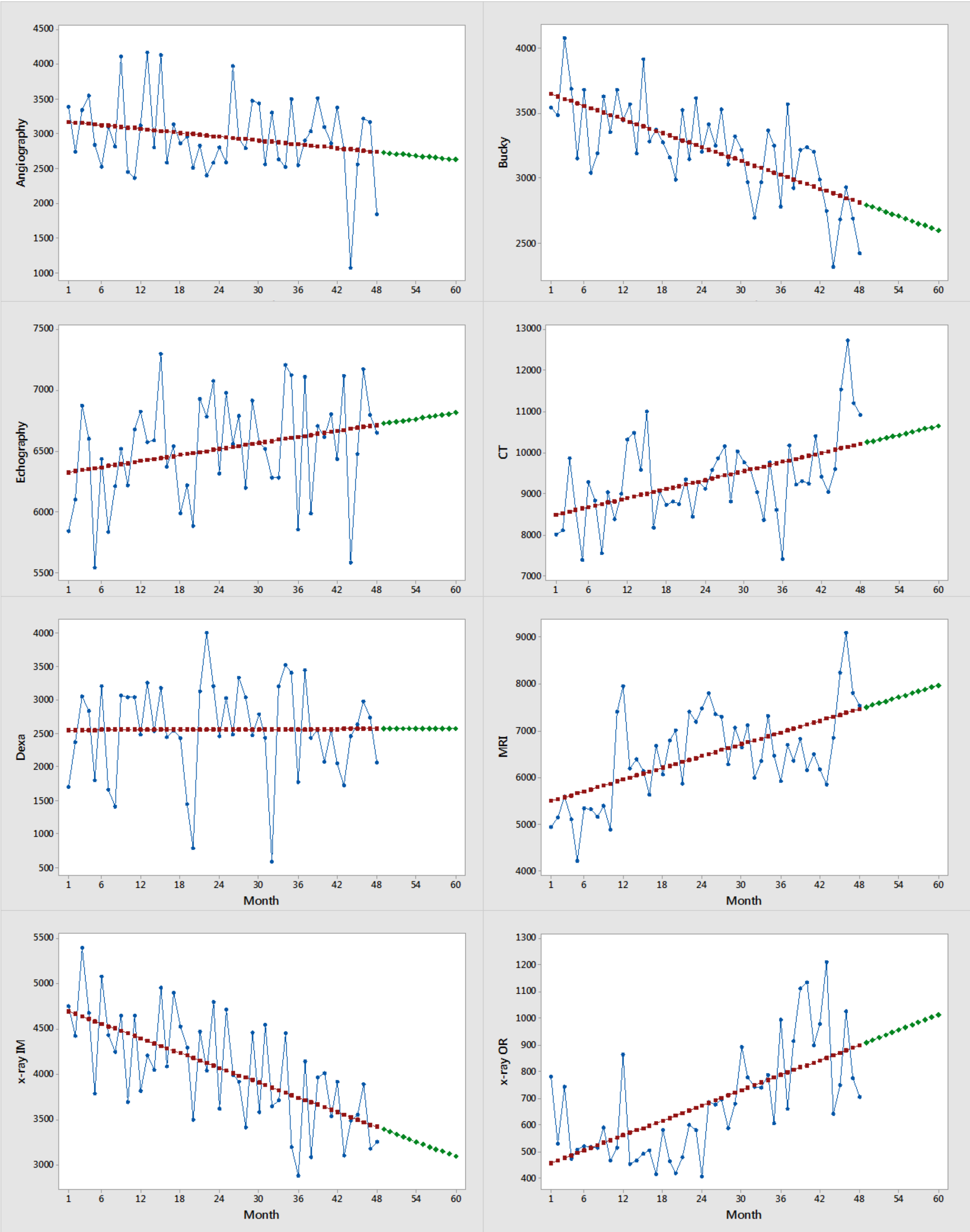
Specialty	Angio	Bucky	CT	Dexa	Echo	Mammo	MRI	X-ray (IM)	X-ray (OR)	Total
Anaesthetics	65	8090	524		194	1	82		109	9065
Cardiology		7577	733	1	354	2	508		18	9193
Clinical chemistry		9								9
Clinical geriatrics					1		5			6
Dentistry		4								4
Dermatology		54	3		62		3			122
ENT	8	173	1458		64		337	132		2173
External health assessment		13								13
External specialist			2				4			6
Gastroenterology	17	963	1775	71	1558	3	336	922	22	5667
GPs	2	32822	148	628	13248	2329	363	34		49611
Gynaecology	3	362	231	61	333	78	126	110	6	1310
Internal medicine	27	7878	4346	545	4100	111	767	22	10	17811
Neurology	17	2316	3988	1	134	6	6261	21		12744
Neurosurgery	140	1245	399		9	1	743	4	1670	4211
Nuclear medicine		1					1			2
Nursery		196	6	2	32		9	1		246
Obstetrics		1			4		2		1	8
Ophthalmology	15	33	6				64			118
Oral surgery		52	99		81		29			276
Orthopaedics	2	20876	1378	222	832		1731	953	1005	27010
Other specialties		2				38				40
Pathology		2				16				18
Pediatrics		2145	75	4	761		202	37	3	3227
Physiotherapy		10	1	1	6			1		19
Plastic surgery	37	2678	125		224	23	149	1	11	3248
Podiatry		1								1
Psychiatry		66	17	1	15		26	1		126
Pulmonary medicine	7	8473	3120	11	299	2	171	37	10	12130
Radiology	1757	5	37		286	1		4	190	2280
Radiotherapy		125	72		111	127	83	7		525
Revalidation		672	3		20		7			703
Rheumatology		5564	20	127	134	1	184	4		6035
Sports medicine		1								1
Surgery	412	14296	2540	248	7067	3508	830	198	1620	30735
Thoracic anaesthetics		58	17		54				4	133
Thoracic surgery		3203	161		74		8		66	3512
Urology	1	1415	949		2326		111	80	1015	5897
Total	**2510**	**121381**	**22233**	**1923**	**32383**	**6247**	**13142**	**2569**	**5760**	**208235**

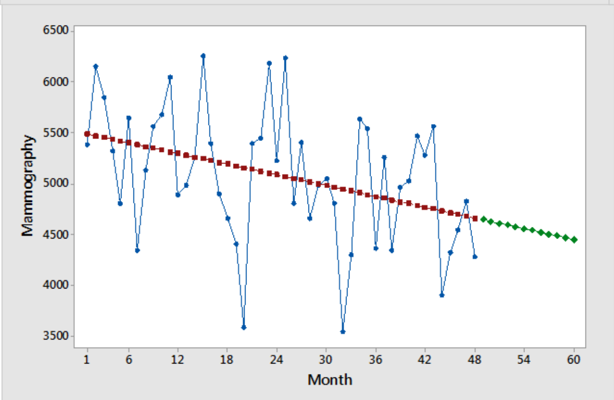
Appendix 3 – Shifts and working hours

	Regular workinghours (7.45 – 16.30)										
Day	Mon		Tue		Wed		Thu		Fri		Total (Sun-Sat)
morning/afternoon	mor	aft	mor	aft	mor	aft	mor	aft	mor	aft	
Bucky	13	13	12	14	13	13	12	14	13	13	130
CT	5	5	5	5	5	5	5	5	5	5	50
Dexa	1	1	1	0	1	1	1	1	0	0	7
Echography	8	7	8	7	7	7	7,5	7	7	7	72,5
Mammography	2	2	2	2	2	2	2	2	2	2	20
MRI	6	6	6	6	6	6	6	6	6	6	60
Angiography	3	3	3	3	3	3	3	3	3	3	30
X-ray IM	1	1	1	2	1	1	1	2	1	1	12
X-ray OR	4	4	4	4	4	4	4	4	4	4	40
Total	43	42	42	43	42	42	41,5	44	41	41	421,5

	Evening shifts					
	Mon	Tue	Wed	Thu	Fri	Total
Early evening shift (13.30 – 21.45)	1	1	1	1	1	5
Late evening shift (15.00 – 23.15)	1	1	1	1	1	5
Night shift	1	1	1	1	1	5
Total	3	3	3	3	3	15

Appendix 4 - Trend of monthly production over workload





$Yt_{angio} = 3180 - 9{,}18 \times t$

$Yt_{bucky} = 3664{,}1 - 17{,}77 \times t$

$Yt_{echography} = 6317 + 8{,}29 \times t$

$Yt_{CT} = 8456 + 36{,}62 \times t$

$Yt_{dexa} = 2553 + 0{,}35 \times t$

$Yt_{MRI} = 5450 + 41{,}99 \times t$

$Yt_{x\text{-}ray\ IM} = 4716 - 27{,}13 \times t$

$Yt_{x\text{-}ray\ OR} = 446{,}7 + 9{,}43 \times t$

$Yt_{mammography} = 5507 - 17{,}60 \times t$

Appendix 5 – Data registration

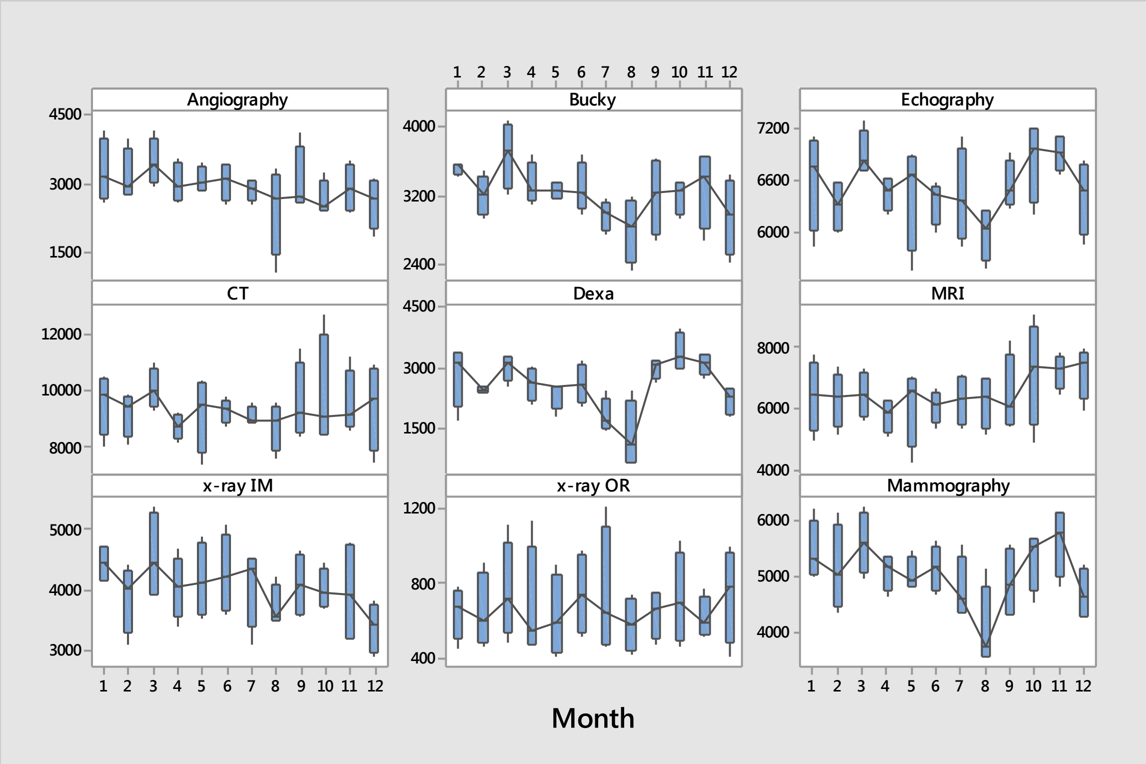
Difference in appointment duration within examination type

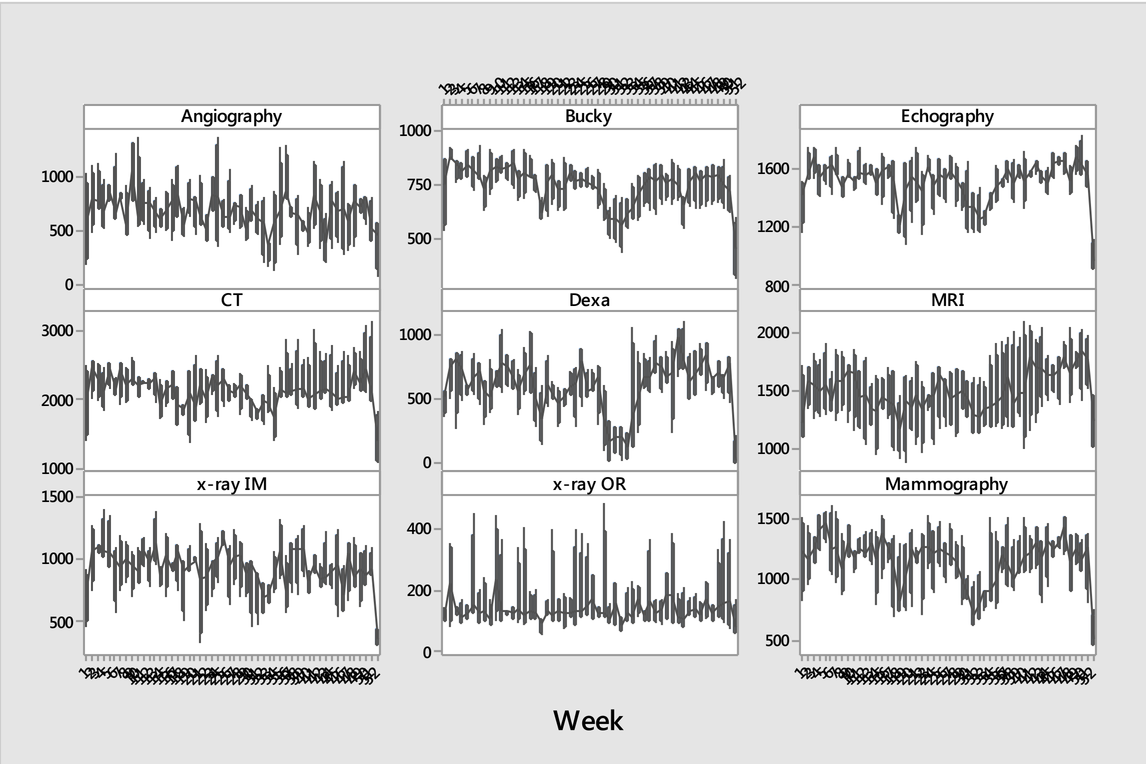
PatientID	ContactDate	Weekday	App.Time	Modality	ExaminationType	Duration	RequestDate	Req.Time
239606	24-12-2013	Tuesday	10:50	MRI	MRI enkel rechts	25	2013-12-17	12:57
333500	17-2-2014	Monday	9:45	MRI	MRI enkel rechts	40	2014-01-29	09:56
1158668	26-11-2013	Tuesday	13:50	MRI	MRI enkel links	30	2013-11-25	14:36
14332242	25-11-2013	Monday	11:20	MRI	MRI enkel rechts	40	2013-11-19	09:02
16089858	29-7-2013	Monday	12:30	MRI	MRI enkel links	35	2013-07-22	09:09

Production on non-mammae poli days

PatientID	ContactDate	Weekday	App.Time	Modality	ExaminationType	Duration	RequestDate	Req.Time
14140464	17-2-2014	Monday	10:50	MRI	MRI knie links LC	35	2014-02-07	09:24
14140464	17-2-2014	Monday	11:25	MRI	MRI knie rechts LC	35	2014-02-07	13:22
14140464	18-2-2014	Tuesday	15:20		Studie	20	2014-01-24	10:43
14140466	15-11-2013	Friday	8:15	Mammo	Mammografie	15	2013-11-06	14:04
14140466	15-11-2013	Friday	8:05	Echo	Echo mamma L	20	2013-11-15	09:12
14140466	15-11-2013	Friday	8:05	Echo	Echo oksel links	20	2013-11-15	09:12
14140466	25-11-2013	Monday	9:00		Nieuwe patiënt mammapoli	15	2013-11-20	16:16
14140466	25-11-2013	Monday	13:55		Controle patiënt mammapoli	15	2013-11-20	16:16
14140466	25-11-2013	Monday	9:55	Echo	Echo MP-mamma L	20	2013-11-20	16:17
14140466	25-11-2013	Monday	9:15	Adm	Multi diciplinair overleg	5	2014-01-30	09:15
14140466	4-2-2014	Tuesday	10:00	Echo	Echo mamma L	30	2014-01-29	08:23
14143876	26-11-2013	Tuesday	13:35	Bucky	Knie links	10	2013-11-26	12:01
14143876	26-11-2013	Tuesday	13:25	Bucky	Knie rechts	10	2013-11-26	13:56

Appendix 6 – Workload variability per month and week





Appendix 7 – Assumptions list

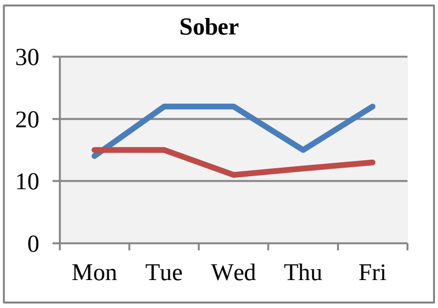
- Peaks in the workload (service time per FTE) determine the experienced workload.
- The number of no-shows and refusals is negligible
- The time between the first intake consult and the moment that the request is send to the radiology department is negligible.
- Radiologists only discuss the following findings directly after examination:
  - Emergency patients
  - Inpatients
  - Examination echo mammae
  - Examination echo armpit
- There is no significant difference in the service time per technician
- Each emergency patient requires access on the same day as the day of request
- The arrival rate of outpatients depends on the hour, weekday, and week
- The arrival rate of outpatients is significant lower at national holidays
- The arrival rate of outpatients depends on the block schedules of the outpatient clinics
- There is no relation between the week and the busiest weekday
- There is no relation between the weekday and busiest hour
- The service time depends on the patient type (E, I, or O), the type of examination (14 types), and the need for a radiologist.
- The medical review by the radiologist is not person dependent
- The medical review by the radiologist is not dependent on the experienced workload
- The service time for each patient is normally distributed
- The time of request equals the time of the first intake consult
- For 90% of the patients, the scheduled appointment time for patients is comparable to the sum of the preparation time, service time, and medical review by the radiologist

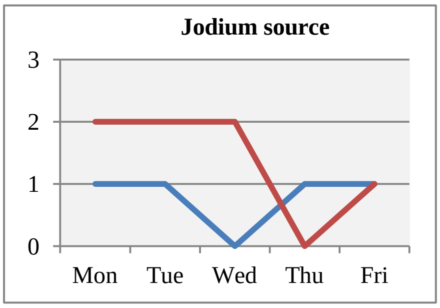
Appendix 8 – Student's T-test

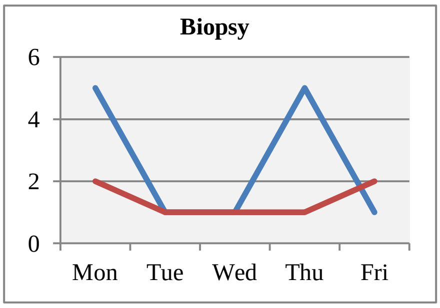
Measurements of the statistical differences in daily arrivals

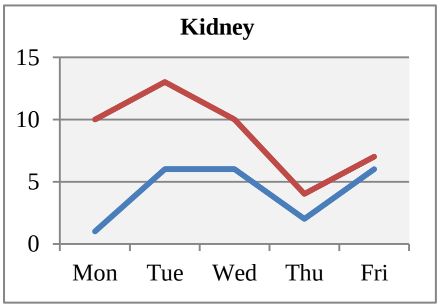
	P-value	DF
Mon-Tue	0,455	40
Mon-Wed	0,051	40
Mon-Thu	0,475	40
Mon-Fri	0,014	40
Tue-Wed	0,061	40
Tue-Thu	0,478	40
Tue-Fri	0,033	40
Wed-Thu	0,052	40
Wed-Fri	0,000	40
Thu-Fri	0,018	40

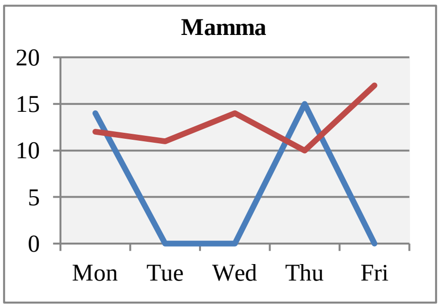
Appendix 9 – Required slots versus current available slots

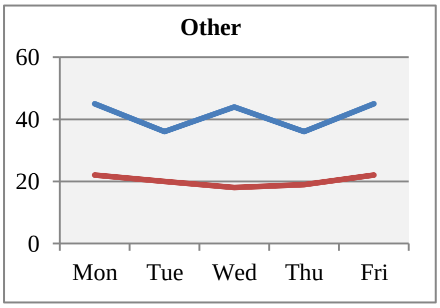


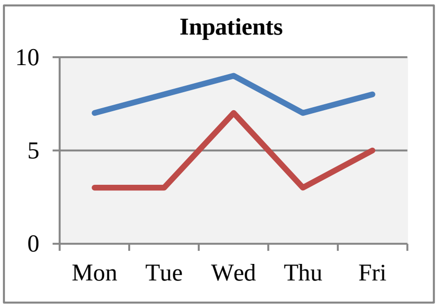


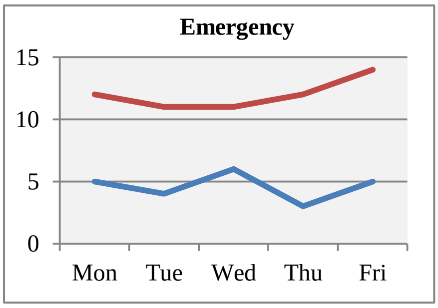


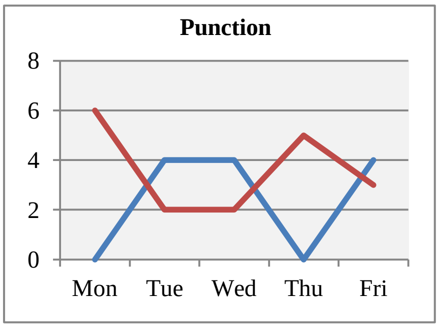


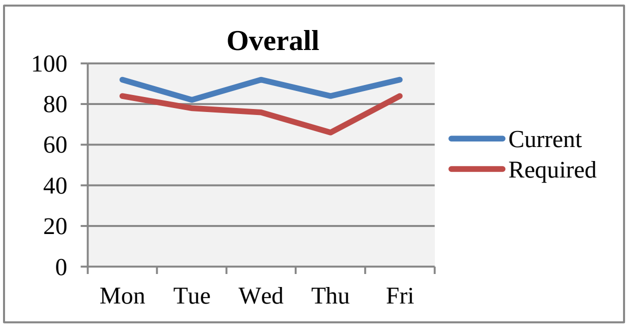




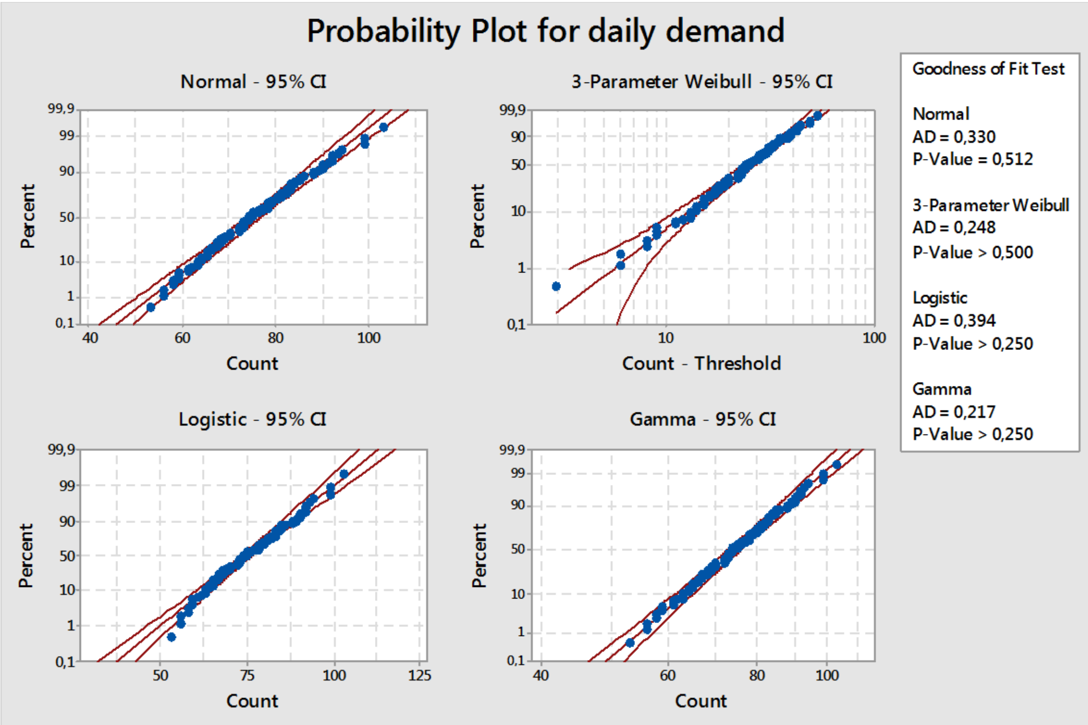


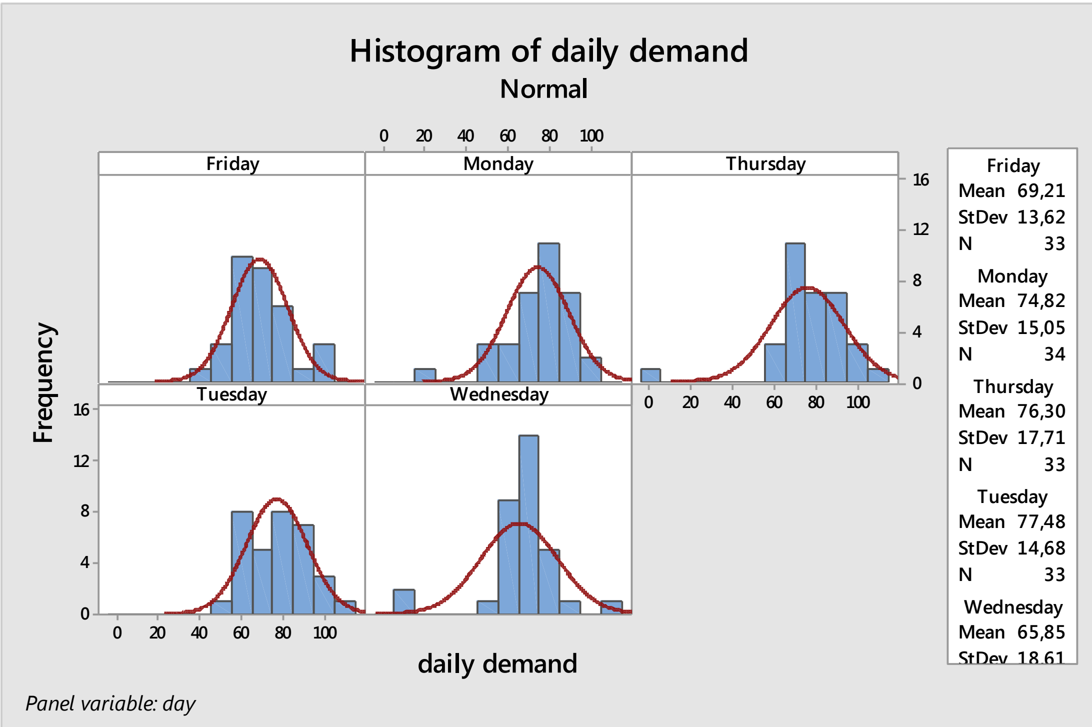




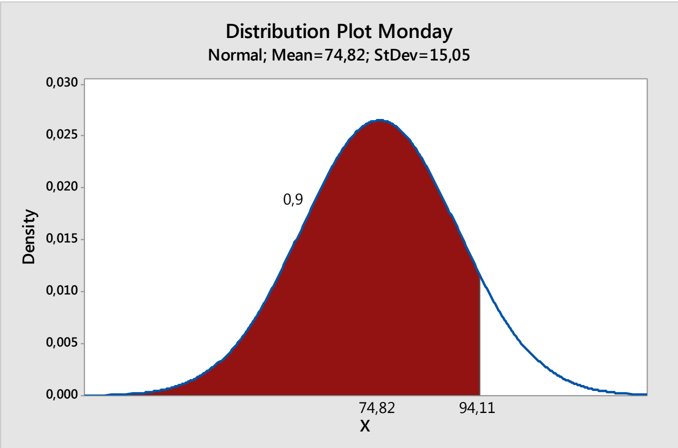


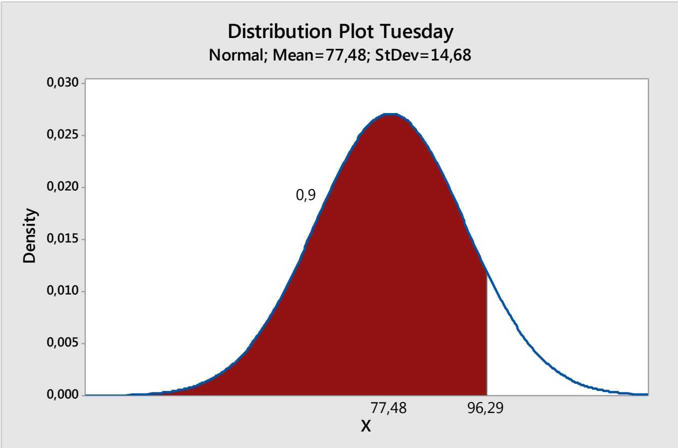
Distribution identification

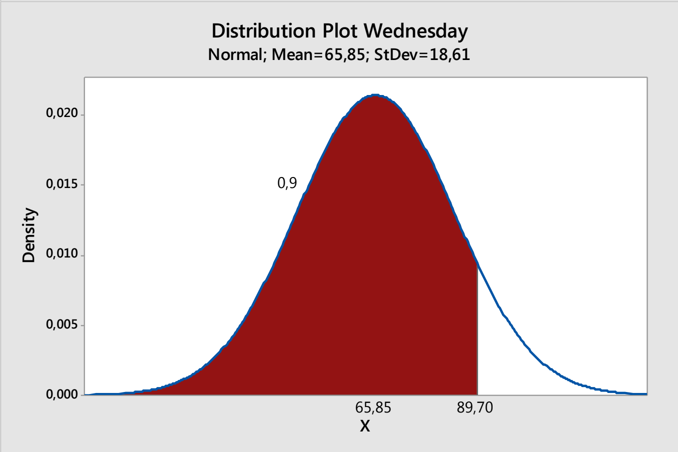


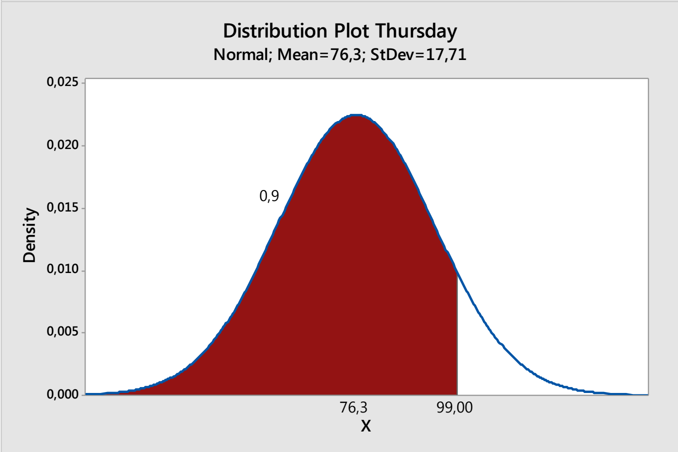


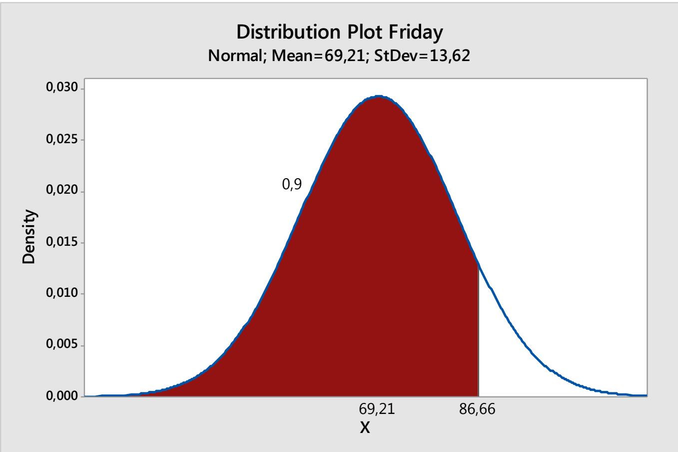
Distribution of required slots per weekday



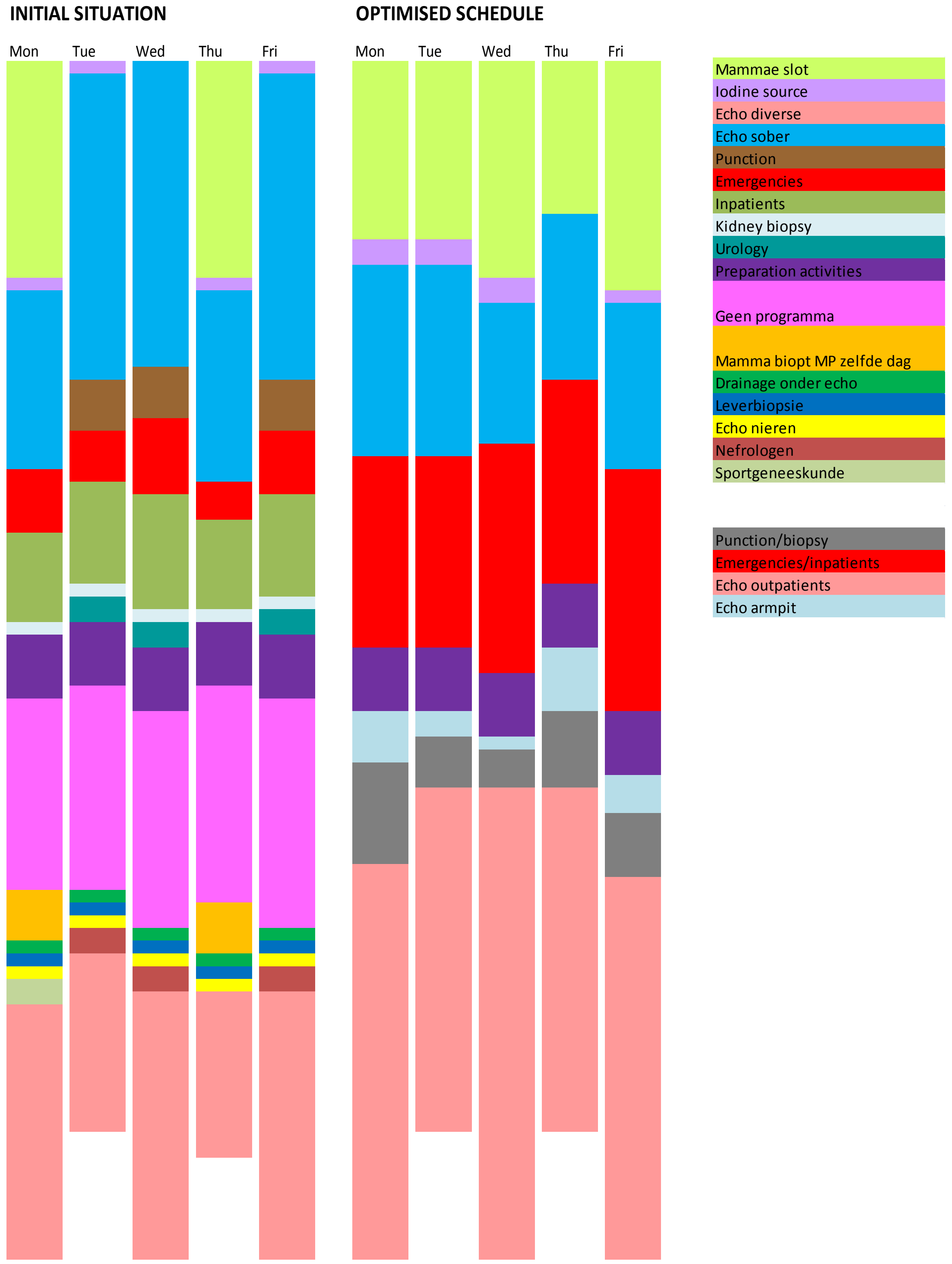




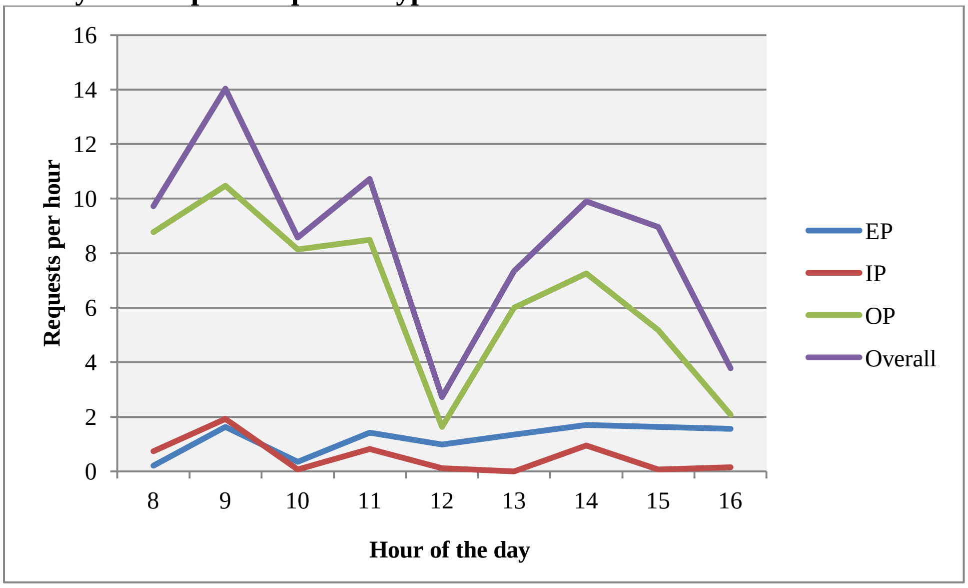




Appendix 11 – Initial block schedule versus new block schedule



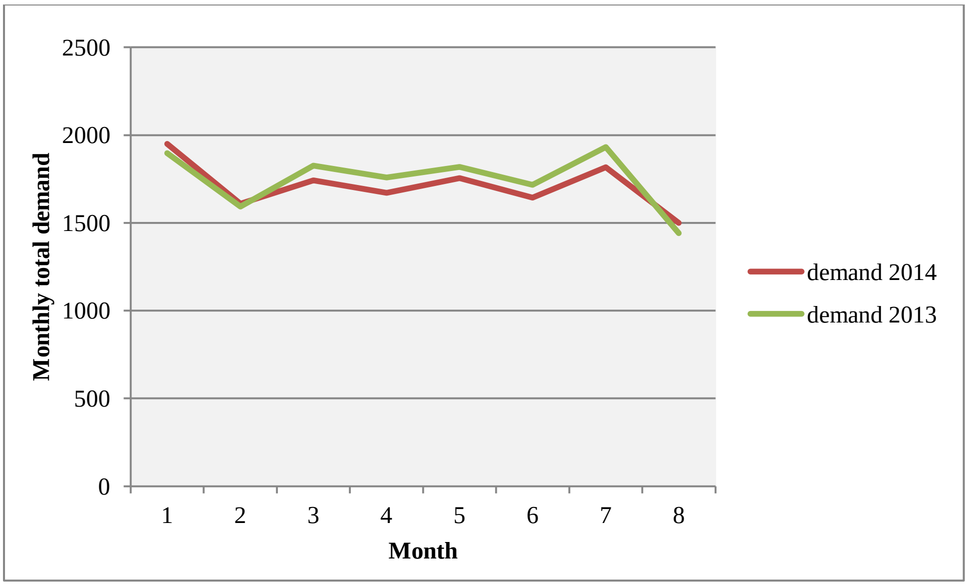
Hourly arrival pattern patient types



Hourly arrival rates patient types

h	$\square_h^{\square\square}$	$\square_h^{\square\square}$	$\square_h^{\square\square}$
8	1.36	0.74	10.48
9	1.14	0.62	8.77
10	1.23	0.67	9.49
11	0.89	0.49	6.91
12	0.28	0.15	2.17
13	0.79	0.43	6.09
14	0.73	0.40	5.67
15	0.96	0.53	7.42
16	0.37	0.20	2.82

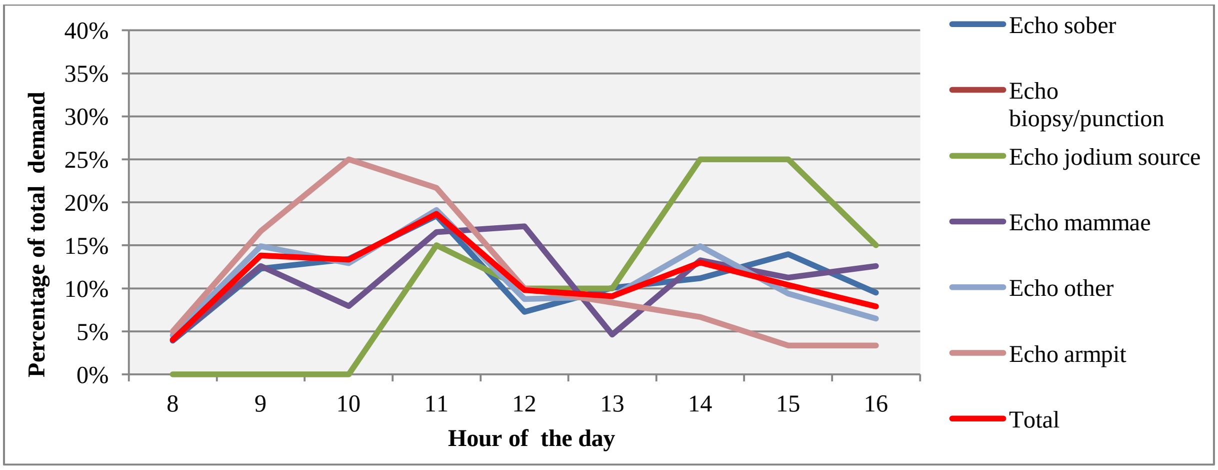
Weekly demand pattern patient types 2013-2014 (before-after new building)



Week factors patient types

Week	E	I	O	Week	E	I	O
1	0.66	0.86	0.84	27	1.13	0.97	1.08
2	0.79	1.08	1.09	28	1.27	0.96	1.06
3	0.86	1.16	1.15	29	1.37	0.96	1.02
4	0.79	1.17	1.12	30	1.10	0.92	0.89
5	0.87	1.05	1.09	31	1.11	0.96	0.84
6	0.74	1.16	1.10	32	0.93	0.91	0.79
7	0.73	1.06	1.15	33	1.06	0.80	0.77
8	0.83	1.04	1.11	34	0.90	0.96	0.80
9	0.70	1.13	1.09	35	1.04	0.91	0.82
10	0.74	1.11	1.07	36	1.04	1.01	0.96
11	0.83	1.20	1.10	37	1.15	1.05	0.95
12	0.76	1.14	1.11	38	1.16	0.99	0.94
13	0.93	1.15	1.10	39	1.24	0.88	0.96
14	0.73	1.07	1.07	40	1.17	0.91	0.97
15	0.80	1.02	1.05	41	1.22	0.86	0.95
16	0.77	1.19	1.15	42	1.02	0.95	1.01
17	0.87	1.10	1.12	43	1.08	1.05	0.97
18	0.82	0.94	0.86	44	1.08	1.03	0.95
19	0.83	1.04	0.90	45	1.37	0.90	0.93
20	0.87	1.04	0.97	46	1.33	0.82	1.03
21	0.96	0.98	1.09	47	1.06	0.98	1.04
22	0.96	0.95	1.04	48	0.97	0.99	0.97
23	1.17	0.93	1.01	49	1.02	0.86	1.00
24	1.26	0.98	1.08	50	1.27	1.00	1.04
25	1.16	0.98	1.03	51	1.33	1.02	1.00
26	1.07	0.99	1.03	52	1.10	0.80	0.73

Hourly pattern examination types



Emperical hourly distribution for examination type

	8	9	10	11	12	13	14	15	16
Echo abdomen	0.22	0.71	0.77	1.06	0.42	0.58	0.64	0.80	0.55
Echo arm	0.34	0.68	1.35	0.00	0.34	1.35	0.68	0.34	0.68
Echo legs	0.20	0.98	0.52	0.98	0.65	0.52	0.98	0.65	0.26
Echo biopsy	0.31	0.63	0.21	0.63	0.52	1.36	1.04	0.63	0.42
Echo upper abdomen	0.27	0.82	0.62	1.16	0.34	0.41	1.09	0.68	0.34
Echo neck	0.72	0.72	0.36	1.08	0.36	0.72	0.72	0.36	0.72
Echo jodium	0.00	0.00	0.00	0.86	0.57	0.57	1.44	1.44	0.86
Echo groin	0.00	0.82	0.62	1.03	0.62	0.62	0.82	0.41	0.82
Echo mammae	0.23	0.72	0.46	0.95	0.99	0.27	0.76	0.65	0.72
Echo kidneys	0.39	0.78	0.97	0.68	0.19	0.39	1.12	0.97	0.24
Echo armpit	0.29	0.96	1.44	1.24	0.57	0.48	0.38	0.19	0.19
Echo punction	0.08	1.10	1.57	1.49	0.31	0.31	0.39	0.31	0.16
Echo shoulder	0.36	0.36	0.00	2.15	0.36	0.00	1.08	1.08	0.36

Emperical daily distribution for examination type

	Monday	Tuesday	Wednesday	Thursday	Friday
Echo abdomen	17.01	14.89	13.11	13.47	11.70
Echo arm	0.68	2.04	1.36	0.34	1.70
Echo legs	10.05	5.21	5.96	7.08	6.33
Echo biopsy	2.41	1.12	1.77	1.45	2.09
Echo upper abdomen	7.15	8.34	5.56	5.96	7.15
Echo neck	0.94	2.34	0.47	1.40	2.34
Echo jodium	2.42	2.02	2.02	0.81	1.21
Echo groin	2.72	0.00	1.13	0.91	1.81
Echo mammae	12.20	11.77	14.82	10.89	17.87
Echo kidneys	11.70	15.60	11.70	5.20	9.10
Echo armpit	4.65	2.46	1.64	4.92	3.01
Echo punction	6.45	2.81	2.81	5.33	3.37
Echo shoulder	0.96	1.28	1.28	1.60	0.00

Appendix 13 – Slot types of the block schedules

Patient type	Description
1	Echo shoulder
2	Echo arm
3	Echo groin
4	Echo neck
5	Echo iodine source positioning
6	Echo biopsy
7	Echo armpit
8	Echo punction
9	Echo upper abdomen
10	Echo leg
11	Echo kidney
12	Echo mammae
13	Echo abdomen

Slot type	Description	Suitable patient type(s)	Available capacity (# slots)				
			Mon	Tue	Wed	Thu	Fri
1	Mammae slot	7, 12	15	0	0	15	0
2	Break	-	13	12	14	10	14
3	Iodine source	5	1	1	0	1	1
4	Echo diverse	1,2,3,4,7,9,10	45	36	44	36	45
5	Biopsies (slots: kidney biopsy + liver biopsy +	6	6	2	2	6	2
6	Sober examinations	9, 13	14	22	22	15	22
7	Punction	8	0	4	4	0	4
8	Emergency	Emergencies of each type	5	4	6	3	5
9	Inpatients	Inpatients of each type	7	8	9	7	8
10	Kidney examinations	11	1	4	4	2	4
11	Urology	11	0	2	2	0	2
12	Preparation activities	-	5	5	5	5	5
13	Back-up slot	-	21	21	22	22	23