University of Twente
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Master Thesis

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MDL department without waiting time?

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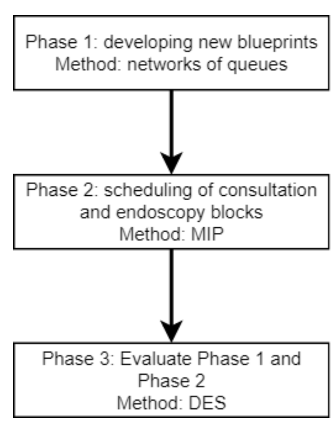
Management Summary

This research aims to reduce the access and waiting time for endoscopies of the stomach, instentines and live (MDL) department of Deventer Hospital such that it is within the norms set by the government.

Problem description
The average access time for intake is increasing and is currently 7 weeks which is 3 weeks above the norm set by the government. The waiting time for endoscopies is 5 weeks. In total, there is sufficient capacity to meet the demand. However, we see differences when looking per patient type. The rising access time is explained by a lack in capacity allocated to this appointment type.

The department uses a three month planning horizon. Every three months, a schedule for one week is determined by the planner. This schedule describes on which day and when (morning or afternoon) all doctors have their consultation or endoscopy block. This schedule is repeated for three months. Throughout the year, consultation and endoscopy blocks are cancelled due to unavailability of doctors. For these cancelled blocks no corrections takes place resulting in high access and waiting time for endoscopies. Furthermore, due to these cancelled blocks, approximately 10% of the National Screening patients (NS-patients) could not be treated.

Approach
To achieve our research objective, we follow a three-phase approach. In Phase 1, we use the networks of queues of Creemers and Lambrecht [2007] to revise the blueprint consultation and endoscopy such that we have sufficient capacity for each type of patient demand. In Phase 2, we use a linear approximation of the mixed integer program (MIP) based on Van de Vrugt [2016] and Hulshof et al. [2011a]. We develop practical guidelines with regard to the weekly number of consultation and endoscopy blocks to schedule by using the MIP. The practical guidelines describes the weekly number of consultation and endoscopy blocks to schedule as function of the weekly number of available doctor days. We develop a new scheduling rule that dynamically distributes the National Screening patients (NS-patients) over the weeks. In Phase 3, we use Discrete Event Simulation (DES) to evaluate the new blueprints from Phase 1, the guidelines from Phase 2 and the new scheduling rules for the NS-patients.



Results
The average number of intakes per consultation blocks increases from 2.7 to 4 as a result of Phase 1. Furthermore, the access time can be reduced from an average of 7 weeks to an average 2.03 weeks. The average waiting time for colonoscopy can be reduced from 5 to 1.67 weeks. The new scheduling rule for the NS-patients prescribes the following.

1. Schedule 0 NS-patients per consultation block if number of consultation blocks < 14
2. Schedule 1 NS-patient per consultation block if number of consultation blocks ≥ 14 and < 20
3. Schedule 2 NS-patients per consultation block if number of consultation blocks ≥ 20

While using this scheduling rule for the NS-patients, on average yearly 1060 NS-patients can be treated and the average intake slot utilization is 96%. Furthermore, the access and waiting time for endoscopies of the regular patient types are all within the norms.

Contribution to practice
This research contributes to practice because the access and waiting time for endoscopies decreases. As a consequence, the quality of care increases because these patients gets treated earlier as compared to the previous situation. Furthermore, it is expected that receptionists receives less complaints from patients who wants to make an appointment. As a result, the quality of labor increases for the receptionists.

Contribution to theory
The MDL department deals with uncertainty in the weekly number of new patients arrivals and uncertainty in the weekly routing of different patient types to different appointment types. Besides that, MDL has to decide how many NS-patients are treated in which week. This research contributes to theory because we provide a framework for departments similar to the MDL department. The framework entails that we want to treat as many NS-patients as possible while the access and waiting time for endoscopies of the regular patient types are within the norms.

Implementation
The implementation of the new scheduling rule of the NS-patients is the recommendation. The reason is that the access and waiting time for endoscopy are still above the norms, despite the new blueprints for consultation from Phase 1 and the practical guidelines from Phase 2. Therefore, we recommend to communicate with the institute that organizes the NS invitations to determine the exact deadline at which the institute has to know how many NS-patients can be treated in which week by MDL. Ideally, MDL announces the weekly number of NS-patients once every 3 months. This is because for every 3 months the available doctor capacity is known and therefore the number of scheduled consultation and endoscopy blocks are known.

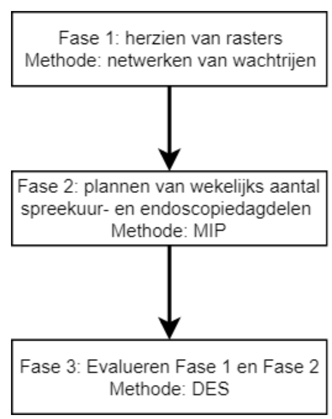
Management Samenvatting

Dit onderzoek heeft als doel reductie van de toegangs- en wachttijd voor endoscopieen van de afdeling maag, darm en leverziekten (MDL). Deze reductie moet ervoor zorgen dat de toegangs- en wachttijden voor endoscopieen weer binnen de treeknorm is.

Probleembeschrijving
De gemiddelde toegangstijd voor intakes is stijgend en is momenteel 7 weken. Dit betekent dat deze 3 weken boven de treeknorm is. De wachttijd voor endoscopieën is gemiddeld 5 weken. In totaal is er voldoende capaciteit om aan de vraag te kunnen voldoen. Echter, per patiënt type bekeken zien we tekorten. De toenemende toegangstijd wordt veroorzaakt doordat te weinig capaciteit is toebedeeld aan intake en nieuwe patiënten.

De afdeling MDL hanteert een planningshorizon van drie maand. Elke drie maand wordt een blauwdruk raster van één week vastgesteld. In deze blauwdruk is te zien welke arts op welke dag wanneer (ochtend/middag) zijn spreekuur- of endoscopiedagdeel heeft. Deze blauwdruk wordt herhaald voor drie maand. Gedurende het jaar worden spreekuur- of endoscopiedagdelen geannuleerd door afwezigheid van artsen. Voor deze geannuleerde dagdelen vindt geen correctie plaats met als gevolg hoge toegangs- en wachttijden voor endoscopieën. Als gevolg van de geannuleerde dagdelen konden ongeveer 10% BVO-patiënten niet geholpen worden.

Probleemaanpak
Wij maken gebruik van een drie-fasen aanpak om onze doelstelling te kunnen behalen. In Fase 1 gebruiken wij de netwerken van wachtrijen benadering van Creemers and Lambrecht [2007] om het poli- en endoscopieraster te herzien. In Fase 2 gebruiken wij een linaire approximatie van een mixed integer program (MIP) gebaseerd op Van de Vrugt [2016] en Hulshof et al. [2011a]. Wij ontwikkelen praktische richtlijnen voor het wekelijkse aantal te plannen spreekuur- en endoscopiedagdelen als functie van het wekelijks aantal beschikbare artsdagen. Daarnaast ontwikkelen wij nieuwe plannningsregels die de BVO-patiënten op een dynamische wijze over de weken verdeeld. In Fase 3, gebruiken wij Discrete Event Simulation (DES) om de nieuwe rasters van Fase 1, de richtlijnen van Fase 2 en de nieuwe planningsregels voor BVO patienten te evalueren.



Resultaten
Het gemiddelde aantal intakeplekken neemt toe met 1.3 intakes per spreekuurdagdeel, als gevolg van Fase 1. Daarnaast kan de toegangstijd gereduceerd worden van gemiddeld 7 weken naar gemiddeld 2.03 weken. De gemiddelde wachttijd voor coloscopie kan gereduceerd worden van 5 weken naar 1.67 weken. De nieuwe planningsregel voor de BVO-patiënten schrijft het volgende voor.

1. Plan 0 BVO-patiënten per spreekuurdagdeel als het aantal spreekuurdagdelen < 14
2. Plan 1 BVO-patiënt per spreekuurdagdeel als het aantal spreekuurdagdelen ≥ 14 en < 20
3. Plan 2 BVO-patiënten per spreekuurdagdeel als het aantal spreekuurdagdelen ≥ 20

Door het gebruik van deze planningsregel kunnen jaarlijks 1060 BVO-patiënten gezien worden. De gemiddelde intake slotbezettingsgraad 96%. Daarnaast is de toegangs- en wachttijd voor endoscopie van de reguliere patiënttypen binnen de treeknorm.

Bijdrage aan de praktijk
Dit onderzoek draagt bij aan de praktijk omdat de toegangs- en wachttijd voor endoscopieën reduceert wordt. De kwaliteit van zorg neemt hierdoor toe omdat patienten eerder geholpen kunnen worden. Daarnaast is de verwachting dat secretaresses minder klachten ontvangen van patiënten wanneer zij afspraken maken. Hierdoor zal de kwaliteit van arbeid toenemen.

Bijdrage aan de wetenschap
De afdeling MDL heeft te maken met onzekerheden in het wekelijks aantal nieuwe patiënten aankomsten en onzekerheden in de routering van verschillende patiënt typen naar verschillende afspraak typen. Daarnaast moet MDL aan het begin van het jaar doorgeven hoeveel BVO-patiënten in welke week geholpen kunnen worden. Dit onderzoek levert een raamwerk voor afdelingen soortgelijk aan MDL. Dit raamwerk houdt in dat we zoveel mogelijk BVO-patiënten willen behandelen, maar daarnaast ook aan de treeknorm voor de reguliere patiënt typen willen voldoen.

Implementatie
De implementatie van de nieuwe planningsregels voor de BVO-patiënten is de aanbeveling. De reden hiervoor is dat de toegangs- en wachttijd voor endoscopieën nog steeds hoger zijn dan de treeknorm, ondanks de invoering van de nieuwe rasters van Fase 1 en de richtlijnen voor het inplannen van dagdelen van Fase 2. Wij raden daarom aan om door middel van communicatie met het BVO-instituut vast te stellen wanneer het instituut moet weten hoeveel BVO-patiënten in welke week behandeld kunnen worden. In de meest ideale situatie geeft MDL dit eens per drie maand door. De reden hiervoor is dat de artsbeschikbaarheid eens per drie maand bekend is en daardoor is ook bekend hoeveel spreekuur- en endoscopiedagdelen worden gedaan (volgens de richtlijnen van Fase 2).

Preface

Staring at my lunch box with the old logo of the University of Twente, I am thinking about how unreal it feels. I received the lunch box when I sent my first idea *(something to do with global warming and a giant refrigerator for polar bears)* for a research to the University when I was a 8-year old boy. However, the University could not do much with it at that time. Now, almost 20 years later, I deliver a result that can actually be implemented.

I would like to thank Gréanne Leeftink for her help and support. She makes sure that my research stayed on track and that I kept the focus during the research. The help regarding the modelling and the tips to keep the overview, I owe it to Erwin Hans. I thank Deventer Ziekenhuis for the opportunity to do this research in the hospital. I thank my girlfriend for her support in periods when the research was not going as planned. Because of her, I kept on going with the research. And last but not least, I would like to Arjan Pannekoek for the good collaboration during the study and his support during the research.

Benjamin Lubach
Enschede, June 2018

1 Introduction

This research aims to reduce the access and waiting time for endoscopies of the stomach, instentines and live (MDL) department of Deventer Hospital such that it is within the norms set by the government.

This chapter provides background information of this research in Section 1.1. The problem description can be found in Section 1.2 from which we make a problem cluster in Section 1.3. The research objective (Section 1.4) and research questions (Section 1.5) are based on the problem description. Section 1.6 describes the data gathering. This chapter concludes with the scope of the research in Section 1.7.

1.1 Background

Since 2009, Deventer Ziekenhuis (DZ) is involved in Lean Six Sigma projects. Lean focuses on process optimization by reducing, for example, waste. Six Sigma aims to reduce variation in the processes. The goal of the combination of the two is to improve the system performances. In addition, Integral Capacity Management (ICM) is part of the strategy of the hospital since 2017. ICM aims to align the demand and capacity resulting in better utilization of the resources, higher service rate for patients and lower access and waiting times. This research is part of Integral Capacity Management.

1.1.1 Deventer Hospital

Deventer Hospital (DZ) is formed by the merger of Sint Geertruiden Ziekenhuis and Sint Jozef Ziekenhuis. Currently 2237 (1690 FTE) employees work at the hospital. Every year approximately 220.000 patients are being treated at DZ. Every specialty is represented by a research group.

1.1.2 MDL department

The MDL department is one of the departments at DZ. MDL patients are referred by the General Practitioner (GP) in case the patient needs an endoscopy. The doctor first sees the patient during a consultation in which the doctor decides what endoscopy type is needed. During the endoscopy, the doctor uses a small viewing device in the intestine or stomach. The goal is to seek for infections and damaged parts of the body of these specific organs.

1.2 Problem description

We define the time between the request for intake and the actual intake date as the access time. The time between the intake and the endoscopy is defined as waiting time for endoscopy, as illustrated in Figure 1. Both are expressed in weeks. After the endoscopy, the patient might become a recurrent patient. This patient is under the supervision of the doctor.

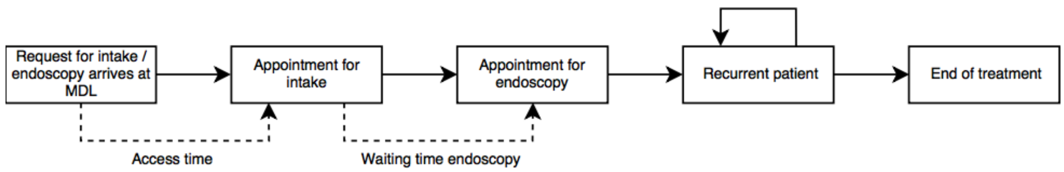


Figure 1: Access time and waiting time for endoscopy

In 2000, the Dutch Care Authority (NZA) introduced the "treeknormen" for care providers. The treeknorm is the maximum acceptable access and waiting time for the patient and depends on the stage in the care path of the patient (see Figure 1). For both the access and waiting time the treeknorm is 4 weeks. The research problem arises from the fact that the norms are not met. The access time is increasing and is currently on average 7 weeks. The waiting time for endoscopies is on average 5 weeks. A problem cluster is made to identify the possible causes of this problem and is explained in Section 1.3.

1.3 Problem cluster

A problem cluster helps with structuring the possible causes of the research problem and demarcation of the problem (see Section 1.7). Interview techniques with the manager and planners of MDL are used to identify the possible causes of the research problem. The complete problem cluster can be found in Appendix A. We identify two possible causes of the problem.

Mismatch in patient demand and available capacity
In 2016, there was a mismatch between patient demand and the availability of resources. Either doctors or nurses were on holidays. This results in a decreased number of endoscopies being performed, since there where no guidelines with regard to the timing of the holidays. As a consequence, the waiting time for the endoscopies increased. The Operational Manager (OM) of MDL already identified this problem and wants to introduce guidelines for the timing of these holidays.

No flexibility in allocation of capacity to cope with variability in patient arrivals
The combination of variability in patient arrivals and no flexibility to cope with this variability causes an increasing access and waiting time for endoscopies. Currently, MDL uses a fixed number of appointment slots per week while it is dealing with variability in patient arrivals. The usage of fixed number of appointment slots possible causes the research problem.

1.4 Research objective

The following research objective is formulated in accordance with the Operating Manager (OM) of MDL:

To reduce the access time and waiting time for the endoscopy for patients at the MDL department

1.5 Research questions

The research objective is translated in the following main research question:

How can the access time and waiting time for endoscopy be reduced?

To answer, we formulated the following four sub-questions:

1. *What is the current situation at the MDL department?*

   (a) Which processes can be identified at MDL?
   (b) What resources are used at MDL?
   (c) How are the resources planned and controlled?
   (d) What are the key performance indicators (KPIs) at MDL?
   (e) How does MDL score on these KPIs?

   The current situation can be found in Chapter 2. We identify the processes and available resources with the use of stakeholder interviews. Furthermore, the key performance indicators (KPIs) are determined with the use of interview techniques with the stakeholders of MDL. The current performance of these KPIs are used as zero-measurement. Lastly, decisions made on how patients are planned are identified.

2. *What models can be used to reduce the access and waiting time at the MDL department?*

   (a) What models in the healthcare sector are known from literature?
   (b) What are organizational restrictions?
   (c) What models are applicable according to the stakeholders of MDL?

   The literature review can be found in Chapter 3. Applicable models to reduce the access and waiting time at a hospital are gathering from literature. We use interview techniques to formulate feasible models to model the MDL department which can be found in Chapter 4.

3. *What feasible interventions score the best with regard to the KPIs?*

   Feasible interventions from the literature are tested and evaluated in Chapter 5 with the use of simulation. The performance of the KPIs are calculated for each intervention. We select the intervention that scores the best with regard to the KPIs.

4. *How can the best scoring interventions be implemented on tactical and operational level*?

   The implementation plan can be found in Chapter 6. The implementation plan describes the changes in practices that has to be made on a tactical and operational level.

1.6 Data gathering

Interview techniques with employees of the MDL department are used to define the problem cluster (see Section 1.3). The data used to quantify the root causes is gathered from the registration system of DZ and by using interview techniques with the manager and the planners of MDL.

It is chosen to use data that covers the period from September 1st 2016 to August 31th 2017. Before June 2016, the nurse of the recovery room and the doctor where doing the intake with the patient together. This intake process is changed. Nowadays, the patient sees the nurse in the first 20 minutes. Directly after that, the patient sees the doctor for another 5 minutes. This change has major consequences for the required capacity of doctors in the intake process. Therefore, data covers the period from September 1st 2016 to August 31th 2017.

1.7 Scope of the research

There is a mismatch between patient demand and availability of resources, as concluded in Section 1.3. The OM already wants to introduce guidelines for the timing of the holidays. Therefore, this problem is of lower priority. In this research, we focus on the flexibility in allocation of capacity to cope with variability in patient arrivals, also stated in Section 1.3.

2 Current Situation

In this chapter, we describe the current situation and performance with regard to the access and waiting time for endoscopies. Section 2.1 describes the process description of MDL. Section 2.2 gives insight in the available resources. Next, Section 2.3 describes the planning and control of the resources. Section 2.4 and Section 2.5 give insight in the influence of the patient arrivals and available resources in the access and waiting time. This chapter ends with a description of the core problem in Section 2.6.

2.1 Process description

A patient enters the MDL department if they need an endoscopy. A patient can enter the department through the following four ways as shown in Figure 2.

1. Referral from the General Practioner (GP)
2. Referral from other department within the hospital
3. Referral via the National Screening (NS-patients)
4. Referral from the Emergency Departments (ED) both for consultations and endoscopies

The patient needs an intake if the patient enters the MDL department for the first time. The intake takes place during a consultation. During the intake, the nurse and the doctor try to define the physical symptoms of the patient. The doctor decides if the patient has to undergo an endoscopy or not. Directly after the intake, the patient makes an appointment for an endoscopy at the receptionist if an endoscopy is needed. For the remainder of this report, we define the date at which the appointment is made as the request date. The date at which the actual appointment takes place is defined as the appointment date.

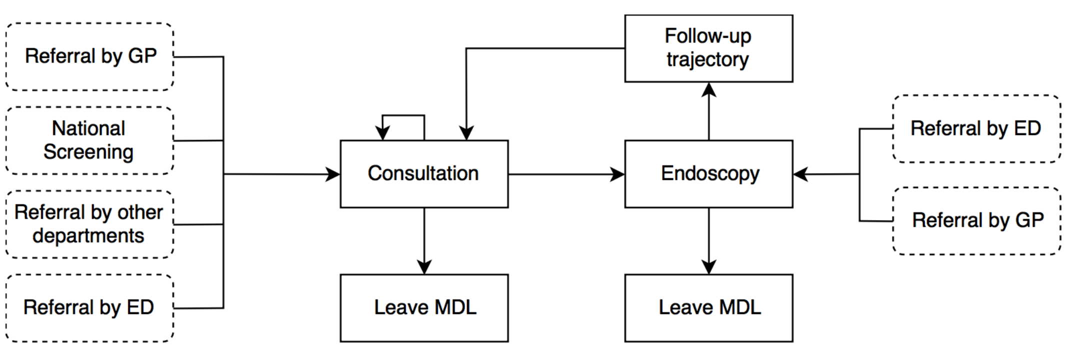


Figure 2: Care pathway in the MDL department

There are many types of endoscopies at MDL. In general, a distinction can be made between endoscopies where the patient needs narcosis and endoscopies where the patient does not need narcosis. The patient goes to the recovery room first when narcosis is needed. After this preparation the patient undergoes the endoscopy. When finished, the patient enters the recovery room again. If narcosis is not needed, the patient enters and leaves the endoscopy room without visiting the recovery room.

The patient might need a follow-up trajectory after the endoscopy or they leave MDL. A patient that needs a follow-up trajectory is called a 'recurrent patient'. The patient might visit the consultation several times depending on the symptoms of the patient. During each of these consultations the doctor decides if the patient needs another consultation, an endoscopy or may leave MDL.

Since 2014, the government introduced a national call for the age group from 55 to 75 year, these are called National Screening patients (NS-patients). The goal is to identify colorectal cancer at an early stage. The government sends invitations to the patients. The invited patients execute a self-test at home. The patient needs an intake if this test is positive. The goal of the government is that the time between sending an invitation and the endoscopy is at most 7 weeks. NS-patients follow the same care path as the regular patients.

Another group of patients are those with clinical admission. These patients are not able to prepare for the endoscopy themselves. Therefore, they are getting prepared at the ward. The ward is not a physical part of the MDL department. However, the outflow of patients from the ward to the recovery room will be taken into account in this research.

2.2 MDL resources

There are six doctors performing either consultations or endoscopies in their regular shifts. Besides their regular shifts, a doctor can be a VK for one week. The VK performs fewer appointments during the working day, since time buffers are used between two subsequent appointment slots to cope with emergency cases and phone calls.

Next to the doctors, there are two types of nurses. The first nurse type assists the doctor in performing the intakes. The first 20 minutes of the intake is performed by the nurse only, followed by 5 minutes performed by the doctor without the nurse. On average two nurses of this type are performing intakes on a daily basis and one nurse performs at most nine intakes per day. This implies that the number of intakes depends on the availability of type one nurses and the doctor. The second nurse type is specialized in performing endoscopies. Each endoscopy has to be attended by two nurses of this type. Therefore, the number of endoscopies depends on the availability of nurses of type two and the doctors.

All the dependencies are shown in Figure 3.

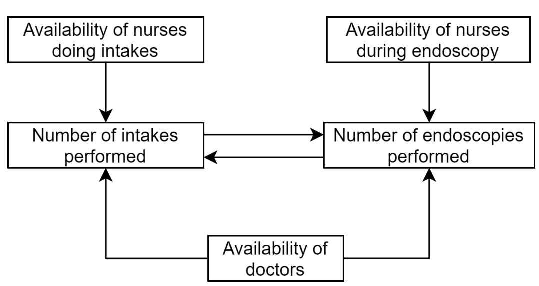


Figure 3: Dependencies within the MDL department

The consultations are performed in one of the five consultation rooms. For the endoscopies, four examination rooms are available. The recovery room contains 14 beds available for patients that need narcosis during the endoscopy.

A working day is divided into two blocks, the morning and afternoon block. The morning block starts at 8:30am to 12:30pm and the afternoon block starts at 13:00pm to 17:00pm. Every doctor has to be scheduled for the complete block. Between these two blocks there is a short break. A block is filled with one consultation block or one endoscopy block and during a consultation (or endoscopy) block, only consultation (or endoscopy) types are performed. Figure 4 shows an example.

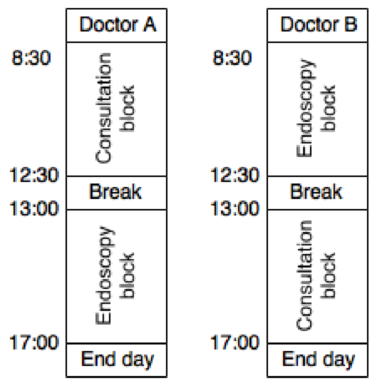


Figure 4: Blocks for doctors

During each consultation or endoscopy block different appointment types are performed by the doctor. Each appointment type has their own appointment duration, shown in Table 1.

Table 1: Different consultation and endoscopy types with their appointment length

Consultation type	**Duration**
New	20 minutes
Intake	5 minutes
Recurrent	10 minutes
Telephone	5 minutes
Emergency	30 minutes
NS-intake	5 minutes

Endoscopy types	**Duration**
Colonoscopy (also NS)	45 minutes
Gastroscopy	15 minutes
Sigmoscopy	15 minutes
ERCP	60 minutes
Emergency	45 minutes
Endo-echo	45 minutes

Various consultation or endoscopy type appointments are allocated to different time stamps in a consultation or endoscopy block. We explain the creation of these blocks in Section 2.3.

2.3 Planning and control of resources

In this section, we describe the way MDL plans and controls the resources. It is divided into two parts. Subsection 2.3.1 explains the planning of the resources at MDL and Subsection 2.3.2 explains how the patients are planned.

2.3.1 Tactical planning

MDL uses a three month planning horizon. Every three months, a schedule for one week is determined by the planner. This schedule describes on which day and when (morning or afternoon) all doctors have their consultation or endoscopy block. Also, the specific consultation or endoscopy types with their starting time are scheduled in the blocks, as shown in Table 2.

Table 2: Consultation and endoscopy schedule

Monday morning				
Consultation block			Endoscopy block	
Doctor 1			Doctor 2	
8:30	New		8:30	Gastroscopy
9:00	Recurrent		8:45	Gastroscopy
9:10	Telephone		9:00	NS-Colonoscopy
9:15	NS-intake		9:45	Sigmoscopy
9:20	Emergency		10:00	Colonoscopy
9:50	Intake		10:45	Emergency
..	..		..	..

We define, for example, the consultation type 'Recurrent' at 9:00 as a 'Recurrent'-slot. A slot is reserved capacity on a specific day and time for a specific consultation or endoscopy type.

The weekly schedule is repeated for three months. Scheduled blocks are cancelled if doctors are unavailable (e.g, holidays or conferences). Once a block is cancelled, no corrections for this block takes place later in time. The result is a blueprint for the coming three months. In this blueprint, it is known which doctor performs a specific consultation or endoscopy type on which day and time. In general, every three month may be considered as the same, since changing appointment slot types does not occur.

The current practice of setting the blueprint is that the total number of intakes, emergencies and endoscopies is evenly distributed over the doctors. But, the total number of recurrent patient slots may deviate among the doctors. Some doctors prefer seeing recurrent patients more frequently than other doctors. The doctor decides the recurrent rate of a patient, i.e. the doctor tells the patient to call MDL for a new appointment after a predefined number of weeks. However, guidelines are introduced to control the recurrent rate of a patient. The guideline entails that the patient calls for a new appointment only if it is needed.

Besides the regular patient types, planners at MDL have to decide how many and when NS-patients are treated during the year. These decisions is made before the beginning of a new year. An intake slot is reserved for each NS-patient and each NS-patient has to undergo a colonoscopy within one week after their intake (norm set by the government). The total number of NS-intakes and NS-colonoscopy is based on the total number of doctors and is evenly distributed over the doctors and over all weeks within a year. For example, for 2016 decided is that 1100 NS-patients could be treated in total. This means that every doctor does on average 3.5 (1100/6 doctors/52 weeks) intakes and colonoscopies per week. Important to note is that every NS-intake results in a colonoscopy. In reality, 10% of the total number of NS-patients could not be treated because consultation- or endoscopy blocks are cancelled.

2.3.2 Operational planning

A patient can be scheduled by several triggers. Either by referral (from GP, by other departments or by ED), by decision of the doctor after a consultation or because a patient has been put on the waiting list, see Figure 5.

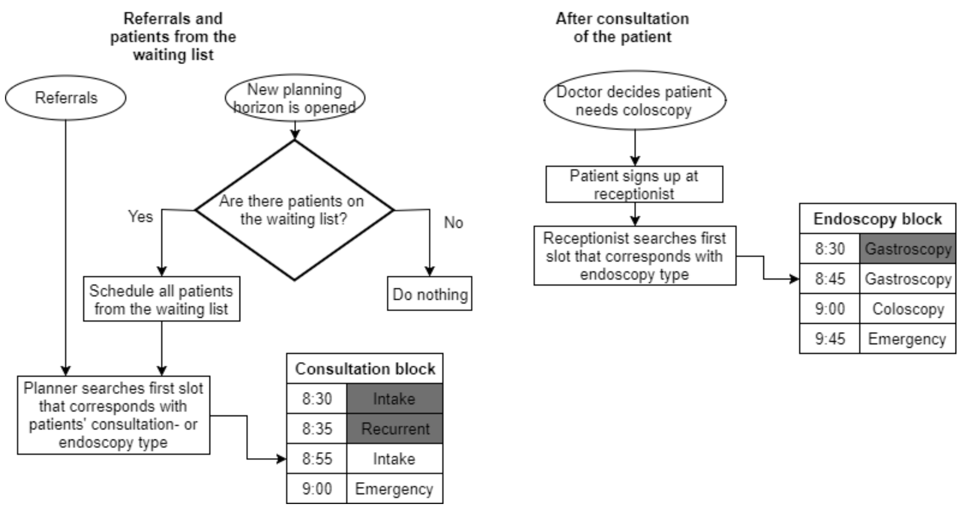


Figure 5: Triggers in the patient planning process

The waiting list contains patients who already had a consultation or endoscopy but need another consultation or endoscopy. These can be recurrent patients who need a consultation after a predefined number of weeks or patients who needs a new intake after one year. These patients are not planned because all slots of the patient type in the current planning horizon are full or the new schedule has not been defined yet. Patients from the waiting list are non-urgent patient who do not have to be scheduled in a certain week.

As time goes by, patients are scheduled in the slots of their corresponding patient type ('New', 'Recurrent' or 'Gastroscopy', 'Colonoscopy') in a First-Come-First-Serve (FCFS) manner. Emergency cases are handled manually, and planned in the corresponding slots. If necessary, the schedulers reschedule other appointments in order to plan the emergency cases within one week. Patients from the waiting list are scheduled FCFS as soon as the new planning horizon is open.

In practice, every new planning horizon is opened approximately halfway the current planning horizon. This means that the period in which patients can be scheduled varies between 1.5 months and 4.5 months, as illustrated in Figure 6.

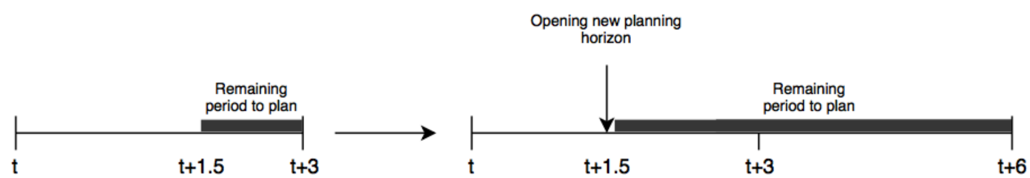


Figure 6: Length of the planning horizon

We analyze the total number of reserved and required consultation and endoscopy type slots in Subsection 2.3.3. The goal is to determine if the number of slots reserved is enough to meet the specific consultation or endoscopy type demand.

2.3.3 Required versus available capacity

From literature it is known that there are several causes for the existence of access and waiting times [Silvester, 2004]. Insufficient capacity to meet the total demand is one of them. We need to get insight in the total available capacity and total demand to see if this issue is the case at MDL.

The total demand in hours for a specific appointment slot type is based on the total number of requests for a consultation or endoscopy type. This demand is defined in Section 2.3.2. The total number of available consultation and endoscopy type slots is based on the planning grid from Section 2.3.1. We define the total number of available slots as available slots after taking into account holidays of doctors and cancelled blocks. We express the capacity both in the total number of appointment slots and in the total number of hours, shown in Table 3.

Table 3: Required versus needed capacity

Block type	**Slots offered**	**Hours**	**Demand**	**Hours**
Consultation	10327	1914	10407	1988
Endoscopy	7187	4115	6043	3334
Total	17514	6029	16450	5323

We conclude that the total demand expressed in hours is smaller than the total available hours. This means that on average there is sufficient capacity to meet the demand. However, we see deficits when looking per appointment type. For example, the total demand for intakes is higher than the total number of hours available for this appointment type during the period from September 2016 to August 2017. This might explain the increasing access time as stated in Section 1.2, since there is a lack of capacity offered for this patient type.

2.4 Consultations

Currently, most of the patients at consultations are recurrent patients, as shown in Table 4. As mentioned in Subsection 2.3.2, MDL uses a waiting list for non-urgent patients. This might lead to increasing access and waiting time, since less appointment slots are available for regular patients. Therefore, the last column of Table 4 gives insight in what percentage of the total scheduled consultations was on the waiting list. For example, 18.7% of the total recurrent patients were placed on the waiting list before being scheduled.

Table 4: Number of consultation type appointments
(Hix, n=12486, Sep 2016 - Aug 2017)

Consultation type	**Total**	**Relative**	**From waiting list**
Recurrent patients	5277	42.3%	18.7%
Regular intakes	3441	27.6%	4.5%
Telephone	2188	17.5%	6.6%
NS-intakes	773	6.2%	0%
Emergencies	709	5.7%	0%
Administration	98	0.8%	0%

On average 27.6% of the total number of appointments is a regular intake. We take the intakes for NS-patients separately, since the access time norm for NS-patients is lower. For example, the time between the requests for a NS-intake and the NS-colonoscopy may not be longer than one week.

The number of requests for intake directly influences the access time. Therefore, in the next section the arrival of new intake requests is mapped.

2.4.1 Arrival of intake requests

On average 62.8 new intake requests arrive at MDL per week with a standard deviation of 14 patients. Peaks (e.g. 96 requests) and dips (e.g. 38 requests) occur throughout the year.

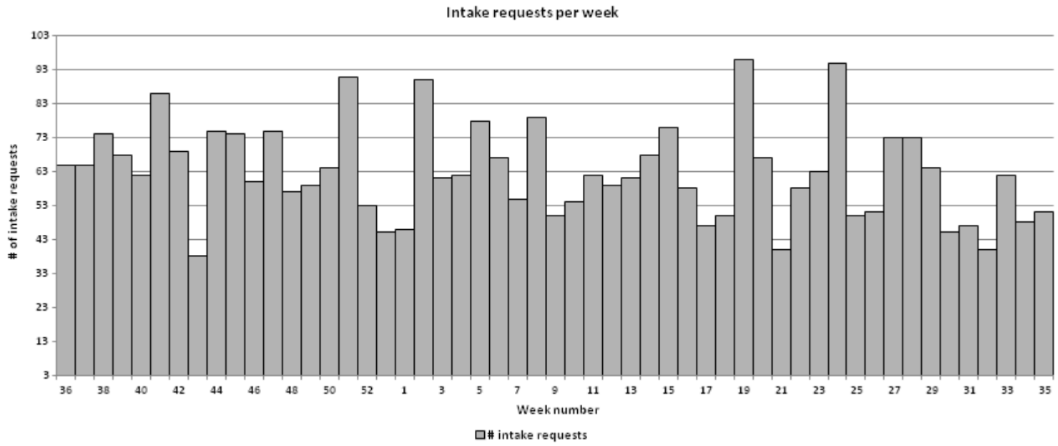


Figure 7: Intake requests per week
(Hix, n=2624, Sep 2016 - Aug 2017)

The peaks in the arrival of intake requests might be caused by the holidays of the doctors (e.g. Spring break or May holidays), as a result less consultations and endoscopies are performed in those weeks. Therefore, less patients are treated at MDL. Consequently, planners and receptionists have more time left to schedule patients which were placed on the waiting list. Dips in the number of arrival of intake requests are caused by the holidays of the GPs, resulting in less referrals of new patients in these holiday weeks. We conclude that the number of requests for intake fluctuates during the year.

The access time, in combination with the number of requests for intake, is mapped in the next section.

2.4.2 Access time

DZ calculates the access time for intake per week. They use the method of the 'third free spot', to avoid coincidentally very low access times due to cancellations of patients. However, this method seems to be inaccurate because only one measurement (at a random point in time) is done per week. Mapping these measurements with the intake arrivals yielded some unexplainable peaks in the access time. Therefore, we use the realized access time. This is defined as the average time between the request date and the actual appointment date of all intake requests in a certain week. Both for the realized access time and the third free spot, the access time norm of four weeks is never achieved. Table 5 shows the statistics for both the realized access time and the third free spot measurement. In Table 5, we define $P(X > 4)$ as the probability of exceeding an access time of four weeks.

Table 5: Access time statistics in weeks

	$\bar{x}$	σ	Min	Max	$P(X > 4)$
Realized access time	10.48	1.58	6.6	13.8	1.00
Third free spot	7.02	1.37	4.14	10.43	0.99

Figure 8 shows the access time and the arrival of intake requests.

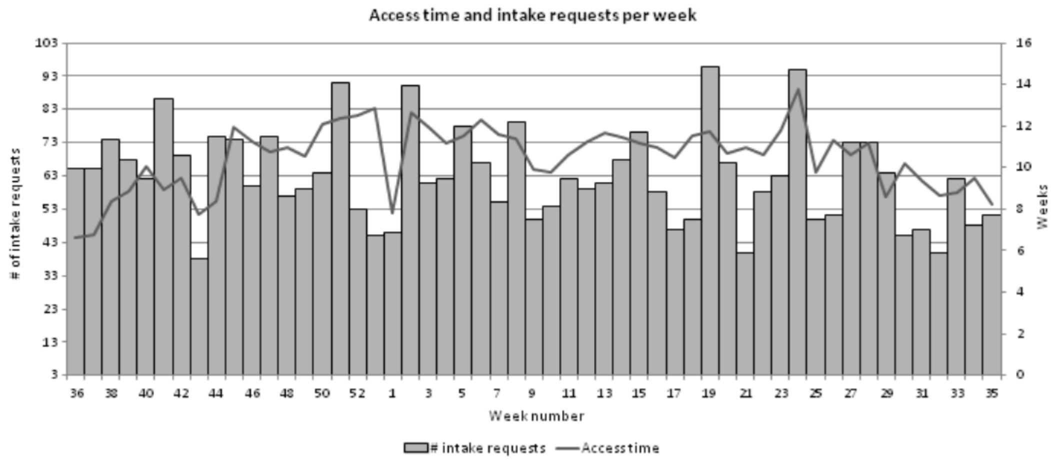


Figure 8: Access time and intake requests per week
(Hix, n=2624, Sep 2016 - Aug 2017)

At week 2 and 24 peaks occur both in access time and new requests for intake. However, in week 51, 52 and 53 the access time keeps rising, while the number of new intake requests drops. This is caused by cancelling approximately 42% of the consultation blocks during the holidays of the doctors. Therefore, less appointment slots for intakes are available which leads to increasing access times.

Peaks in arrivals do not necessarily mean that the access time is high, see week 19 and 24. Both weeks have an arrival of 93 intake requests, but the access time for week 19 is 11.7 weeks and for week 24 is 13.7 weeks. This is caused by an increase in the available capacity in week 19, resulting in an increase of the number of consultation blocks.

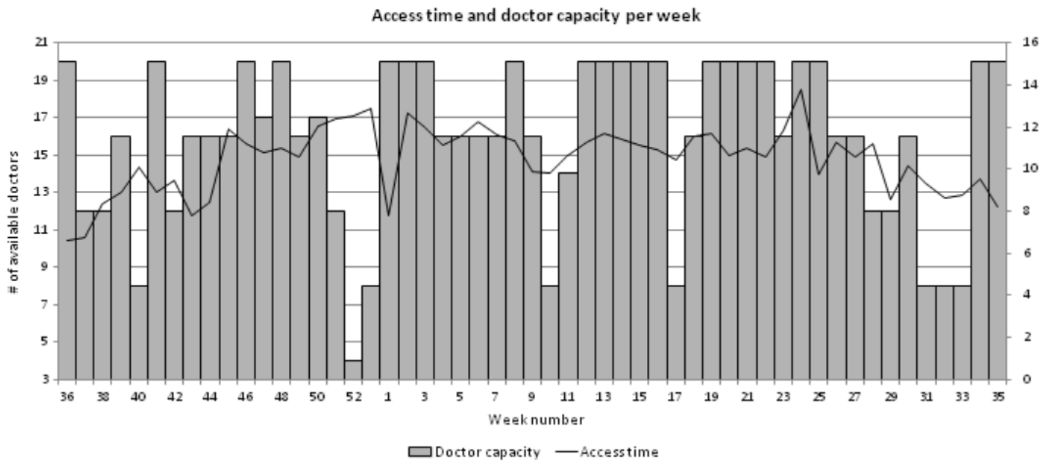


Figure 9: Access time and available doctor capacity per week
(Hix, n=2624, Sep 2016 - Aug 2017)

Figure 9 shows the relationship between the access time and the available doctor capacity. We define the available doctor capacity as the total number of available doctor days per week. From week 28 to week 33, we observe a reduction in the available doctor capacity. The reduction in these weeks does not result in an increasing access time, because the number of requests for intakes decreases as well due to the holidays in these weeks, shown in Figure 8.

On the other hand, we observe that the access time increases in week 50. This is caused by a combination of an increase in the number of intake requests and a reduction in the available doctor capacity.

We conclude that the variability in number of intake requests influences the access time. Furthermore, the number of specific consultation type appointments (e.g. intakes) per consultation block is fixed throughout the year. This means that cancelling consultation blocks leads to a decrease in the available capacity for intakes, since no corrections for cancelled blocks takes place.

2.4.3 Conclusion

The total number of consultation blocks per week depends on the availability of the doctors. Thus, the number of cancelled consultation blocks increases when the number of unavailable doctors increases. The number of intakes decreases when the number of consultation blocks decreases, since MDL uses a fixed number of consultation type appointments per consultation block per week throughout the year. Therefore, the combination of variability in arrivals of new intakes and periods in which less consultation blocks are performed leads to an increasing access time.

We analyze the endoscopy type appointment in the next section.

2.5 Endoscopies

The biggest fraction of endoscopies performed at MDL is the colonoscopy, shown in Table 6.

Table 6: Number of endoscopies scheduled
(Hix, n=7019, Sep 2016 - Aug 2017)

Endoscopy types	**Total**	**Relative**
Colonoscopy	2779	39.6%
Gastroscopy without narcosis	1443	20.6%
NS colonoscopy	738	10.5%
Sigmoscopy	529	7.5%
Gastroscopy with narcosis	440	6.3%
Emergency	264	3.8%
Sedation	222	3.2%
Sonde	219	3.1%
Endo-echo	188	2.7%
ERCP	146	2.1%
Dilatation	51	0.7%
Total	7019	100%

For the remainder of this chapter, we focus on the analysis of the colonoscopy. Reason being is that the colonoscopy is the most frequently occurring endoscopy type. In addition, taking into account all endoscopy types in this chapter does not improve the overview. Therefore, in the next section, only the requests for colonoscopies (no NS-colonoscopies) are mapped.

2.5.1 Waiting time for colonoscopy

The norm for the waiting time for endoscopies is set on four weeks. Table 7 shows waiting time statistics for the colonoscopy.

Table 7: Waiting time for colonoscopy statistics (in weeks)

	$\bar{x}$	σ	Min	Max	$P(X > 4)$
Realized waiting time	4.73	1.07	2.87	7.85	0.95
Third free spot	4.95	1.48	1.57	7.43	0.96

The probability of exceeding four weeks, $P(X > 4)$, is in both the realized waiting time and third free spot respectively 0.95 and 0.96. There are two causes for the waiting time of the colonoscopy. This is either caused by the number of intake appointments in a certain week or by cancelling endoscopy blocks. We explain both causes next.

Number of intakes

From Subsection 2.4.2, we know that the number of requests influences the access time. The same goes for the waiting time for the colonoscopies, shown in Figure 10.

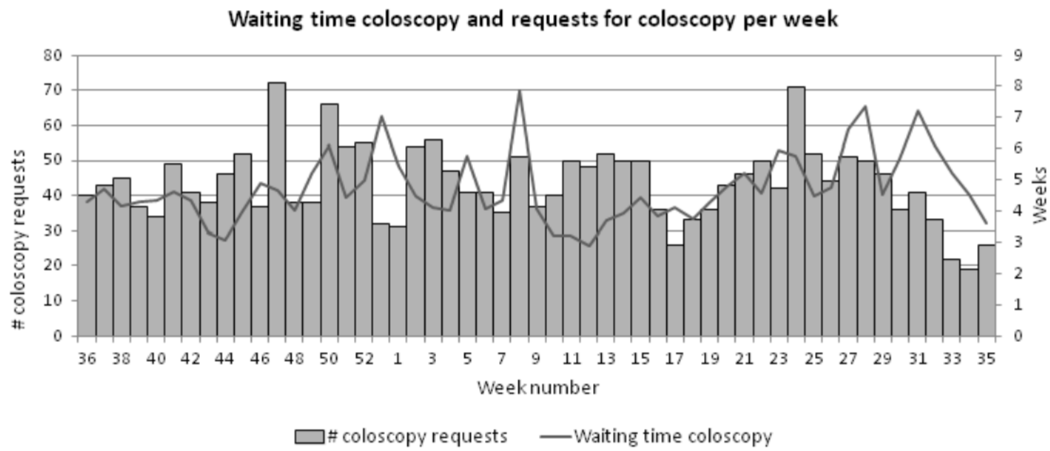


Figure 10: Requests for colonoscopy and waiting time for colonoscopy (Hix, n=2279, Sep 2016 - Aug 2017)

Recall that the patient might make an appointment for the colonoscopy directly after the intake. This implies that the request date for a colonoscopy is the date at which the appointment for the colonoscopy is made. Thus, the actual appointment date of the intake and the request date for the colonoscopy are the same. Figure 11 shows this relationship between the two dates.

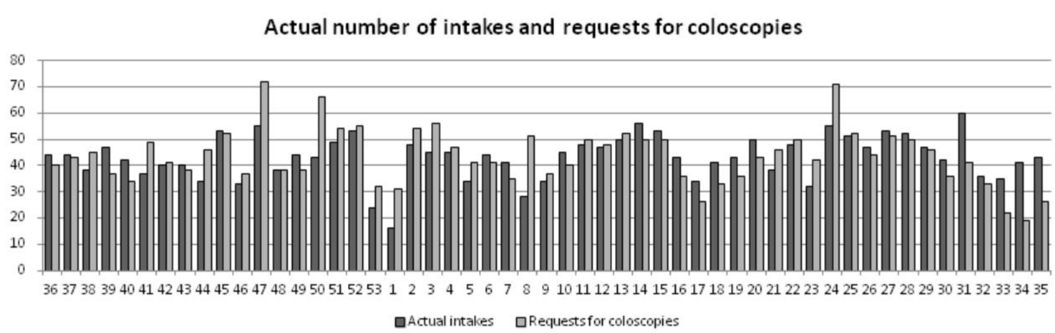


Figure 11: Actual number of intakes and requests for colonoscopies (Hix, n=2279, Sep 2016 - Aug 2017)

On average 72% of the intakes results in a colonoscopy. This means that the peaks in the number of requests for colonoscopies in week 47, 50 and 24 can be linked by the peaks in the number of actual intake appointments. Therefore, the variability in colonoscopy arrivals, and thus the waiting time for colonoscopies, is caused by the planning of actual intakes.

Another cause of the increasing waiting time for colonoscopies is the cancellation of endoscopy blocks. The cancellation of endoscopy blocks leads to less capacity for colonoscopies and therefore increasing waiting times. From Figure 10, we see that the number of requests for colonoscopies in week 8 and 45 is both approximately 50. But, the waiting time for colonoscopies is 7.9 weeks in week 8 and in week 45 it is 4 weeks. The difference is caused by cancelling 10% of the endoscopy blocks in subsequent weeks of week 8.

We conclude that there are two causes for the waiting time for colonoscopies. The first cause is the number of requests of colonoscopies induced by the number of actual intake appointments. The second cause is the cancellation of endoscopy blocks leading to less capacity for colonoscopies and therefore increasing waiting times.

2.6 Core problem description

The average access time for intake is increasing and is currently 7 weeks which is 3 weeks above the norm set by the government. In total, there is sufficient capacity to meet the demand. However, we see differences when looking per patient type. The rising access time is explained by a lack in capacity allocated to this appointment type. Furthermore, the norm for the access time is never achieved in the period from September 2016 to August 2017 which means that the access time was always above 4 weeks. The average waiting time for endoscopies is 5 weeks and the norm is not achieved in 82.85% of the weeks.

MDL uses a fixed number of consultation and endoscopy type appointments per consultation- and endoscopy block throughout the year. Consultation and endoscopy blocks are cancelled during the year due to unavailability of doctors. Therefore, the combination of variability in new patients arrivals, the use of fixed number of consultation type appointments and the cancellation of consultation blocks causes fluctuations in the access times. Fluctuating waiting times for endoscopies are caused by the combination of taking in new patients at a certain time and subsequent periods in which the total number of endoscopy blocks is decreasing.

The literature review focuses on a dynamic allocation of capacity in an setting in which patients needs multiple appointments in their care pathway. Directions for the dynamic allocation are: (1) optimize both the number of consultation and endoscopy blocks per week and the allocation of slots within these blocks simultaneously. Or, (2) to cope with cancelled blocks, the total number of consultation and endoscopy blocks is yet to be determined per week. Both directions have to take into account variability in patient arrivals and variability in available capacity, with as a goal to minimize the access time and waiting time for endoscopies. The literature review is performed in Chapter 3.

3 Literature review

In this chapter, we outline the current available literature with regard to the research problem. The research is positioned in a framework in Section 3.1, we dive into the tactical level of the framework in Section 3.2. Section 3.3 describes relevant models that can used to tackle the research problem. This chapter ends with a conclusion in Section 3.4.

3.1 Positioning of the research

The framework for health care and control of Hans et al. [2011] is used to position the research problem. The strategic level involves long term decision making, such as dimensioning of resource capacity (staffing or medical instruments) [Hulshof et al., 2011b]. The decisions at strategic level demarcate the level of freedom at tactical level. The tactical level entails the organization of the health care delivery process on the medium term planning horizon, in which questions such as: 'what', 'where', 'how', 'when' and 'who' are important for the planning of this process. The operational level involves decisions made on a short-term planning horizon and entails the execution of the health care delivery process, such as patient-to-appointment assignments [Hulshof et al., 2011b]. The hierarchical level of this research concerns the tactical level, as described in Section 1.7.

MDL is a so-called ambulatory (outpatient) care service, according to the taxonomy of Hulshof et al. [2011b]. In the next section, we describe relevant topics with regard to the tactical planning of outpatient clinics based on both Hans et al. [2011] and Hulshof et al. [2011b].

3.2 Tactical planning

Much literature focuses on the tactical planning level within the health care sector. To structure the available literature, it is chosen to use topics as defined by Hulshof et al. [2011b] and Hans et al. [2011].

Capacity Allocation
In capacity allocation, a date and time are assigned to blocks. The available resource capacity is subdivided over different patient groups. If seasonality in patient demand exists, a dynamic subdivision based on length of waiting lists and predictions on future demand performs better than a static approach, shown by Vermeulen [2009]. Block schedules can be repeated periodically [Hulshof et al., 2011b]. On the other hand, there is open (empty block) scheduling. Open scheduling is more flexible, since no subdivision to different patient groups takes place [Hulshof et al., 2011b]. A drawback is that it might lead to imbalances in doctors' schedules, some doctors might see more specific type of patients due to open spots in the schedule that can be filled [Guerriero and Guido, 2011]. Block scheduling can overcome this drawback [Hulshof et al., 2011b], since the total workload can be equally divided among the doctors. Disadvantage is that it is most of time based on historical data [Erdogan and Denton, 2011]. In practice, many hospitals use a combination of block scheduling and open scheduling [Erdogan and Denton, 2011].

Temporary capacity change
The access time of patients may be improved by increasing the resource capacity, to cope with patient demand fluctuations [Hulshof et al., 2011b]. For this research, the temporary change in available capacity is considered as an intervention, as stated in research question 2 (Section 1.5).

Staff shift scheduling
Staff shift scheduling deals with selecting what shifts and how many employees should be assigned to each shift to meet the patient demand. The objective of staff shift scheduling is to minimize the number of staff hours to cover staff levels [Hulshof et al., 2011b]. This objective is not in line with the research objective (recall: to minimize access time and waiting time for endoscopies). Therefore, no further research is performed with regard to staff shift scheduling.

Patient admission control
Patient admission control entails rules on which patient type to admit to the hospitals' department. The type of resources that is required for the patient type is important to decide if a patient may be scheduled or not [Adan and Vissers, 2002]. Objectives are to control the access time for different patient groups [Hulshof et al., 2011a] and controlling the idle time of resources. Factors taking into account are, for example, available capacity, future demand and length of the waiting list of the patient type. However, most of the literature about patient admission planning are focused on inpatient clinics, since prioritizing patients significantly affect patient' length of stay [Van de Vrugt, 2016].

We conclude that relevant topics for this research are capacity allocation, temporary capacity change and patient admission control. Per topic, Hulshof et al. [2011b] states OR techniques that can be applied. Therefore, these OR techniques are reviewed in the next section.

3.3 Models for the health care sector

Van de Vrugt [2016] states that using OR techniques in the health care sector has great potential to aid in decision making, since a lot of different interventions can be (safely) evaluated. Hulshof et al. [2011b] state that mathematical programming and computer simulation are applicable for all relevant topics from Section 3.2. In addition, Joustra et al. [2010] applied mathematical programming to minimize the access time for the endoscopy department of the AMC.

We observe that a large part of the literature focuses on reducing the access time, in which the patient needs only one appointment [Van de Vrugt, 2016] or only needs one resource [Marynissen and Demeulemeester, 2016]. They optimize the access time per patient group but are not taking into account the increasing waiting time for a procedure downstream in the process [Hulshof et al., 2011a]. Patients might need multiple appointments involving multiple resource types [Van de Vrugt, 2016]. At MDL, patients frequently need multiple appointments. Therefore, in the remainder of this chapter the focus lies on OR techniques that are applicable in multiple appointment and multiple resource scheduling.

3.3.1 Mathematical Programming

Mathematical programming is a term related to several different types of models that optimizes (minimize or maximize) a goal function, subjected to a set of constraints [Van de Vrugt, 2016]. This method has been proven as a viable approach for patient and resource scheduling [Pérez et al., 2009]. Different methods are applied in hospital environments: Markov Decision Process [Sauré et al., 2012], Dynamic Programming [Hulshof et al., 2016], Queueing Theory [Creemers and Lambrecht, 2007] and (I)LP [Hulshof et al., 2011a], [Bikker et al., 2015].

Hulshof et al. [2011a] use mixed integer linear programming (MIP) that allocates resource capacity among consecutive stages of different care pathways. The model is applicable in situations in which a patient follows a finite number of stages in their care pathway. Hulshof et al. [2011a] models each stage as a queue, and different care pathways may share the same queue. Different queues are connected with each other via a routing matrix. For the routing, a multinomial distribution can be used as Tsai [2007] did. The model of Hulshof et al. [2011a] determines the total number of a patient type to serve in each time unit by minimizing the number of a patient type in each queue.

Van de Vrugt [2016] uses a stochastic mixed integer programming (SMIP). The model is able to cope with stochastic arrivals by introducing a discrete time Queueing Model. The aim of the Queueing Model is to determine how many specific appointment slots have to be reserved per week such that the weekly expected access time reaches a certain target. The MIP provides the number of blocks per week, and the number of appointment slots in each block type for each patient type by using the Queueing Model as input. The study of Van de Vrugt [2016] only focuses on the access time of the outpatient clinic of JBH. Extensions can be made with regard to the Queueing Model by considering the hospital department as a networks of queues [Boucherie and Van Dijk, 2010] and [Creemers and Lambrecht, 2007].

Bikker et al. [2015] developed an integer linear program (ILP) that generates a weekly cyclic doctors' scheme (block schedule) for the radiotherapy, in which the number of consultation- and scan contouring slots are predetermined. The model uses two objectives. The first objective is to find the optimal moments in which the consultations and treatments has to take place. A second objective minimizes the difference between the total number of reserved time slots per day and number of demand per day for a time slot. In the model, the care pathways and the guidelines for the patient routing are medically prescribed. Also, the number of consultation and contouring time slots to be reserved are defined before the patient start the treatment.

Hulshof et al. [2011a] and Bikker et al. [2015] use a finite number of stages visited by the patient in their care pathway. Furthermore, in the model of Bikker et al. [2015], the patient routing and number of slots needed by a patient are known in advance (conform medically prescription). At MDL, a patient might become a recurrent patient. The number of stages in a care pathway depends on the symptoms of the patient, and is therefore subjected to randomness. For example, the number of future recurrences of a recurrent patient is not known in advance. This implies that the models of Hulshof et al. [2011a] and Bikker et al. [2015] are not directly applicable in this research, since both authors use finite care pathways. However, Creemers and Lambrecht [2007] invokes Queueing Models to deal with recurrent patients by using a routing matrix. In their model each patient is allowed to join the next queue (surgery), enter the same queue (consultation) or may leave the system [Creemers and Lambrecht, 2007] after each visit. The model is developed to obtain (approximate) performance measures, and is not able to optimize over a set of variables.

Another study of Hulshof et al. [2016] uses Dynamic Programming (DP) to develop a tactical planning by modelling the healthcare as a DP-problem. However, the problem can become intractable due to the curse of dimensionality [Powell, 2007]. Sauré et al. [2012] use Markov Decision Process (MDP) to identify good policies for allocating available capacity to incoming demand. However, like DP, MDP suffers from the curse of dimensionality. Therefore, MDP and DP is not used in this research.

3.3.2 Evaluation methods

From practice, it is well-known that the use of quantitative models contributes to the decision making in the manufacturing sector. In a literature review, Kuljis et al. [2007] states that many models are also potentially applicable for the health care sector. Queueing theory and simulation are two models that can be used to model processes [Law et al., 2007]. But, according to Zonderland et al. [2009], simulation is mostly used to model hospitals' department. Especially discrete-event simulation (DES) is widely used to model health care systems [Borgman, 2017]. Joustra et al. [2010] uses DES to model the complex environment of the endoscopic department of AMC. It is used to evaluate the performances of their improved weekly master schedule.

DES aims to provide statistically estimates of the true behaviour of variables that characterizes a stochastic system [Law et al., 2007]. Input for DES are, for example, distributions of the patient arrivals and service times.

3.4 Conclusion of the literature review

MDL is an ambulatory (outpatient) care service. Relevant research topics about tactical planning for MDL are capacity allocation, temporary capacity change and patient admission control. Mathematical programming is often used to solve planning issue at the tactical level. However, these mathematical programs are using finite number of stages for the care pathway of the patient. Also, the mathematical programs are not able to deal with stochastic arrivals, except for the model of Van de Vrugt [2016]. Therefore, the model of Van de Vrugt [2016] is used to express the access and waiting time as function of the number of scheduled appointment slots. We use the work of Hulshof et al. [2011a] and Bikker et al. [2015] to determine the weekly number of block types to schedule.

The design of the solution approach can be found in Chapter 4.

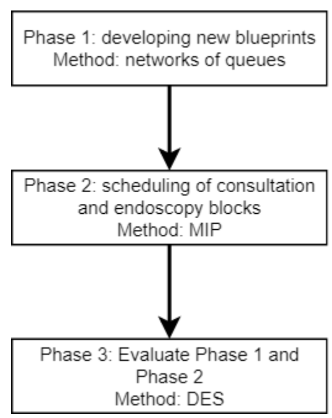
4 Solution approach

In this chapter, we design a solution approach to overcome the problems that arise from Chapter 2, using the literature research of Chapter 3. We explain the conceptual model in Section 4.1. Section 4.2 explains the data gathering process. The solution approach consists of three phases. Phase 1 focuses on a new blueprint for the consultation and endoscopy block derived from the networks of queues approach from Creemers and Lambrecht [2007] and can be found in Section 4.3. In Phase 2, these blocks are used as input for the MIP which is based on the works of Van de Vrugt [2016], Hulshof et al. [2011a] and Bikker et al. [2015]. The MIP is used to perform simulation-based optimization to determine a new base roster. The MIP can be found in Section 4.4. In phase 3, we use Discrete Event Simulation to evaluate the new blueprints from Phase 1 and the base roster from Phase 2. The validation of the used models can be found in Section 4.5.

4.1 Conceptual Model

Currently used blueprints for the consultation and endoscopies are made several years ago and have not been changed in the meantime. Both consultation and endoscopy blueprints are seen separately and do not take into account routing probabilities of all patient types and variability in external patient arrivals. In Phase 1, we develop a new blueprint for the consultation and endoscopy block. We propose a new blueprint for the consultation and endoscopy block based on the networks of queues approach of Creemers and Lambrecht [2007].

Phase 2 solves an adjusted version of the MIP of Van de Vrugt [2016], Hulshof et al. [2011a] and Bikker et al. [2015]. The blueprints from Phase 1 are used to determined the weekly number of consultation and endoscopy blocks. The purpose of the MIP is to determine a new base roster while taking into account the weekly available doctor capacity. The available doctor capacity depends on the timing of holidays of each doctor during the year. As input for the MIP, we use three different holiday rosters each with frequently occurring weekly number of available doctor capacity, shown in Appendix G. We use the MIP for simulation-based optimization where we minimize the access and waiting time for endoscopies for each of the three holiday rosters. For each holiday roster, the MIP determines an weekly schedule for the consultation and endoscopy blocks. We use DES, in Phase 3, to evaluate the performances of the block schedules with regard to the key performances indicators.



The discrete time queueing model of Van de Vrugt [2016] is used in Phase 2 to evaluate the expected access and waiting time as function of the number of scheduled appointment slots. The framework of Hulshof et al. [2011a] is used in Phase 2 to convert the single appointment scheduling problem of Van de Vrugt [2016] and Bikker et al. [2015] into a multi appointment scheduling problem. The objective of the converted version of the MIP of Van de Vrugt [2016] and Bikker et al. [2015] is to minimize the access and waiting time for endoscopies.

We decide on the weekly number of blocks to schedule while taking into account the weekly available doctor capacity. The weekly assignment of blocks to specific doctors is not considered in the model. In all used models, we assume that all patients cannot be treated in the same week of their arrival, except for emergency patients.

4.2 Data gathering

From Hix, we use external arrival data from the period from 2012 to 2017 from which probability distributions are derived. Furthermore, transition probabilities are derived from patient registrations in the period from week 36$^{\text{th}}$ 2016 to week 35$^{\text{th}}$ 2017. We choose this period, since this is the period where this research is focused on. The reader is referred to Appendix D for the explanation of the data gathering process of the arrivals, service rate and delay of patients.

4.3 Phase 1: New blueprints

A blueprint can be seen as a reflection of the demand, specified per patient type p. Therefore, the objective of Phase 1 is to adjust the currently used blueprints such that it is a true reflection of the current demand for care at MDL. We choose to express the total demand for care in time units and not in total number of arrivals, since we cannot change the required time per appointment type, according to the department. Therefore, we determine the total demand for care expressed in time units per patient type by means of a networks of queues approach of Creemers and Lambrecht [2007].

Each appointment type is considered as a queue and external arrivals are modelled as stochastic processes by means of the relevant probability distributions of patient type p based on six year historic data from DZ. The transition flow from the queue of appointment type i to the queue of appointment type j is modelled via the inverse binomial distribution with transition probability q_{ij}.

Random numbers are generated for all transitions to incorporate stochasticity in the number of type p patients arriving at queue j. Figure 12 shows the visualization of the networks of queues approach.

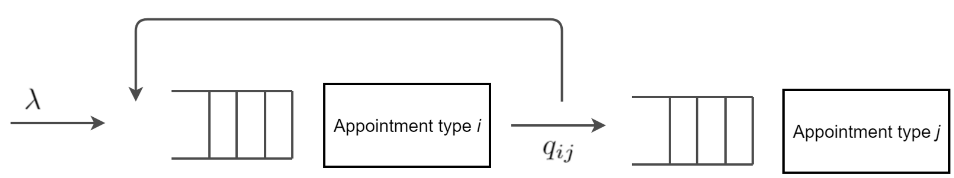


Figure 12: Networks of queues visualization

We multiply the total number of arrivals for each queue of appointment type i by the corresponding required time per appointment to obtain the demand for care in time units for appointment type i, defined as d_i. We derive fractions of the total demand for care by using Equation 1.

$$f_i = \frac{d_i}{\sum_i d_i} \tag{1}$$

We define m_b as the total time available per consultation or endoscopy block. Therefore, we formulate Equation 2 to express the total time allocated to appointment slot i per block b.

$$a_i = f_i \cdot m_b \quad \forall i, b \tag{2}$$

We determine the total number of slots for appointment slot i per block b via Equation 3, where r_i is the service requirement per appointment type i.

$$n_i = \frac{a_i}{r_i} \quad \forall i \tag{3}$$

Table 8 shows the current versus the proposed blueprint based on the networks of queues approach.

Table 8: Current versus proposed consultation blueprint

Consultation type	**Number of slots**
Intake	2.7
Recurrent	7
Telephone	1.3
New	1.5
Emergency	1.3

Consultation type	**Number of slots**
Intake	4
Recurrent	5
Telephone	3
New	2
Emergency	1

In the current situation, doctors have different blueprints depending on the working day. For overview purposes, we take the average number for each appointment type i, therefore the number of slots in the current blueprint are fractional.

The current access time is explained by the difference between the current number of intake slots and the demand, respectively 2.7 and 4 intake slots. This means that the access times are rising as there are not enough intake slots offered to meet the demand, which is also stated in Section 1.2.

Recall that two nurses of the recovery room performs on average 18 intakes on a daily basis. A new schedule was made last year by a nurse of the recovery room to increase the daily number of intakes to 24. However, this new schedule is not in use yet, because it is currently not matched with the consultation blueprints of the doctors. We made, together with the planner and the nurse of the recovery room, a new blueprint for the consultation block where we take into account the new schedule of the nurses and the proposed blueprint from Table 8. These new consultation blueprints are in use since July 2018.

Before the start and during the research, MDL was already trying to adjust the endoscopy blocks. The appointment length of the colonoscopy changed from 45 minutes to 30 minutes. Consequently, the number of colonoscopies increases and therefore the complete endoscopy block is changed.

We use networks of queues to determine whether the total number endoscopy types within the endoscopy blocks in the new situation is sufficient to meet the demand, shown in Table 9.

Table 9: Current versus proposed endoscopy block

Endoscopy types	**Number of slots**
Colonoscopy	3.3
Sigmoscopy	1
Gastroscopy	2
Endo-echo	1
ERCP	1
Emergency	1
Gastro narcosis	1

Endoscopy types	**Number of slots**
Colonoscopy	2
Sigmoscopy	1
Gastroscopy	2
Endo-echo	1
ERCP	1
Emergency	1
Gastro narcosis	1

We conclude that, in the new situation, sufficient appointment slots are reserved for each endoscopy type to meet the demand for the endoscopy types.

4.4 Phase 2: Scheduling of blocks

A discrete time queueing model is used to express the access and waiting time for endoscopies as function of the number of scheduled appointment slots. We use Hulshof et al. [2011a] to convert the single appointment scheduling problem from Van de Vrugt [2016] and Bikker et al. [2015] into a multi appointment scheduling problem. The goal of this MIP is to generate a yearly base roster by scheduling consultation and endoscopy blocks while taking into account the weekly available doctor capacity. The objective of the MIP is to minimize the access and waiting time for endoscopies.

Discrete time queueing model
We develop a discrete time queueing model based on Van de Vrugt [2016]. The goal of the model is to evaluate for each possible number of arriving type p patients and number of scheduled appointment slots for patient type p the access and waiting time for endoscopies. We make adjustments to the original model, since the computation time increases significantly when more details are added. The original model takes into account the (marginal) stationary distribution for each possible number q in the backlog in week w of type p patients. For our model, we only take into account the stationary distribution of the number of patients of type p in the system in week w. The words *appointment type* and *patient type* are mentioned interchangeably in the explanation below.

An appointment type is considered as a queue (e.g. a queue for intake appointments). Each queue has a deterministic service rate, $c_{w,p}$, equal to number of appointment slots per patient type p in week w. The probability of having $N_{w,p}$ patients in the system is calculated by solving the stationary distribution. We define $c_{w,p}(y)$ as the number of appointment slots for patient type p in week $w+y$, where $y > 0$. We calculate the expected access and waiting time for endoscopies for each possible number of arrival and number of scheduled appointment slots, used as input for the MIP. The reader is referred to Appendix B for an extended derivation of the used formulas.

Mixed integer programming

The MIP decides on the weekly number of consultation and endoscopy blocks to schedule. These block types are set in Section 4.3. In the following we define the sets, parameters, variables and constraints of the model.

Let P denote the set of patient types and let W denote the set of weeks in the planning horizon. B denotes the set of block types, where a block type is consultation or endoscopy. Let D be the set of doctors. Furthermore, let A and C be the (auxiliary) sets used to generate the matrices which expresses the expected access and waiting time for endoscopies from the discrete time queueing model. Let both matrices be the Cartesian product of $|A|$ and $|C|$.

Let a_w be the number of 'available doctor days' in week w. This means that $a_w = 4$ if one doctor is available for the complete working week w, since doctors are working at most four days. Let $l_{p,b}$ denote the number of appointment slots for patient type p per block b conform the blueprints from Phase 1. Let $t_{p,c,pp}$ be the matrix that denotes the average flow from the queue of patient type p to the queue of patient type pp. We use historic data of DZ to determine the transition probability $q_{p,pp}$. For each c, the average flow is defined as $c{\cdot}q_{p,pp}$.

Let $\lambda_{w,p}$ be the external arrival rate of type p patients in week w. External arrivals are modelled as stochastic processes by means of the relevant probability distributions of the patient type based on six year historic data from DZ. Furthermore, $d_{p,pp}$ denotes the delay matrix from the queue of patient type p to the queue of patient type pp, where the delay is expressed in weeks and is based on historic data of DZ.

We define $X_{w,p,c}$ as a binary variable, with value 1 if c is the number of scheduled appointment slots for patient type p in week w. Let the integer variable $N_{w,b}$ denote the number of scheduled type b blocks in week w. Integer variable $A_{w,p}$ is the total number of arriving type p patients in week w.

We aim to minimize the weekly access and waiting time per patient type p. Therefore, we formulate the following objective:

$$Minimize \quad \sum_{w} \sum_{p} f^a(A_{w,p}, C_{w,p}) \tag{4}$$

Where the function f^a relates the weekly number of scheduled appointment slots for patient type p to the weekly expected access and waiting time. We do not use a function for the number of empty slots per patient type p, due to computation time reasons. Function f^a is derived from the discrete time queueing model from Van de Vrugt [2016]. In Equation 4, $C_{w,p} = \sum_c c \cdot X_{w,p,c}$ denoting the number of appointment slots scheduled for patient type p in week w. Let $X_{w,p,c}$, $Y_{w,p,a}$ and $Z_{w,p,a,c}$ be auxiliary variables to read the access and waiting time for endoscopies from the array for each week w and for each patient type p. These variables are explained in Appendix E.

Table 10 shows a summary of the sets, indices, variables and parameters of the MIP.

Table 10: Sets, indices, variables and parameters of the model

Sets and indices	
$d \in D$	Doctors
$w \in W$	Weeks
$p \in P$	Patient types
$b \in B$	Block types
Variables	
$N_{w,b}$	The number of scheduled blocks b in week w
$C_{w,p}$	The number of patient type p served in week w
$A_{w,p}$	The number of arriving patient type p in week w
$X_{w,p,c}$	Binary variable denoting 1 if c number of slots are scheduled in week w for patient type p
$Y_{w,p,a}$	Binary variable denoting 1 if a number of patient of type p arrives in week w
$Z_{w,p,a,c}$	Binary variable denoting 1 if in week w the number of scheduled slots is equal to c and the number of arriving patients of type p is equal to a
Parameters	
$\lambda_{w,p}$	External arrival rate of patient type p in week w
$l_{p,b}$	Number of patient type p in one block b
$t_{p,c,pp}$	Number of transitions of patient type p to patient type pp given that c number of appointment slots are scheduled for patient type p
$d_{p,pp}$	Transition delay from queue of patient type p to the queue of patient type pp
Variable types	
X, Y, Z as $\mathbb{B}$	
A, C, N as $\mathbb{Z}$	

We formulate the following set of constraints. Equation 5 makes sure that c number of appointment slots have to be chosen for each patient type p for each week w.

$$\sum_{c} X_{w,p,c} = 1 \qquad \forall w, p \tag{5}$$

Equation 6 ensures that the weekly number of scheduled appointment slots per patient type p does not exceed the number of arrivals of patient type p.

$$C_{w,p} \leq A_{w,p} \qquad \forall w, p \tag{6}$$

We define $A_{w,p}$ based on the framework of Hulshof et al. [2011a]. Each queue for patient type p is feeded by external arrivals and transition flows from other queues within the network.

$$A_{w,p} = \lambda_{w,p} \qquad \forall p, w \leq d_{pp,p} \tag{7}$$

$$A_{w,p} = \lambda_{w,p} + \sum_{pp} \sum_{c} X_{w-d_{pp,p},pp,c} \cdot t_{pp,c,p} \qquad \forall p, w > d_{pp,p} \tag{8}$$

Equation 9 ensures that the number of scheduled appointment slots for patient type p in week w is bounded from above by the number of type b blocks, multiplied by the number appointment slots for patient type p in block b.

$$C_{w,p} \leq N_{w,b} \cdot l_{p,b} \qquad \forall w, p, b \tag{9}$$

Equation 10 makes sure that the weekly number of consultation blocks does not exceed the weekly number of available doctors days. As preferred by MDL, each doctor performs at most one consultation block per day.

$$N_{w,b} \leq a_w \qquad \forall w, b = consultation \tag{10}$$

Doctors can have two endoscopy blocks on a daily basis, as shown in Equation 11.

$$N_{w,b} \leq 2 \cdot a_w \qquad \forall w, b = endoscopy \tag{11}$$

The last constraint ensures that the total number of scheduled blocks does not exceed the total capacity. Where m_w denotes the total number of blocks that may be scheduled, depending on the total weekly number of available doctor days.

$$\sum_b N_{w,b} \leq m_w \qquad \forall w \tag{12}$$

4.4.1 Iterative linear approximation

In this section, we explain a linear approximation of the objective function used in our original model. We use linear approximation to reduce the complexity of the problem and therefore to reduce the computation time of the original model as described in Section 4.4. The validation of the model can be found in Section 4.5.

The original model uses an array with a non linear relationship between two unknown integer variables, $C_{w,p}$ and $A_{w,p}$. The graph of this array is shown in Appendix E. We use auxiliary variables $X_{w,p,c}$, $Y_{w,p,a}$ and $Z_{w,p,a,c}$ to transform the non linear model into a MIP. However, the MIP is not able to solve an instance of one year within a reasonable amount of time. For example, an instance of eight weeks yields an integrality gap of 19% after running for 18 hours. Reason for this computation time is binary variable $Z_{w,p,a,c}$ which is used to read the associated access and waiting time from the array. We want to avoid binary variable $Z_{w,p,a,c}$ and improve the running time by using a piece-wise linear approximation of the objective function. A linear approximation is a technique that uses piece-wise linear function to approximate a nonlinear function [Geißler et al., 2012].

Let set n be the beginnings and endings of each piece-wise interval. Let set a be the set of arrivals. Let $x_{a,n}$ denote the x-value of the n^{th} breakpoint for arrival a and let $y_{a,n}$ be the value function of the n^{th} breakpoint for arrival a. Let $p_{a,n}$ denote non-negative weights for each n^{th} interval for each arrival a summing to unity. The complete derivation of the linear approximation is shown in Appendix E.

A trade-off is made with regard to the linear approximation. Either (1) we aggregate all arrivals (e.g. into one bin) per appointment slot c, or (2) linearize a function for each possible number of arrival a. Using the first approach leads to loss of details, since we only take into account the number of scheduled appointment slots and discard the number of arrivals a. For example, the access and waiting time in case of 10 arrivals is the same as the access and waiting time in case of 80 arrivals. However, this approach improves the computation time significantly. Using the second approach leads to an increase of the computation time. Reason is that we have a piece-wise linear function for each possible number of arrival a which results in 150 different piece-wise linear functions for our model.

We choose to use an iterative linear approximation approach in which we generate initial solutions for each subsequent MIP run until the number of scheduled blocks convergences. We decide on the number of MIP runs by using the sequential procedure [Law et al., 2007] such that the average weekly number of scheduled blocks is within the relative error. By doing so, we balance the computation time (e.g. complexity of the MIP) and the level of detail with regard to the solutions. The flowchart of the iterative linear approximation is attached in Appendix E.

We define k_i as the number of arrival bins used in the i^{th} iteration and let $a \exists k_i$. The choice to use arrival bins instead of bins for appointment slots is partly based on Van de Vrugt [2016]. They use a discrete time queueing model to express the access time as function of the number of scheduled appointment slots. We are able to express access and waiting time for endoscopies as function of the number of scheduled appointment slots if we use arrival bins.

The total number of arrivals is uniformly distributed among the bins. We choose an uniform distribution since this is the easiest way to create different bins. However, possibly more accurate results can be achieved if other methods are used to create bins. We start the iteration with $k_1 = 1$ bin (no distinction made in the number of arrivals) and solve the MIP. The solution of the first MIP run is used for the next iteration where $k_2 = 2$. The solution of the second MIP run is used for the next iteration and so on. We continue the iterations until the weekly number of scheduled blocks converges.

4.5 Validation

The proposed blueprints for the consultation and endoscopy from Phase 1 are validated by the department. Furthermore, these blueprints are currently already implemented by the department. The feasibility of the MIP is validated by the planner of the department. The feasibility entails if the weekly number of consultation and endoscopy blocks fits within the available capacity of the department. For example, the weekly number of consultation blocks is constrained by the total weekly number of available consultation rooms. According to the planner, the MIP results in feasible solutions.

Black box validation of the MIP shows that the model behaves the same as in the practical case. For example, the expected access and waiting time for endoscopies increases in periods with less capacity or in periods with increasing number of patient arrivals.

The three holiday rosters are developed together with the planner of the department.

4.5.1 The simulation model

In Phase 3, we use a DES implemented in Plant Simulation to evaluate the performances of the holiday rosters. The DES simulates the behaviour of the realized access and waiting time for endoscopies over time. For each week, we generate new external patient arrivals based on their distributions from Subsection D.1. Furthermore, for each week, there is an internal routing of patients according to Subsection D.3. Each arriving patient type joins the queue corresponding to their type. The total weekly number of scheduled consultation and endoscopy blocks from our MIP is used as input to determine the weekly number of available appointment slots for a specific patient type (parallel servers). Each patient type is served FCFS. Furthermore, for each week, the total number of patients of type p that can be treated is at most the weekly number of available appointment slots for patient type p.

The outcomes of the DES are validated with the department. The reader is referred to Section 5.2 for the warm up length and the number of replications. The complete documentation of the simulation model can be found in Appendix F. Furthermore, as stated in Section 1.2, there is insufficient slot capacity for the intake and new patient types to meet the demand. The simulation model shows this behaviour, since it never reach steady state for these patient types. The waiting time for colonoscopy is similar in both the simulation model and the actual realized waiting time for colonoscopy. Therefore, we conclude that the DES is a valid representation of the MDL department. With regard to the NS-patients, scheduling rules are formulated and validated by the department.

5 Computational results

In Chapter 4, we propose new blueprints for the consultation and endoscopy blocks in Phase 1. The model from Phase 2 minimizes the access and waiting time for endoscopies by scheduling the blueprint blocks while taking into account the available doctor capacity. We explain the performance indicators for our model in Section 5.1. We elaborate on the experimental design in Section 5.2. The experimental design includes defining the experimental factors, warm up length, run length and required number of replications. Section 5.3 shows the performances of each block schedule. In Section 5.4, we use the model from Phase 2 to determine a new base roster. Based on the base roster, we derive practical rules for the scheduling of blocks and evaluate the performances of the rules in Subsection 5.4.1. In Section 5.5, we use DES to test and evaluate new scheduling rules with regard to the NS-patients. We conclude this chapter in Section 5.6

5.1 Key performance indicators

The objective of this research is to minimize the access and waiting time for endoscopies. Therefore, we use the access and waiting time for all endoscopies as key performance indicators. Additionally, we use the slot utilization as performance indicator, since the department does not want to have a low slot utilization. We define slot utilization as the fraction of the total number of appointment slots offered for patient type p that is fulfilled. Furthermore, we are interested in the standard deviation of the access and waiting time for endoscopies.

5.2 Experimental design

We use our MIP to perform experiments by using simulation-based optimization where we generate new external patient arrivals for each week (randomization). The goal is to determine a robust yearly block schedule that minimizes the access and waiting time for endoscopies for different values of new patient arrivals for each holiday roster. For each holiday roster, we determine a yearly block schedule which entails the weekly number of scheduled consultation and endoscopy blocks. For our experiments, we obligate that the number of scheduled blocks in week w in year y is the same as the number of scheduled blocks in week w for all subsequent years for each week w.

A trade-off is made with regard to the generation of the yearly block schedule for each holiday roster. Ideally, we use the batch means method to run the MIP once for many years for each holiday roster to (1) obtain an optimal yearly block schedule and (2) to construct a 95% confidence interval for the weekly mean access and waiting time for endoscopies. Since, the longer the run length of the MIP, the higher the probability of finding the optimal yearly block schedule, because we optimize over more different values of external patient arrivals. On the other hand, increasing the run length of the MIP leads to an exponentially growth of the running time.

We are not able to have a run length that is long enough to obtain one optimal yearly block schedule. Therefore, we choose to use a run length of 15 year to generate five different yearly block schedules for each holiday roster, since this is within a reasonable computation time. We stop our MIP once the integrality gap is $\leq 5\%$.

Per holiday roster, we choose one block schedule based on the performance and preferences of the department. We evaluate each selected block schedule using DES to determine the performance with regard to the access and waiting time for endoscopies and the slot utilization. We use the same seed value for each n^{th} run for each block schedule to compare the block schedules. While evaluating a block schedule, we use different seed values for subsequent runs to make independent runs.

We start each simulation run with an empty system, therefore we use Welch's graphical procedure to determine the warm-up length. We use a warm-up length of 40 years, shown in Appendix C, to achieve a steady state system. We incorporate stochasticity in external patient arrivals, routing of patients and delay time of the patients to determine the robustness of each block schedule. For each yearly block schedule, we use 800 replications to construct a 95% confidence interval for the weekly mean access and waiting for endoscopies using the replication/deletion approach.

5.3 Performances of chosen block schedules

For each holiday roster, we select one block schedule based on the performances of the KPIs and preferences of the department. In this section, we only show the selected block schedules. The reader is referred to Appendix H for the performances of all block schedules. Table 11 shows the performances, based on DES, of each chosen consultation block schedule.

Table 11: Performances chosen consultation block schedules each holiday roster

	Roster 1			**Roster 2**			**Roster 3**		
Patient type	$\bar{x}$	σ	Utili.	$\bar{x}$	σ	Utili.	$\bar{x}$	σ	Utili.
Intake	1.85	0.18	75.0%	1.84	0.18	76.8%	1.84	0.17	75.9%
New	2.59	0.60	94.6%	2.58	0.60	96.2%	2.69	0.55	95.7%
Emergency	0.02	0.14	94.4%	0.02	0.13	95.5%	0.02	0.13	94.9%
Recurrent	1.91	0.21	60.4%	1.90	0.21	80.6%	1.91	0.22	64.0%
Telephone	0.96	0.12	50.1%	0.95	0.13	51.5%	0.95	0.13	50.5%

The explanation for the relatively low utilization of the intake and recurrent appointment slots is that we still have to add the NS-patients. We decide to introduce the NS-patients later, since we have flexibility in when and how many NS-patients may be scheduled during the year. We first evaluate the performance of each holiday roster while only taking into account the regular patient types (no NS-patients). In this way, we are able to get insight in the required number of appointment slots by regular patient types throughout the year. For example, in week 24, we see that the average intake slot utilization is 50% which indicates that in this week slots are unused. This is caused by periods in which 20 consultation blocks are scheduled, shown in Appendix I.

We formulate two scheduling rules for NS-patients to increase the intake slot utilization for these weeks.

1. Depending on weekly number of consultation blocks
2. Depending on weekly number of available doctors

We use DES again to evaluate each scheduling rule, see Section 5.5. The low utilization of the telephone appointment slot can be explained by the fact that there is an unclear separation between telephone appointments and administration work performed by the doctors on daily basis.

Table 12 shows the performances of each chosen endoscopy block schedule.

Table 12: Performances endoscopy block schedules of each holiday roster

	Roster 1			**Roster 2**			**Roster 3**		
Patient type	$\bar{x}$	σ	Utili.	$\bar{x}$	σ	Utili.	$\bar{x}$	σ	Utili.
Colonoscopy	1.84	0.13	74.5%	1.84	0.11	75.9%	1.84	0.14	74.1%
Sigmoscopy	1.88	0.10	80.0%	1.85	0.11	80.2%	1.86	0.11	78.6%
Gastroscopy	1.84	0.20	76.1%	1.84	0.21	75.7%	1.85	0.20	75.5%
Endo-echo	0.99	0.04	44.1%	0.99	0.02	44.7%	0.99	0.03	45.1%
ERCP	0.97	0.06	53.0%	0.97	0.06	53.4%	0.97	0.06	53.1%
Emergency	0.09	0.17	67.2%	0.11	0.16	69.8%	0.11	0.19	68.9%
Gastro narcosis	1.96	0.09	68.6%	1.96	0.18	82.9%	1.91	0.10	79.7%

The utilization of the colonoscopy is relatively low, for the same reasons as the patient type intake from Table 11. The utilization of the colonoscopy increases when incorporating the NS-patients into the system. Furthermore, a patient that needs an ERCP or Endo-echo has to be treated as soon as possible. As a result, we reserve more slots than the demand which keeps the utilization low, but also results in a low waiting time for these patient types.

5.4 The base roster

The base roster entails the weekly number of scheduled consultation and endoscopy blocks while taking into account the available doctor capacity. Table 13 shows the first seven weeks of each holiday roster. The complete table can be found in Appendix J.

Table 13: Number of scheduled blocks in each holiday roster

	Schedule 1		**Schedule 2**		**Schedule 3**	
Week	Consult.	Endo.	Consult.	Endo.	Consult.	Endo.
1	8	8	8	8	8	8
2	20	20	20	20	20	20
3	20	20	20	20	20	20
4	20	20	20	20	20	20
5	15	17	12	12	15	17
6	16	16	20	20	16	16
7	16	16	12	12	16	16
...	...	...	...	...	...	...

The available doctor capacity is the same in week one up to and including week four, shown in Appendix G. This results in the same number of scheduled consultation and endoscopy blocks. However, available doctor capacity differs from week five up to and including week seven due to different holiday rosters. Therefore, the MIP schedules different number of blocks in these weeks. Furthermore, we see that the ratio of consultation and endoscopy blocks differs in these weeks. For example, in week 5, the MIP schedules 15 consultation and 17 endoscopy blocks in case of holiday roster 1. But, in case of holiday roster 2, the MIP schedules 12 consultation and 12 endoscopy blocks. We are able to derive practical guidelines using the outcomes of the MIP. The practical guidelines can be found in Subsection 5.4.1.

5.4.1 Practical guidelines for scheduling blocks

Although each holiday roster is a realistic representation of the weekly available doctor capacity, it is desired by the department to formulate practical guidelines with regard to the number of blocks to schedule. The reason is that the available doctor capacity expands in the near future. Consequently, the number of scheduled blocks, shown in Table 13, might not be accurate anymore. However, we are able to define guidelines for the weekly number of scheduled consultation and endoscopy blocks. These guidelines can be translated into the total number of consultation and endoscopy blocks to schedule given a certain number of available doctors during the week. We do not choose to use a percentage of the number of blocks since we may end up with a fractional number of scheduled consultation or endoscopy blocks.

It is more practical to define guidelines for months instead of weeks, since holiday weeks may lie in different months and in different years. For each week, we determine the number of consultation and endoscopy blocks to schedule as function of the weekly available number of doctors. We simplify the guidelines to develop one guideline for each week. For each week, we develop a guideline for the scheduling of blocks that occurs in all cases or in 2/3 of the cases.

As an example, for holiday roster 1 and 2, we have in total 4 doctors available in week 5. Each doctors works four days, this means that the total number of available doctor days in week 5 is equal to 16. The MIP schedules 15 consultation and 17 endoscopy blocks in week 5 for holiday roster 1 and 2. We define the following scheduling rule for week 5, since it occurs in 2/3 of the cases (for holiday roster 1 and 2).

- Number of consultation blocks = number of available doctor days - 1;
- Number of endoscopy blocks = number of available doctor days + 1;

Table 14 shows the guidelines for each week.

Table 14: Guidelines for the scheduling of blocks

	Number of blocks	
Week	Consultation	Endoscopy
1 - 4	Doctor days	Doctor days
5	Doctor days - 1	Doctor days + 1
6 - 9	Doctor days	Doctor days
10	Doctor days - 1	Doctor days + 1
11 - 20	Doctor days	Doctor days
21	Doctor days - 1	Doctor days + 1
22 - 23	Doctor days	Doctor days
24	Doctor days - 1	Doctor days + 1
25 - 26	Doctor days	Doctor days
27	Doctor days - 1	Doctor days + 1
28 - 46	Doctor days	Doctor days
47	Doctor days - 2	Doctor days + 2
48 - 51	Doctor days	Doctor days
52	Doctor days - 1	Doctor days + 1

With the use of DES, we evaluate the performances of the guidelines by using the available doctor capacity of each holiday rosters. We compare the performances of the guidelines with the performances of the corresponding holiday rosters, shown in Section 5.3.

Table 15 shows the comparison between the rosters and the guidelines. For overview purposes, we only show the access and waiting time for endoscopy. The reader is referred to Appendix K for the comparison of all key performance indicators.

Table 15: Comparison between the rosters and guidelines, results from DES

Patient type	**Roster 1**	**Guidelines 1**	**Roster 2**	**Guidelines 2**	**Roster 3**	**Guidelines 3**
Intake	1.85	1.85	1.84	1.84	1.84	1.83
New	2.59	2.59	2.58	2.59	2.69	2.57
Emergency	0.02	0.02	0.02	0.02	0.02	0.02
Recurrent	1.91	1.91	1.90	1.91	1.91	1.91
Telephone	0.96	0.95	0.95	0.96	0.95	0.97
Colonoscopy	1.84	1.84	1.84	1.85	1.84	1.82
Sigmoscopy	1.88	1.85	1.85	1.87	1.86	1.86
Gastroscopy	1.84	1.83	1.84	1.84	1.85	1.85
Endo-Echo	0.99	0.99	0.99	0.99	0.99	0.99
ERCP	0.97	0.97	0.97	0.97	0.97	0.99
Emergency	0.09	0.10	0.11	0.04	0.11	0.12
Gastro narcosis	1.96	1.97	1.96	1.94	1.91	1.93

The guidelines are derived from the weekly number of scheduled blocks of the three holiday rosters. As a result, when following the guidelines of block scheduling, small deviations with regard to the weekly number of scheduled consultation and endoscopy blocks may occur.

For example, there is a difference in the access time for new patients for holiday roster 3 (2.69 weeks) and the guidelines (2.57 weeks). This is caused by scheduling an additional three consultation blocks if we following the guidelines resulting in more capacity for new patients and therefore a lower access time for new patients. Nevertheless, we conclude that the weekly number of scheduled blocks according to the practical guidelines is a good representation of the weekly number of scheduled blocks in each holiday roster.

5.5 Scheduling NS-patients

We state in Subsection 2.3.1 that NS-patients are evenly distributed over all weeks and evenly distributed over all consultation and endoscopy blocks throughout the year. As a result, approximately 10% of the NS-patients could not be treated since consultation or endoscopy blocks are cancelled. Furthermore, DES shows that this way of scheduling NS-patients results in an unstable system, since there is a lack of capacity left for the regular patient types. Together with the department, we formulate two new scheduling rules for the NS-patients that dynamically distributes the NS-patients over the weeks. We evaluate the rules with the use of DES. These rules aims to use the unused appointment slots as shown in Section 5.3. We select the scheduling rule that is preferred by the department.

1. Weekly number of consultations
Schedule two NS-patients per consultation block only if the weekly number of scheduled consultation blocks is equal to or higher than 20. Schedule one NS-patients per consultation block only if the weekly number of consultation blocks is equal to or higher than 14, but lower than 20. Schedule zero NS-patients if the weekly number of scheduled consultation is smaller than 14. The performances of this scheduling rule is shown in Table 16.

Table 16: Performance of chosen block schedules using scheduling rule 1 (in weeks)

	Roster 1			**Roster 2**			**Roster 3**		
Patient type	$\bar{x}$	σ	Utili.	$\bar{x}$	σ	Utili.	$\bar{x}$	σ	Utili.
Intake	2.03	0.13	97.9%	2.01	0.17	98.0%	2.42	0.26	98.7%
New	2.76	0.61	96.2%	2.77	0.66	95.4%	3.02	0.55	96.6%
Emergency consult	0.12	0.11	97.7%	0.12	0.12	96.9%	0.13	0.12	97.8%
Recurrent	1.90	0.21	69.6%	1.89	0.22	69.3%	1.91	0.20	69.9%
Telephone	0.96	0.10	54.7%	0.95	0.13	55.0%	0.96	0.12	54.8%
Colonoscopy	1.67	0.25	93.1%	1.71	0.26	92.3%	1.73	0.24	92.3%
Sigmoscopy	1.86	0.10	81.2%	1.85	0.12	82.0%	1.86	0.11	80.2%
Gastroscopy	1.85	0.20	75.9%	1.85	0.19	75.4%	1.85	0.19	74.7%
Endo-echo	0.99	0.02	47.7%	0.97	0.14	48.7%	0.99	0.02	47.5%
ERCP	0.97	0.05	56.6%	0.97	0.06	55.8%	0.97	0.06	54.8%
Emergency endo	0.11	0.18	72.6%	0.11	0.17	72.1%	0.11	0.20	71.0%
Gastro narcosis	2.29	0.24	94.4%	2.19	0.20	92.7%	2.11	0.19	92.3%

On average 1058 NS-patients could be yearly scheduled if this schedule rule is used for NS-patients.

2. Weekly doctor availability
We found that our DES results in a unstable system if we schedule two NS-patients per consultation block when four or more doctors are available during a week. This is caused by a lack of capacity that is left for the regular patient types. Therefore, we *schedule two NS-patients per consultation block only if the weekly number of available doctors is equal to five.* The performances of this scheduling rule is shown in Table 17.

Table 17: Performance of chosen block schedules using scheduling rule 2 (in weeks)

	Roster 1			**Roster 2**			**Roster 3**		
Patient type	$\bar{x}$	σ	Utili.	$\bar{x}$	σ	Utili.	$\bar{x}$	σ	Utili.
Intake	1.80	0.16	90.7%	1.81	0.16	90.7%	1.81	0.17	88.8%
New	2.63	0.53	95.7%	2.68	0.69	95.1%	2.84	0.53	96.9%
Emergency consult	0.12	0.11	97.4%	0.12	0.21	96.6%	0.12	0.13	97.7%
Recurrent	1.90	0.20	68.2%	1.89	0.21	68.7%	1.91	0.20	68.1%
Telephone	0.96	0.11	53.5%	0.97	0.12	54.0%	0.97	0.10	53.3%
Colonoscopy	1.71	0.25	87.9%	1.73	0.24	88.9%	1.74	0.26	86.1%
Sigmoscopy	1.85	0.11	81.9%	1.85	0.11	81.5%	1.85	0.11	79.8%
Gastroscopy	1.87	0.20	75.3%	1.84	0.19	76.2%	1.86	0.21	76.1%
Endo-echo	1.00	0.00	46.5%	0.97	0.14	46.5%	0.99	0.02	47.2%
ERCP	1.00	0.00	53.4%	0.97	0.05	55.1%	0.98	0.04	54.0%
Emergency endo	0.11	0.16	72.2%	0.10	0.17	72.0%	0.11	0.19	70.7%
Gastro narcosis	1.96	0.14	91.0%	2.00	0.13	91.0%	1.46	0.42	87.7%

On average 824 NS-patients could be yearly scheduled if this scheduling rule is used for NS-patients. However, this is less than schedule rule 1. Consequently, the average slot utilization is lower and therefore the average access and waiting time for endoscopies is lower, since there are less patients in the system. This means that there is a trade-off between the access and waiting time for endoscopy on the one hand and on the other hand the yearly number of NS-patients that can be scheduled.

The department prefers scheduling rule 1, since they want to treat as much NS-patients as possible and the access and waiting time for endoscopies for the regular patient types are still within the norms. Furthermore, in Subsection 2.4.2, we define $P(X > 4)$ as the probability of exceeding an access or waiting time for endoscopy of four weeks. DES shows that for each holiday roster and for each patient type, $P(X > 4) = 0$.

5.6 Conclusion

In this chapter, we evaluate five different block schedules for each holiday roster. For each holiday roster, we select one block schedule that is preferred by the department. We derive and evaluate practical guidelines with the use of the chosen block schedule. DES shows that the guidelines are a good representation of the chosen block schedules, since the performances are approximately equal to each other. We formulate and evaluate two scheduling rules for NS-patients. The department prefers the scheduling rule where the weekly number of NS-patients depends on the weekly number of scheduled consultation blocks. While using this scheduling rule, approximately 1058 NS-patients can be treated yearly, which is 234 more than the scheduling rule based on the weekly number of available doctors. Furthermore, comparing with historical performances of the department, the access and waiting time of the regular intake patients can be reduced to an average of 2.03 weeks for intake patients and 1.67 weeks for colonoscopy patients if the practical guidelines are used.

6 Conclusions and recommendations

Our research goal is to *reduce the access and waiting time for the endoscopy for patients at the MDL department.*

In Section 6.1, we discuss the conclusions from this research followed by the contributions to both practice and theory in Subsection 6.1.1. In Section 6.2, we give recommendations for the MDL department. The recommendations for further research can be found in Subsection 6.2.2. The implementation plan can be found in Section 6.3. The discussion of this research can be found in Section 6.4.

6.1 Conclusions

Currently, the access time is 7 week and the waiting time for endoscopies is 5 weeks. In total, there is sufficient capacity to meet the demand. However, we see differences when looking per patient type. The rising access time is explained by a lack in capacity allocated to intakes. Furthermore, consultation and endoscopy blocks are cancelled during the holidays of the doctors. For these cancelled blocks, no corrections takes place before or after the holidays resulting in high access and waiting time for endoscopies.

In this research, we develop in Phase 1, a model that allocates capacity to different patient types by means of a networks of queues approach. By doing so, the consultation and endoscopy blocks are revised, for example the average number of intake slots per consultation block increases from 2.7 to 4. The revised blocks are now able to meet the current demand for care. Currently, these revised consultation and endoscopy blocks are already implemented. In Phase 2, we determine three different scenarios for the weekly number of available doctors, defined as a holiday roster. For each holiday roster, we use a mixed integer program (MIP) that generates a yearly block schedule for the weekly number of scheduled consultation and endoscopy blocks. The objective of the MIP is to minimize the expected access and waiting time for endoscopies. Furthermore, the MIP takes into account the organizational restrictions such as the limited number of weekly available endoscopy rooms. We retrieve practical guidelines with regard to the weekly number of consultation and endoscopy blocks as function of the weekly available number of doctor days.

In Phase 3, we use discrete event simulation (DES) to evaluate the access and waiting time for endoscopies for each yearly block schedule. DES shows that, if the practical guidelines are used, the access and waiting time for endoscopies are all within the norms set by the government. Furthermore, we formulate two scheduling rules that dynamically distributes the NS-patients over the weeks. The first scheduling rule depends on the weekly number of scheduled consultation blocks and the second scheduling rule depends on the weekly number of available doctors. The department prefers the first schedule rule for the NS-patients. This scheduling rule prescribes that we only schedule 2 NS-patients per consultation block if the weekly number of scheduled consultation blocks is 20 or higher. Schedule 1 NS-patients per consultation block if the weekly number of scheduled consultation blocks is 14 or more, but smaller than 20. Schedule no NS-patients if the weekly scheduled consultation blocks is smaller than 14. By using this scheduling rule, approximately 1060 NS-patients can be treated yearly.

Furthermore, the access and waiting time for endoscopies for each patient type is within the norms set by the government. The access time can be reduced from 7 weeks to 2.03 weeks and the waiting time for colonoscopy can be reduced from 5 weeks to 1.67 weeks.

6.1.1 Contributions to practice and theory

In this subsection, we discuss the contributions to both practice and theory.

Contributions to practice

We develop a new blueprint for the consultation and endoscopy blocks. These new blueprints ensure that the access time for intake and new patient types decreases. Consequently, the quality of care increases because these patients gets treated earlier as compared to the old blueprints. Furthermore, while using the old blueprints, receptionists got complaints from the patients about the high access time. We expected that the number of complaints decreases. As a result, the quality of labor for the receptionists increases.

We believe that the guidelines for scheduling the weekly number of consultation and endoscopy blocks contributes to practice. The reason being is that the process of scheduling blocks becomes easier, since no trade-offs have to be made anymore.

Contributions to theory

Our research contributes to theory, because we use the work of Hulshof et al. [2011a] and Van de Vrugt [2016] to perform a case study. We prove that the theory contributes to practice which might result in an increase of credibility of the application of science in practice.

As far as we know, there is no research that is directly applicable to the case of MDL department. The MDL department deals with uncertainty in the weekly number of new patients arrivals and uncertainty in the weekly routing of different patient types to different appointment types. Besides that, in the current situation MDL has to decide before the beginning of the next year, how many NS-patients has to be treated in which week. The decision of the weekly number of scheduled NS-patients influences the available capacity for the regular intake patients and therefore influences the access time for the regular intake patients. In Phase 1 of our research, we take into account the required capacity for all patient types (including NS-patients). In Phase 2, when scheduling blocks, we see that we have a low intake slot utilization in weeks where the available doctor capacity is near the maximum. In these specific weeks, we have the opportunity to schedule NS-patients while maintaining the access and waiting time for the regular patient types. We believe that this approach is also applicable to departments similar to the MDL department.

6.2 Recommendations for MDL

In this section, we propose recommendations with regard to our research. We discuss some general recommendations in Subsection 6.2.1. We conclude this section with recommendations for further research in Subsection 6.2.2.

6.2.1 General recommendations

In this subsection, we describe four general recommendations with regard to the scheduling of patients.

Time registrations of the appointments
Current practice is that appointments are scheduled in their corresponding time slots. However, time registration of the realized appointment duration do not take place. We recommend to use time registrations for each appointment. In this way, insights be attained in overtime probabilities of appointments, idle time of appointments and treatment time deviations between doctors. Consequently, opportunities may arise with regard to the scheduling of patients. For example, more patients may be treated in the same time if the idle time of this patient type is high.

Keep track of number of visits by a patient
At MDL, a patient may visit a particular appointment type several times. The appointment duration may depend on the total number of times a patient visits an appointment type. For example, a patient who (re)visits the intake appointment for the second time may need less instructions before undergoing their endoscopy. Therefore, this appointment does require less time than that is reserved. We recommend to get insight in the total number of visits for each appointment by a patient and adjust the required time accordingly. By doing so, more intakes can potential being performed since on average these intakes may require less time.

Defining return frequency of recurrent patients
A patient may become a recurrent patient. Different doctors prefer to see some patients more frequently than other doctors, due to many reasons. We recommend to get insight in the decision making of the recurrency rate for each doctor. When evaluating this decision making, it may be possible that less recurrent appointment slots are needed.

Use of priority rules for patients from the waiting list
From Subsection 2.4, we know that MDL uses a waiting list for patients who needs a new appointment after one, two or three years after their last appointment. The patients from the waiting list may most of the time be marked as non-urgent patients, according to the department. Current practice is that every patient is scheduled FCFS. Every patient type, from or not from the waiting list, is scheduled as soon as a new planning horizon is open. We recommend to make a distinction between patients from and not from the waiting list. Potentially, this capacity can be used for other patient types.

6.2.2 Further research

In this subsection, we recommend three topics for further research.

Bottleneck analyses of the recovery room
The total number of daily endoscopy patients depends on different factors. One of them is the daily bed and nurse capacity of the recovery room. The daily available number of beds and nurses may be a limited factor if the daily number of endoscopies increases. Since, in the near future, available doctor capacity increases (shown in Subsection 5.4.1) which may influence the bed utilization of the recovery room. Furthermore, the appointment length of the colonoscopy decreases from 45 minutes to 30 minutes, shown in Section 4.3. The decrease of the appointment length of the colonoscopy may also lead to an increase in the bed utilization of the recovery room, since each colonoscopy patients need to get prepared in the recovery room. The combination of an increase in available doctor capacity and the decrease of the appointment length may lead problems with regard to the capacity of the recovery room. We recommend a further research to the relationship of the bed utilization and the maximum capacity of the recovery room since these changes may occur in the near future.

Operational appointment scheduling
Current practice is that each patient is scheduled FCFS. At MDL, a distinction is made between emergency cases and the regular patient types. The emergency cases have to be scheduled within one week and are scheduled in the corresponding slots in the consultation and endoscopy blocks. The remaining patient types are the regular patient types. Currently, each regular patient is scheduled FCFS as soon as a new planning horizon is open. However, a further distinction can be made between patients from the waiting lists and patients not from the waiting list. In general, patients from the waiting list do not have to be scheduled in a certain week. This means that there is flexibility with regard to the scheduling of these patient types. We recommend to identify the characteristics of each patient type, followed by a classification based on the urgency level of the patient. Furthermore, Markov Decision Process can be used to decide when a patient has to be scheduled based on the urgency level.

Recurrent intakes without medical changes
Currently there is a Lean Six Sigma project being performed by a nurse of the recovery room. The goal of the project is to get insight in the number of intakes performed by patients without medical changes. At MDL, patients have to get a new intake if there last intake is more than one year ago. However, it frequently occurs that these patients' medical condition does not change in the period between their last intake and the new intake. The Lean Six Sigma project aims to get insight in these kind of patients and wants to introduce additional guidelines. Ultimately, patients without medical changes do not have to get an intake anymore, but may undergo an endoscopy immediately. This has consequences for the required capacity for intakes. Therefore, we recommend a revision of the consultation and endoscopy blocks, after a period of three years after the introduction of these new guidelines. The reason being is that these new guidelines influences the distribution of the new patient arrivals, as well as the routing probabilities of the patients. Therefore, less capacity is required for intakes which means that a revision of the consultation blocks is needed.

6.3 Implementation plan

In this subsection, we discuss a plan to implement the results of Phase 1, Phase 2 and the new scheduling rules of the NS-patients from this research.

Phase 1: Use the new consultation and endoscopy blueprints
We aim to decrease the access and waiting time for endoscopies as soon as possible. Therefore, we recommend to use the new developed blueprints for the consultation and endoscopy blueprints as soon as the new planning horizon is open. The new developed blueprints for the consultation and endoscopy blocks are already approved by the department. However, the patient planning system (HiX) is currently freezed due to maintenance till July 2018. But, the new developed blueprints are going to be used starting from July 2018.

Phase 2: Practical guidelines for block scheduling
In Subsection 5.4.1, we derive practical guidelines from our model with regard to the scheduling of consultation and endoscopy blocks. We recommend to schedule the blocks as soon as the available doctor capacity is known. Currently, the available doctor capacity is known for the coming three months. This means that the frequency at which the blocks are scheduled in the new situation remains the same as compared with the old situation. This may improve the adaption of these guidelines by the department, since the frequency at which the blocks are schedules remains the same.

Scheduling NS-patients
With regard to the scheduling of NS-patients, we recommend to communicate with the institute that organizes the invitation of NS-patients. Furthermore, it is wise to inform them about the intentions of MDL with regard to the new scheduling rule for NS-patients and the performance improvement of the regular intakes for MDL patients. This is likely going to improve the readiness to adapt the policy of the institute.

Recall that the current way of scheduling NS-patient is as follows. At the beginning of the year, MDL has to communicate how many NS-patients can be treated in which week. The implication is that MDL do not know the exact available doctor capacity for the complete year at the moment of communication. Therefore, the main point is to know the exact deadline at which the institute has to know how many NS-patients are treated in which week by MDL. Ideally, MDL communicates how many NS-patients are treated in which week once every three months. Reason is that the available doctor capacity is known for every three months. Therefore, MDL knows how many consultation and endoscopy blocks are scheduled if the guidelines for the scheduling of blocks are followed.

6.4 Discussion

In this section, we discuss the research. In Subsection 6.4.1, we mention (un)expected results from our research. In Subsection 6.4.2, we mention some limitations with regard to model simplifications and assumptions.

6.4.1 Expectations during the research

Capacity for intake appointments

From Chapter 2, we see that the total number of appointment slots reserved for the intake patients is less that the demand. From literature, we know that insufficient capacity leads to increasing waiting times Silvester [2004]. Therefore, at the start of the research, we expected that an insufficient number of intake slots is the main cause for the increasing access time. As expected, we need more intake slots per consultation block.

Weekly number of scheduled blocks

From our guidelines of the weekly number of scheduled blocks in Phase 2, we observe that the weekly number of consultation and endoscopy blocks is almost equal to each other. There are small differences in weeks before or after the holidays. We did not expect these minor differences because MDL deals with fluctuating new patient arrivals. Therefore, it is reasonable to think that more consultation blocks have to be scheduled in weeks with a higher number of new patient arrivals in the MIP. On the other hand, in our MIP, we obligate that the number of scheduled blocks in week w in year y is the same as the number of scheduled blocks in week w for all subsequent years for each week w. On top of that, the weekly number of new patient arrivals and weekly number of internal flow of patients may converge to a certain average number due to the runlength of 15 years that is used for the MIP. Consequently, the weekly number of consultation and endoscopy blocks are (approximately) equal to each other.

Modelling choice for the scheduling of blocks

Our MIP from Phase 2 uses the work of Hulshof et al. [2011a] and Van de Vrugt [2016]. The initial MIP, with binary variables $X_{w,p,c}$, $Y_{w,p,a}$ and $Z_{w,p,a,c}$, needs a computation time of 18 hours for an instance of 8 weeks and still having an integrality gap of 18%. As an alternative for the linearization of the MIP, we could have been chosen the simulation based optimization approach with use of DES in Plant Simulation. We could, for example, use the Genetic Algorithm in Plant Simulation to find the (local) optimal input value for the weekly number of scheduled consultation and endoscopy blocks. However, we did not choose this approach, since we are not sure that the found solution of the Genetic Algorithm is a local or global optimum.

6.4.2 Limitations of the applied models

In this subsection, we first mention the limitations of the mixed integer programming model, followed by the limitations of the simulation model.

The mixed integer program
In Section 4.5, we use blackbox validation to validate the MIP. However, we remark some limitations of the MIP.

- We are not able to have a runlength that is long enough to achieve one optimal block schedule for each holiday roster. Instead, we determine 5 different block schedules for each holiday roster. For each holiday roster, we conclude that the weekly number of scheduled blocks does not differ much among the block schedules. Therefore, we assume that, for each holiday roster, the optimal block schedule is reasonable close the 5 block schedules.
- We use linear approximation to have an approximation of the MIP. We use an uniform distribution of the arrival bins. However, from Figure 18 in Appendix E we can conclude that the uniform distribution might not be a good method to generate bins. We do not know the effects of using other methods since we did not quantify the effects of using other methods.

The simulation model
We validated the DES model in Section 4.5. We conclude from Subsection 2.3.3, that there is a lack in capacity reserved for the intake and new patient types (insufficient number of available slots). Consequently, the access time is increasing. The model also shows this behaviour. Furthermore, the waiting time for the colonoscopy are similar to the realized waiting time for colonoscopy. Although DES is assumed to be validate based on these observations, we remark some limitations with regard to the DES.

- No patient-to-doctor allocation. In practice, patients may have doctor preferences. Consequently, the access or waiting time for endoscopies may be higher for these specific patients. Our DES does not take account that into account, since we schedule patients based on the total weekly number of available appointment slots.
- FIFO queuing principle. Each patient is treated based on a FIFO principle. However, in reality, other scheduling rules may be used for specific patients. Other scheduling rules might result in lower or higher access or waiting time for endoscopies, depending on the applied scheduling rule.
- In the DES, we assume that rescheduling of consultation or endoscopy blocks does not occur. In reality, it might occur that consultation- or endoscopy blocks are rescheduled in order to decrease the access- or waiting time. However, we remark that if blocks are rescheduled it might result in an increasing access- or waiting time for endoscopies later in time due to queueing effects.

A Problem cluster

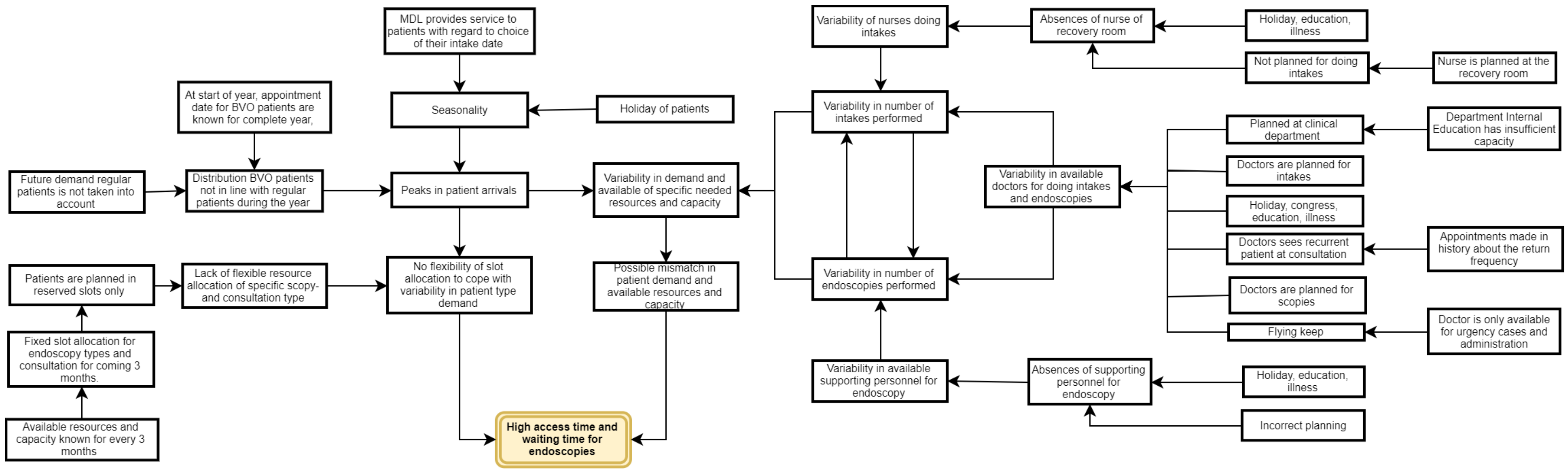


Figure 13: Problem cluster

B Queueing Model

The objective of the queueing model is to determine the expected access and waiting time given a number of arrivals and given a number c of appointment slots, where c is bounded from above by the maximum capacity J in a week. Let $N_{w,p}$ be the number of patient type p in the system at the beginning of week w.

For $j > 0$ and $j \leq C$, the probability of $N_{w,p}$ is calculated:

$$\pi_{j,p} = \pi_{j-1,p}\frac{\lambda_{w,p}}{j} \tag{13}$$

and for $j > C$:

$$\pi_{j,p} = \pi_{j-1,p}\frac{\lambda_{w,p}}{C} \tag{14}$$

Where $\lambda_{w,p}$ is the arrival rate of type p patients in week w. j denotes the number of type p patients in the system in week w. The stationary distribution of $N_{w,p}$ is obtained by solving $\pi\mathbf{P} = \pi$, $\sum_w \pi_w = 1$ and $\sum_w \lambda_{w,p} \leq \sum_w c_{w,p}$ $\forall p$ otherwise the queueing model is unstable.

Let $c_{w,y}(y) = \sum_{i=1}^{y} c_{w+i,p}$ be the total number of appointments slots for patient type p in the period from week $w + 1$ till week $w + y$, where $y \leq 8$ (weeks in planning horizon).

For each week w and for each patient type p, we calculate the expected access time by using Equation 15.

$$E(AT_{w,p}) = \sum_{y=1}^{8} \sum_{j=c_w(y)}^{c_{w(y+1)}-1} y\pi_j \tag{15}$$

For each possible number of arrivals of type p patients and for each possible number of appointment slots for patient type p, Equation 15 determines the corresponding access and waiting time for endoscopies which are used as input for the MIP.

C Warmup length - simulation model

For each yearly block schedule, we determine the warm up length. We only show the graphs of the warm up length for one block schedule, since each block schedule has the same warm up length. Furthermore, for overview purpose, we only show the patient types that requires the longest warm up length.

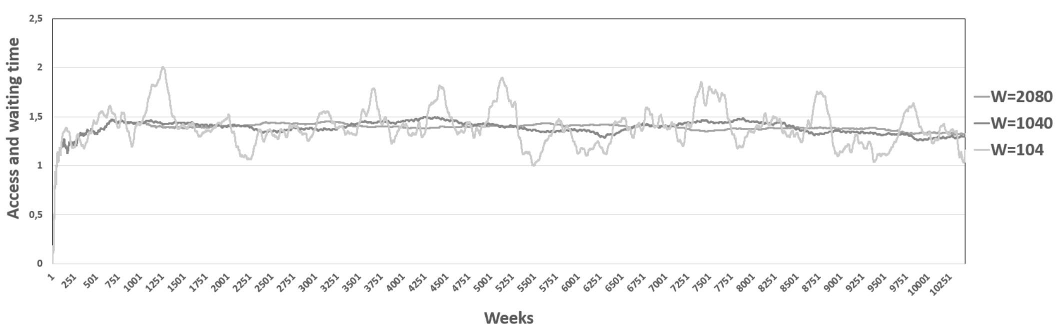


Figure 14: Warmup for patient type new in DES

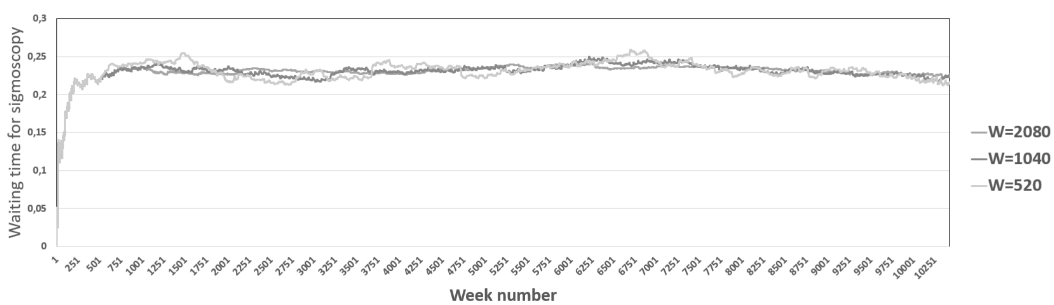


Figure 15: Warmup for patient type sigmoscopy in DES

D Data gathering

This appendix shows the data gathering process. We explain the distribution of the arrivals in Section D.1. The service times used in this research are found in Section D.2. We elaborate on the delay of patients in Section D.3.

D.1 External arrival rates

In total, there are six patient types where external arrivals occur. We determine the arrival distributions for each of these patient types based on six year historic data of DZ. We do not differentiate between parts of a year (e.g, seasonality), since we are able to plot one arrival distribution per patient type. We perform a goodness-of-fit test using the arrival distribution of each patient type. The H_0 hypothesis of the test is that the arrival distributions are a good representation of the underlying historic arrival data. We conclude from the test that we must accept H_0 with a significance level of 95%.

Table 18: External arrival distribution per patient type

Patient type	**Distribution**	**Parameters**				
		$\bar{x}$	s^2	s	α	β
Intake	Normal	41.5	123.7	11.1		
New	Normal	27.3	100	10		
Emergency consultation	Normal	12.1	19.8	4.5		
Emergency endoscopy	Weibull	6.1	12.9	3.6	1.83	6.76
Sigmoscopy	Gamma	8.7	17.6	4.2	4.29	2.02
Gastroscopy	Normal	28.2	61.7	7.9		

D.2 Service times

The current practice is that no time registrations takes place during any of the appointments. Therefore, we assume that the actual service time for an appointment is equal to the reserved time according to the schedule. Table 19 shows the reserved time per appointment type.

Table 19: Service times per patient type

Consultation	**Duration**		**Endoscopy**	**Duration**
Intake	5 min.		colonoscopy	45 min.
New	30 min.		NS colonoscopy	45 min.
Recurrent	10 min.		Gastroscopy dormicum	15 min.
Emergency	30 min.		Gastroscopy	15 min.
Telephone	5 min.		Endo-echo	15 min.
NS-intake	5 min.		Emergency	30 min.
			Sigmoscopy	15 min.
			ERCP	60 min.

D.3 Delay of the patients

At MDL, patients are not directly entering the next queue after they had their appointment. There is a delay time between subsequent appointments. The delay time can be defined by using two different approaches.

1. Time between the first appointment date and the subscription date of the next appointment;
2. Time between the first appointment date and second appointment date;

The first approach takes the time between the first appointment date on t and the subscription date of the next appointment on $t + x$. The subscription date is the date at which the next appointment is made. In this case, the patient joins the queue for the next appointment.

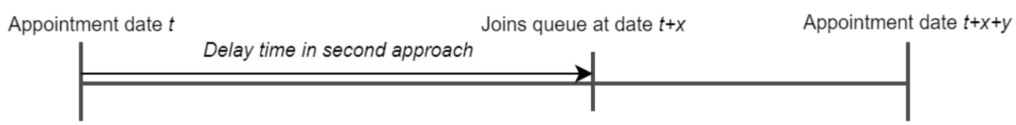


Figure 16: Queue at subscription date

The second approach defines the delay time as the time between two subsequent appointment. This yields an overestimation of the waiting time, since the patient joins the queue at the date of the second appointment.

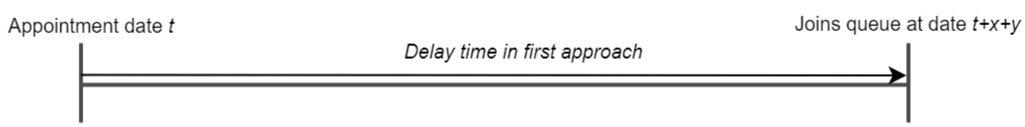


Figure 17: Queue at second appointment date

We use the first approach. We define the delay time as the time between the first appointment date and the subscription date of the next appointment. However, we use a fixed number for the delay which might reduce the variability of internal patient flow.

E Linear Approximation

In our original model from Subsection 4.4, we use binary variables $X_{w,p,c}$, $Y_{w,p,a}$ and $Z_{w,p,a,c}$ to linearize our original non linear model. Where $X_{w,p,c}$ denotes the number of scheduled appointment slots for patient type p in week w. $Y_{w,p,a}$ denotes the number of arrivals of patient type p in week w. Binary variable $Z_{w,p,a,c}$ denotes the number of scheduled of appointment slots equal to c for patient type p in week w given that the number of arrivals of patient type p in week w is a. We introduce the following set of constraints.

Only one column may be chosen for each patient type p and for each week w. A column corresponds with a certain number of scheduled appointment slots equal to c.

$$\sum_c X_{w,p,c} = 1 \quad \forall w, p \tag{16}$$

Only one row may be chosen for each patient type p and for each week w. A row corresponds with a certain number of arrivals equal to a.

$$\sum_a Y_{w,p,a} = 1 \quad \forall w, p \tag{17}$$

We may only choose one row and column in matrix Z. Index (a, c) denotes 1 if a is the number of arrivals and c is the number of scheduled appointment slots for each patient type p and for each week w.

$$Z_{w,p,a,c} = \sum_c X_{w,p,c} + \sum_a Y_{w,p,a} - 1 \quad \forall w, p, a, c \tag{18}$$

$$\sum_{a,c} Z_{w,p,a,c} = 1 \quad \forall w, p \tag{19}$$

The objective function of the original model depends on the number of scheduled appointment slots and the number of arrivals with a non linear relationship, shown in Figure 18.

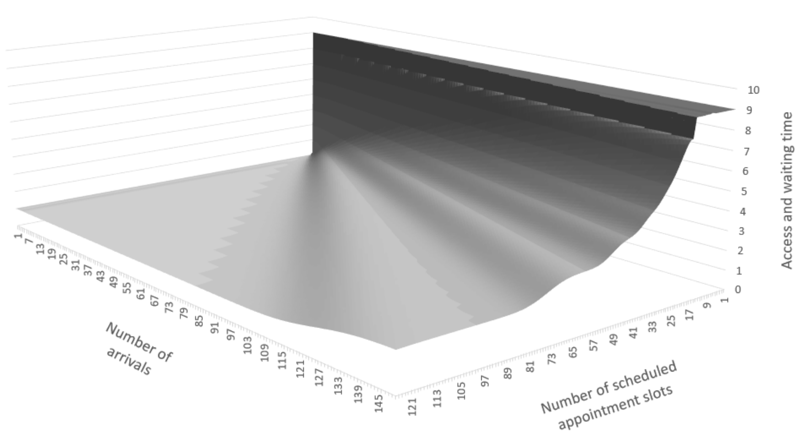


Figure 18: Non linear function

We allow internal transitions in our original model, e.g, transitions from colonoscopy to recurrent appointment slots. Consequently, the number of arrivals depends on the number of scheduled appointment slots at earlier point in time. This implies that the number of integers for binary variable $Z_{w,p,a,c}$ only for one week and for one patient type is already 15625 ($125 \cdot 125$, equal to the dimensions of Z). The computation time increases significantly due to this fact. Therefore, we choose to use linear approximation to linearize the objective function.

E.1 Linearization of the objective function

In Subsection 4.4.1, we conclude that the original model is not solvable within reasonable amount of time. The original model uses a matrix with dimensions equal to the Cartesian product of $|A|$ and $|C|$. For each arrival number a, we know the expected access and waiting time given the number of scheduled appointment slots equal to c. We choose to use an iterative linear approximation approach in which we use an initial solution to solve a new MIP.

We define an arrival bin as an aggregation of arrivals within a certain range. Let k_i be the number of arrival bins used in iteration i. We assume that the number of arrivals are evenly distributed among the bins. For example, for $k_i = 2$, we take the average access and waiting time per appointment slot c for arrivals within the range $[0; 62]$ and within the range $[63; 125]$. For iteration $i = 1$, we do not make a distinction in the number of arrivals a, this means that $k_1 = 1$. At the end of each iteration, we set $k_{i+1} := k_i + 1$ which means that we increase the number of arrival bins with one for the next iteration. We choose to increase with one, since this improves the computation time. For each iteration, we use the solution of iteration i as initial solution for iteration $i + 1$. The iterations continues until the weekly number of scheduled of blocks convergences, because in that case values of $C_{w,p}$ and $A_{w,p}$ are stabilized. After the iterations, we convert the associated access and waiting time using our Queueing Model from Subsection 4.4. Figure 19 shows the flowchart of the iterative linear approximation.

E.2 Finding the breakpoints

We have to find breakpoints in order to apply piece-wise linear functions. We define $k_i = i$ as the number of arrival bins in iteration i, where arrivals $a \exists k_i$. For each k_i, we define a new set of piece-wise linear function where the function depends on the number of arrivals equal to $a \exists k_i$. Let the piece-wise linear function have the form $f_{k_i,n}(c) = t_{k_i,n}c + b_{k_i,n}$, where $t_{k_i,n}$ is the tangent of the n^{th} breakpoint. We determine $t_{k_i,1}$, $t_{k_i,2}$, $b_{k_i,1}$ and $b_{k_i,2}$ using the solver of Excel. The objective of the Solver is to minimize the squared difference between the linear functions and the non-linear function.

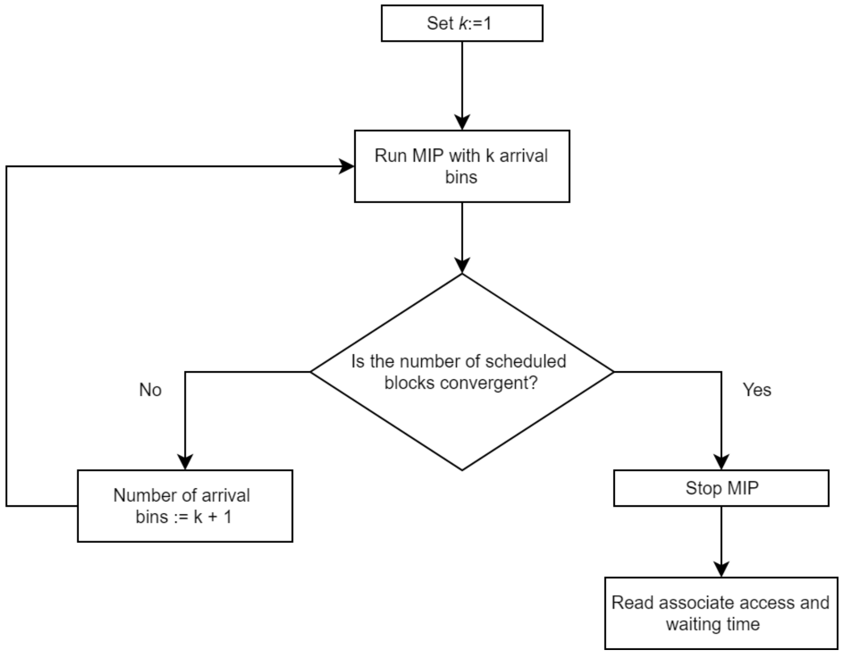


Figure 19: Flowchart of iterative linear approximation

We define $b_{k_i,n}$ as the intersection point for each piece-wise linear function k_i. We already know $b_{k_i,3}$ for each arrival bin k_i which is equal to 1, since the minimum access and waiting time is one week. We determine the intersection points for $b_{k_i,1}$ and $b_{k_i,2}$, for each piece-wise linear function by solving the system of equations.

For each k_i, we have the following piece-wise linear functions used for each iteration i.

$$f_{k_1}(x) = \begin{cases} -0.234x + 9 & , 0 \leq x \leq 30 \\ -0.012x + 2.6 & , 30 < x \leq 125 \end{cases}$$

$$f_{k_2}(x) = \begin{cases} -0.683x + 9 & , 0 \leq a \leq 62, \quad 0 \leq x \leq 11 \\ -0.004x + 1.4 & , 0 \leq a \leq 62, \quad 11 < x \leq 125 \\ -0.176x + 9 & , 63 \leq a \leq 125, \quad 0 \leq x \leq 38 \\ -0.0156x + 2.9 & , 63 \leq a \leq 125, \quad 38 < x \leq 125 \end{cases}$$

$$f_{k_3}(x) = \begin{cases} -0.813 + 9 & , 0 \leq a \leq 39, \quad 0 \leq x \leq 9 \\ -0.006x + 1.6 & , 0 \leq a \leq 39, \quad 9 < x \leq 125 \\ -0.294x + 9 & , 40 \leq a \leq 79, \quad 0 \leq x \leq 24 \\ -0.0116x + 2.1 & , 40 \leq a \leq 79, \quad 24 < x \leq 125 \\ ..... & , 80 \leq a \leq 125, \quad 0 \leq x \leq 40 \\ ..... & , 80 \leq a \leq 125, \quad 40 < x \leq 125 \end{cases}$$

For overview purposes, we do not show every piece-wise linear function. However, for the remaining k_i arrival bins, the same reasoning goes as shown above.

The value functions of k_1 and k_2 are shown in Table 20 and 21. Again, for overview purposes, we only show these two value functions.

Table 20: Value function of k_1

n	b_{k_1}, n	$y_{k_1,n}$
1	0	9
2	30	2.2
3	125	1

Table 21: Value function of k_2

	$a = [0; 62]$		$a = [63; 125]$	
n	b_{k_2}, n	$y_{k_2,n}$	b_{k_2}, n	$y_{k_2,n}$
1	0	9	0	9
2	11	1.48	38	2.31
3	125	1	125	1

Figure 20 shows the plot of the piece-wise linear function for k_1.

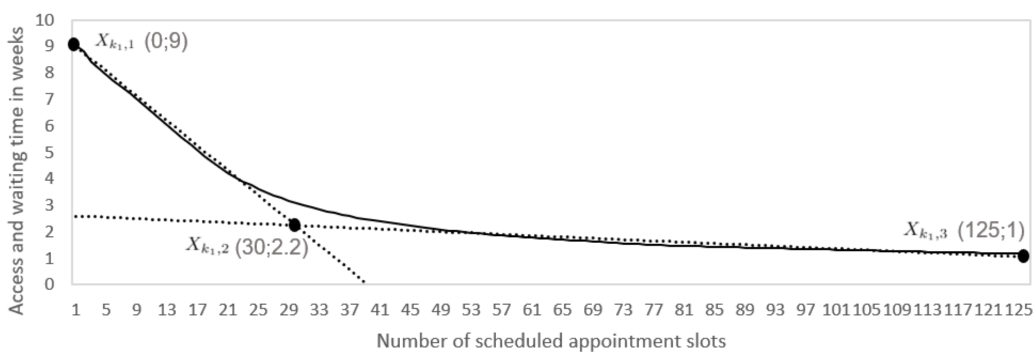


Figure 20: Piece-wise linear function of k_1

E.3 Modelling the piece-wise linear functions

We have to make the following adjustments in the AIMMS in order to apply piece-wise linear functions. Let set n be the beginnings and endings of each piece-wise interval. Let set a be the set of arrivals and let k_i be the number of arrivals bins where $a \exists k_i$. Let $b_{a,n}$ denote the x-value of the n^{th} breakpoint for arrival a and let $y_{a,n}$ be the value function of the n^{th} breakpoint for arrival a. Let $p_{a,n}$ denote non-negative weights for each n^{th} interval for each arrival a summing to unity.

We formulate the following constraints, in addition to the constraints from Section 4.4. We model the weights by means of SOS2-constraints in AIMMS.

$$\sum_n p_{w,p,a,n} = y(w,p,a) \qquad \forall w,p,a \tag{20}$$

Recall that binary variable $y_{w,p,a}$ denotes 1 if the number of arrivals in week w is equal to a.

Given the number of appointment slots for patient type p, we can calculate the value for $p_{w,p,a,n}$

$$\sum_n p_{w,p,a,n} \cdot b_{w,p,a,n} = \sum_c c \cdot X_{w,p,c} \qquad \forall w,p \tag{21}$$

We read the associate access and waiting time for any given value of $p_{w,p,a,n}$

$$\sum_n p_{w,p,a,n} \cdot y_{w,p,a,n} = f_{w,p,a} \qquad \forall w,p,a \tag{22}$$

F Documentation of the simulation model

This appendix contains the documentation of the simulation model.

F.1 Process flow

This subsection contains the process flow within the simulation model.

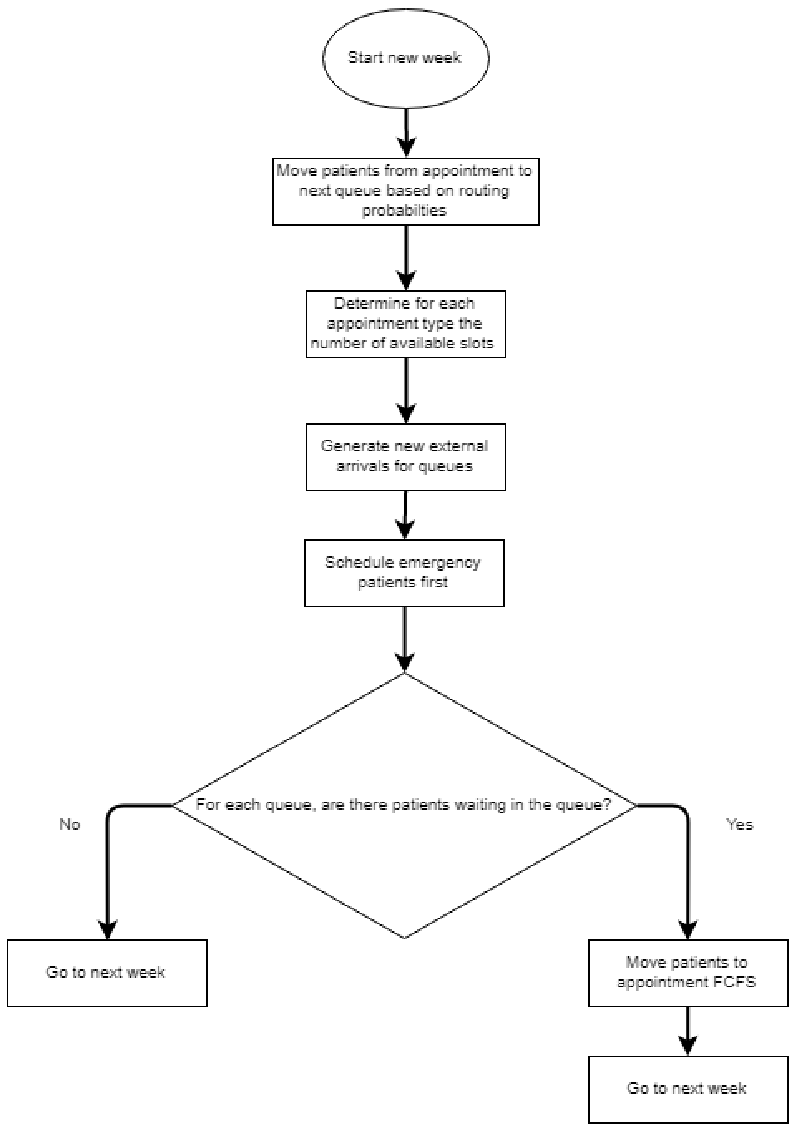


Figure 21: Flowchart of the simulation model

For each week, we first move each patient to the queue of the next appointment based on the routing probabilities. In this process, the patient gets a subscription date which is equal to the week number at which he joins the next queue. After that, we determine the number of slots available for each patient type based on the used block schedule from Subsection F.3.

We first schedule the emergency patients. If the total number of emergency slots are all in use, then the emergency patients are scheduled in the NP-slots. This is a scheduling rule that is used at the MDL department. After this, we schedule all other patients. Each patient gets an appointment date if he moves to the appointment. The appointment date is equal to the week number at which he moves to his appointment.

F.2 Assumptions

In the simulation model, we make the following assumptions to reduce the complexity of the model.

1. Each patient is treated based on a FIFO principle.
2. Rescheduling of consultation or endoscopy blocks does not occur.
3. We do not model the scheduling of patients on daily basis. External and internal arrivals occur at the start of the week and patients are scheduled at the start of the week.
4. We do not model no-show of patients.
5. Absence of doctors due to illness is not modelled.
6. We express the service rate in terms of weekly number of slots available per patient type.

F.3 In and output data

In this subsection, we describe the in and output data that is used in our simulation model.

Input data
We use external arrivals as shown in Appendix D. Each appointment type is modelled as a queue and the routing probability from queue i to queue j is based on historic data from DZ. The probability distribution of the delay (in weeks) is also based on historic data of DZ. The weekly number of available slots for each patient type depends on the weekly number of scheduled consultation or endoscopy blocks. The weekly number of scheduled blocks is the outcome of the MIP from Phase 2.

Output data
The weekly access and waiting time for endoscopies is output data from the simulation model. In our simulation model, we express the access and waiting time for endoscopies as the time between the appointment data and the subscription date. Furthermore, we define the slot utilization of each appointment type. We define the weekly slot utilization as the fraction of the total weekly number of appointment type i slots that is used for patient type i.

F.4 Experiments

From the MIP of Phase 2, we obtain for each holiday roster, 5 different block schedules. We use the simulation model to obtain weekly performances of the access and waiting time for endoscopies for each block schedule. Furthermore, we determine the robust to incorporate stochasticity in the weekly number of patient arrivals, delay of the patients and the routing.

F.5 Warmup and number of replications

The reader is referred to Subsection 5.2 for the warm up length and the number of replications.

F.6 Validation and verification

In this subsection, we describe the validation and verification process during the development of the simulation model.

Validation
The output of the simulation model is validated by the department. Furthermore, as stated in Subsection1.2, there is insufficient slot capacity for the intake and new patient types to meet the demand. The simulation model shows this behaviour, since it never reach steady state for these patient types. The waiting time for colonoscopy is similar in both the simulation model and the actual realized waiting time for colonoscopy. Therefore, we conclude that the DES is a valid representation of the MDL department. With regard to the NS-patients, scheduling rules are formulated and validated by the department.

Verification
During the development of the simulation model, we use the debugger within Plant Simulation to verify if the model works as we wants. This verification entails: routing of patients, delay of patients, generation of external patient arrivals and moving patients to their next appointment. For the calculation of the access and waiting time for endoscopies, we increase the number of arrivals on purpose to see if the access and waiting time behaves as expected.

G Weekly available doctor capacity

This appendix shows the three different holiday rosters that is used as input for the MIP in Phase 2.

Table 22: Holiday roster used as input for the MIP

Week	**1**	**2**	**3**	**Week**	**1**	**2**	**3**
1	8	8	8	27	16	16	16
2	20	20	20	28	16	16	8
3	20	20	20	29	12	12	8
4	20	20	20	30	12	12	8
5	16	12	16	31	16	16	20
6	16	20	16	32	8	8	16
7	16	12	16	33	8	8	16
8	16	20	16	34	8	8	12
9	20	20	20	35	20	20	12
10	16	16	16	36	20	20	20
11	8	8	8	37	12	12	12
12	14	14	14	38	12	12	12
13	20	20	20	39	16	16	16
14	20	20	20	40	8	8	8
15	20	20	20	41	20	20	20
16	20	20	20	42	12	12	12
17	20	20	20	43	16	16	16
18	8	8	8	44	16	16	16
19	16	16	16	45	16	16	16
20	20	20	20	46	20	20	20
21	20	20	20	47	17	17	17
22	20	20	20	48	20	20	20
23	20	20	20	49	16	16	16
24	16	16	16	50	17	17	17
25	20	20	20	51	12	12	12
26	20	20	20	52	4	4	4

H Performance of all block schedules

This appendix shows the performances of all block schedules of each holiday roster.

Performances of the block schedules of holiday roster 1

	x				
Patient type	1	2	3	4	5
Intake	1.84	1.85	1.85	1.84	1.84
New	2.77	2.82	2.59	2.73	2.77
Emergency	0.02	0.02	0.02	0.02	0.02
Recurrent	1.91	1.91	1.91	1.91	1.91
Telephone	0.95	0.96	0.96	0.96	0.95
colonoscopy	1.83	1.82	1.84	1.84	1.83
Sigmoscopy	1.88	1.89	1.88	1.86	1.88
Gastroscopy	1.82	1.84	1.84	1.84	1.82
Endo-echo	0.99	0.98	0.99	0.99	0.99
ERCP	0.97	0.95	0.97	0.97	0.97
Emergency	0.10	0.09	0.09	0.08	0.10
Gastro narcosis	1.94	1.95	1.96	1.95	1.94

	σ				
Patient type	1	2	3	4	5
Intake	0.19	0.18	0.18	0.19	0.19
New	0.62	0.62	0.60	0.62	0.62
Emergency	0.14	0.14	0.14	0.14	0.14
Recurrent	0.22	0.22	0.21	0.21	0.22
Telephone	0.13	0.13	0.12	0.13	0.13
colonoscopy	0.14	0.14	0.13	0.14	0.14
Sigmoscopy	0.11	0.10	0.10	0.11	0.11
Gastroscopy	0.21	0.21	0.20	0.21	0.21
Endo-echo	0.04	0.04	0.04	0.04	0.04
ERCP	0.07	0.06	0.06	0.06	0.07
Emergency	0.18	0.18	0.17	0.18	0.18
Gastro narcosis	0.09	0.09	0.09	0.09	0.09

	Utilization				
Patient type	1	2	3	4	5
Intake	76.7%	74.8%	75.0%	75.4%	76.7%
New	97.0%	97.3%	94.6%	96.6%	97.0%
Emergency	96.6%	97.0%	94.4%	96.3%	96.6%
Recurrent	64.8%	69.1%	60.4%	63.9%	64.8%
Telephone	51.1%	49.9%	50.1%	51.0%	51.1%
colonoscopy	75.0%	74.1%	74.5%	74.3%	75.0%
Sigmoscopy	79.8%	78.8%	80.0%	80.2%	79.8%
Gastroscopy	76.3%	75.8%	76.1%	75.5%	76.3%
Endo-echo	45.7%	58.2%	44.1%	46.5%	45.7%
ERCP	54.7%	71.6%	53.0%	54.1%	54.7%
Emergency	68.7%	67.5%	67.2%	68.3%	68.7%
Gastro narcosis	68.4%	66.2%	68.6%	68.4%	68.4%

Performances of the block schedules of holiday roster 2

	x				
Patient type	1	2	3	4	5
Intake	1.83	1.84	1.84	1.84	1.85
New	2.74	2.61	2.58	2.81	2.70
Emergency	0.02	0.02	0.02	0.02	0.02
Recurrent	1.90	1.91	1.90	1.90	1.90
Telephone	0.94	0.94	0.95	0.94	0.94
colonoscopy	1.80	1.93	1.84	1.77	1.81
Sigmoscopy	1.86	1.88	1.85	1.84	1.87
Gastroscopy	1.85	1.84	1.84	1.85	1.85
Endo-echo	0.99	0.99	0.99	0.99	0.99
ERCP	0.97	0.97	0.97	0.97	0.97
Emergency	0.10	0.06	0.11	0.11	0.11
Gastro narcosis	1.93	1.96	1.96	1.92	1.95

	σ				
Patient type	1	2	3	4	5
Intake	0.18	0.18	0.18	0.18	0.17
New	0.61	0.59	0.60	0.60	0.59
Emergency	0.13	0.13	0.13	0.13	0.12
Recurrent	0.21	0.21	0.21	0.21	0.20
Telephone	0.13	0.13	0.13	0.13	0.12
colonoscopy	0.11	0.11	0.11	0.11	0.11
Sigmoscopy	0.11	0.11	0.11	0.11	0.11
Gastroscopy	0.21	0.21	0.21	0.21	0.19
Endo-echo	0.02	0.02	0.02	0.02	0.02
ERCP	0.06	0.06	0.06	0.06	0.05
Emergency	0.17	0.16	0.16	0.17	0.15
Gastro narcosis	0.19	0.18	0.18	0.18	0.17

	Utilization				
Patient type	1	2	3	4	5
Intake	76.8%	76.8%	76.8%	76.3%	76.5%
New	94.8%	95.1%	96.2%	95.6%	95.4%
Emergency	94.1%	94.6%	95.5%	95.3%	94.6%
Recurrent	75.6%	73.9%	80.6%	78.7%	79.8%
Telephone	50.0%	51.1%	51.5%	51.5%	51.6%
colonoscopy	75.8%	76.5%	75.9%	75.5%	77.0%
Sigmoscopy	79.8%	81.0%	80.2%	79.5%	80.6%
Gastroscopy	74.3%	75.4%	75.7%	74.9%	75.5%
Endo-echo	44.0%	44.9%	44.7%	44.4%	45.2%
ERCP	50.5%	51.4%	53.4%	51.1%	52.7%
Emergency	67.6%	61.3%	69.8%	70.1%	69.5%
Gastro narcosis	82.3%	82.0%	82.9%	81.2%	69.2%

Performances of the block schedules of holiday roster 3

	x				
Patient type	1	2	3	4	5
Intake	1.84	1.83	1.83	1.83	1.84
New	2.68	2.63	2.71	2.74	2.69
Emergency	0.02	0.02	0.02	0.02	0.02
Recurrent	1.90	1.90	1.90	1.91	1.91
Telephone	0.95	0.95	0.93	0.93	0.95
colonoscopy	2.58	1.96	1.86	1.87	1.84
Sigmoscopy	1.87	1.86	1.86	1.86	1.86
Gastroscopy	1.85	1.86	1.86	1.85	1.85
Endo-echo	1.99	0.99	0.99	0.99	0.99
ERCP	1.97	0.96	0.97	0.96	0.97
Emergency	0.11	0.11	0.09	0.12	0.11
Gastro narcosis	1.93	1.89	1.89	1.88	1.91

	σ				
Patient type	1	2	3	4	5
Intake	0.17	0.17	0.17	0.17	0.17
New	0.55	0.53	0.54	0.55	0.55
Emergency	0.13	0.13	0.14	0.13	0.13
Recurrent	0.21	0.22	0.22	0.22	0.22
Telephone	0.12	0.12	0.13	0.12	0.13
colonoscopy	0.15	0.14	0.14	0.15	0.14
Sigmoscopy	0.11	0.11	0.12	0.11	0.11
Gastroscopy	0.21	0.20	0.21	0.20	0.20
Endo-echo	0.03	0.03	0.03	0.03	0.03
ERCP	0.06	0.06	0.06	0.06	0.06
Emergency	0.19	0.18	0.19	0.19	0.19
Gastro narcosis	0.09	0.09	0.09	0.10	0.10

	Utilization				
Patient type	1	2	3	4	5
Intake	76.6%	76.1%	76.0%	75.3%	75.9%
New	95.7%	95.1%	94.3%	94.9%	95.7%
Emergency	95.4%	94.9%	94.9%	95.2%	94.9%
Recurrent	64.8%	66.8%	69.1%	72.4%	64.0%
Telephone	50.8%	50.1%	50.4%	50.4%	50.5%
colonoscopy	74.2%	74.1%	74.0%	73.3%	74.1%
Sigmoscopy	78.4%	80.2%	79.5%	79.7%	78.6%
Gastroscopy	74.5%	74.4%	74.8%	74.6%	75.5%
Endo-echo	43.9%	43.0%	44.9%	45.4%	45.1%
ERCP	53.3%	52.2%	52.9%	52.6%	53.1%
Emergency	68.9%	69.9%	68.9%	71.1%	68.9%
Gastro narcosis	98.0%	95.7%	96.9%	95.0%	79.7%

I Slot utilization of chosen block schedules

DES shows that the average intake slot utilization in week 24 is 50%. In this appendix, we visualize the average intake slot utilization for the complete year in Figure 22. Furthermore, we compare the weekly intake slot utilization with the weekly number of scheduled consultation blocks.

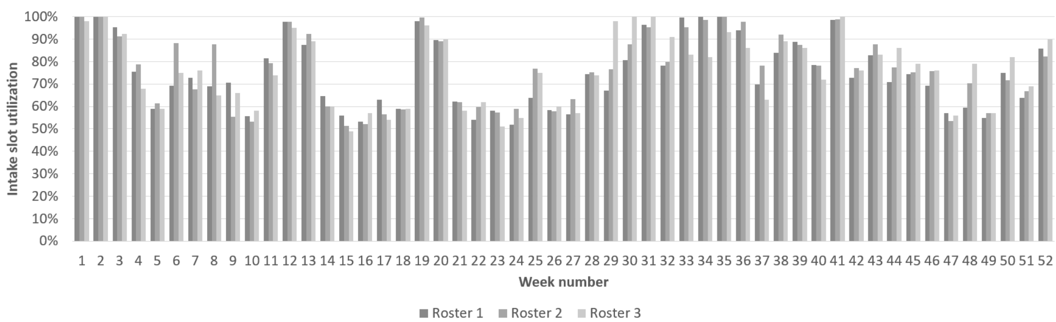


Figure 22: Average intake slot utilization per week for each chosen block schedule

The deviations in the average intake slot utilization is explained by the timing of holidays. For example, in week 29, 30 and 31 we see that the average intake slot utilization for roster 3 is higher than roster 1 and 2. This is caused by different holiday scenarios defined for the summer holidays. In periods where the weekly number of available doctor days is the same for each holiday roster, we see that the average intake slot utilization is also the same. The low slot utilization during the period from week 14-18, week 21-27, 47-51 can be explained the weekly number of scheduled consultation blocks, shown in Figure 23

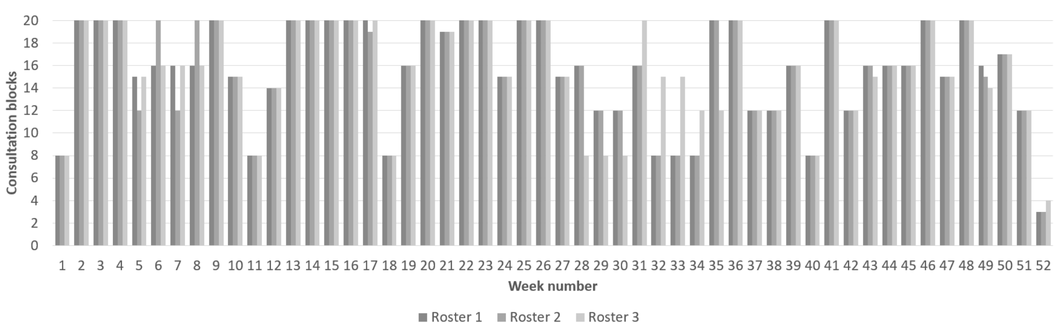


Figure 23: Number of scheduled consultation blocks for each chosen block schedule

The low intake slot utilization is caused by periods in which the weekly number of scheduled consultation blocks is equal to 20. This means that the total available number of intake appointment slots is equal to 80 (20 times the average number of intake slots in a consultation block). Furthermore, we know that the average weekly intake arrivals is equal to 41, see Appendix D. Consequently, for these weeks, there is a probability that intake slots are not filled which results in a low intake slot utilization.

J Complete base roster

Table 23: Block schedules from week 1 till week 26

	Schedule 1		**Schedule 2**		**Schedule 3**	
Week	Consultation	Endoscopy	Consultation	Endoscopy	Consultation	Endoscopy
1	8	8	8	8	8	8
2	20	20	20	20	20	20
3	20	20	20	20	20	20
4	20	20	20	20	20	20
5	15	17	12	12	15	17
6	16	16	20	20	16	16
7	16	16	12	12	16	16
8	16	16	20	20	16	16
9	20	20	20	20	20	20
10	16	16	15	17	15	17
11	8	8	8	8	8	8
12	14	14	14	14	14	14
13	20	20	20	20	20	20
14	20	20	20	20	20	20
15	20	20	20	20	20	20
16	19	21	20	20	20	20
17	20	20	19	21	20	20
18	8	8	8	8	8	8
19	16	16	16	16	16	16
20	20	20	20	20	20	20
21	20	20	19	21	19	21
22	20	20	20	20	20	20
23	20	20	20	20	20	20
24	15	17	15	17	15	17
25	20	20	20	20	20	20
26	20	20	20	20	20	20

Table 24: Block schedules from week 27 till week 52

	Schedule 1		**Schedule 2**		**Schedule 3**	
Week	Consultation	Endoscopy	Consultation	Endoscopy	Consultation	Endoscopy
27	15	17	15	17	15	17
28	16	16	16	16	8	8
29	12	12	12	12	8	8
30	12	12	12	12	8	8
31	16	16	16	16	20	20
32	8	8	8	8	15	17
33	8	8	8	8	15	17
34	8	8	8	8	12	12
35	20	20	20	20	12	12
36	20	20	20	20	20	20
37	12	12	12	12	12	12
38	12	12	12	12	12	12
39	16	16	16	16	16	16
40	8	8	8	8	8	8
41	20	20	20	20	20	20
42	12	12	12	12	12	12
43	16	16	16	16	15	17
44	16	16	16	16	16	16
45	16	16	16	16	16	16
46	20	20	20	20	20	20
47	17	17	15	19	15	19
48	20	20	20	20	20	20
49	15	17	15	17	14	18
50	17	17	17	17	17	17
51	12	12	12	12	12	12
52	3	5	3	5	4	4

K Comparison between the rosters and guidelines

This appendix shows the comparison between the rosters and the guidelines of the key performance indicators: slot utilization and standard deviation.

Table 25: Comparison of slot utilization of roster and corresponding guidelines

Patient type	**Roster 1**	**Guidelines 1**	**Roster 2**	**Guidelines 2**	**Roster 3**	**Guidelines 3**
Intake	75.0%	74.74%	76.8%	74.71%	75.9%	76.59%
New	94.6%	95.20%	96.2%	94.49%	95.7%	95.07%
Emergency	94.4%	94.82%	95.5%	93.63%	94.9%	95.34%
Recurrent	60.4%	60.19%	80.6%	81.92%	64.0%	62.38%
Telephone	50.1%	51.12%	51.5%	50.18%	50.5%	50.52%
colonoscopy	74.5%	74.28%	75.9%	73.56%	74.1%	74.64%
Sigmoscopy	80.0%	81.06%	80.2%	78.69%	78.6%	78.67%
Gastroscopy	76.1%	75.88%	75.7%	75.22%	75.5%	74.46%
Endo-Echo	44.1%	45.68%	44.7%	44.09%	45.1%	44.51%
ERCP	53.0%	53.12%	53.4%	52.64%	53.1%	49.12%
Emergency	67.2%	67.94%	69.8%	52.64%	68.9%	68.78%
Gastro narcosis	68.6%	82.51%	82.9%	82.13%	79.7%	82.23%

Table 26: Comparison of standard deviation of roster and corresponding guidelines

Patient type	**Roster 1**	**Guidelines 1**	**Roster 2**	**Guidelines 2**	**Roster 3**	**Guidelines 3**
Intake	0.18	0.18	0.18	0.19	0.17	0.18
New	0.60	0.64	0.60	0.60	0.55	0.49
Emergency	0.14	0.14	0.13	0.13	0.13	0.13
Recurrent	0.21	0.21	0.21	0.21	0.22	0.22
Telephone	0.12	0.13	0.13	0.11	0.13	0.10
colonoscopy	0.13	0.14	0.11	0.11	0.14	0.12
Sigmoscopy	0.10	0.11	0.11	0.12	0.11	0.12
Gastroscopy	0.20	0.20	0.21	0.20	0.20	0.20
Endo-Echo	0.04	0.03	0.02	0.02	0.03	0.02
ERCP	0.06	0.05	0.06	0.06	0.06	0.02
Emergency	0.17	0.18	0.16	0.13	0.19	0.19
Gastro narcosis	0.09	0.14	0.18	0.11	0.10	0.11

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