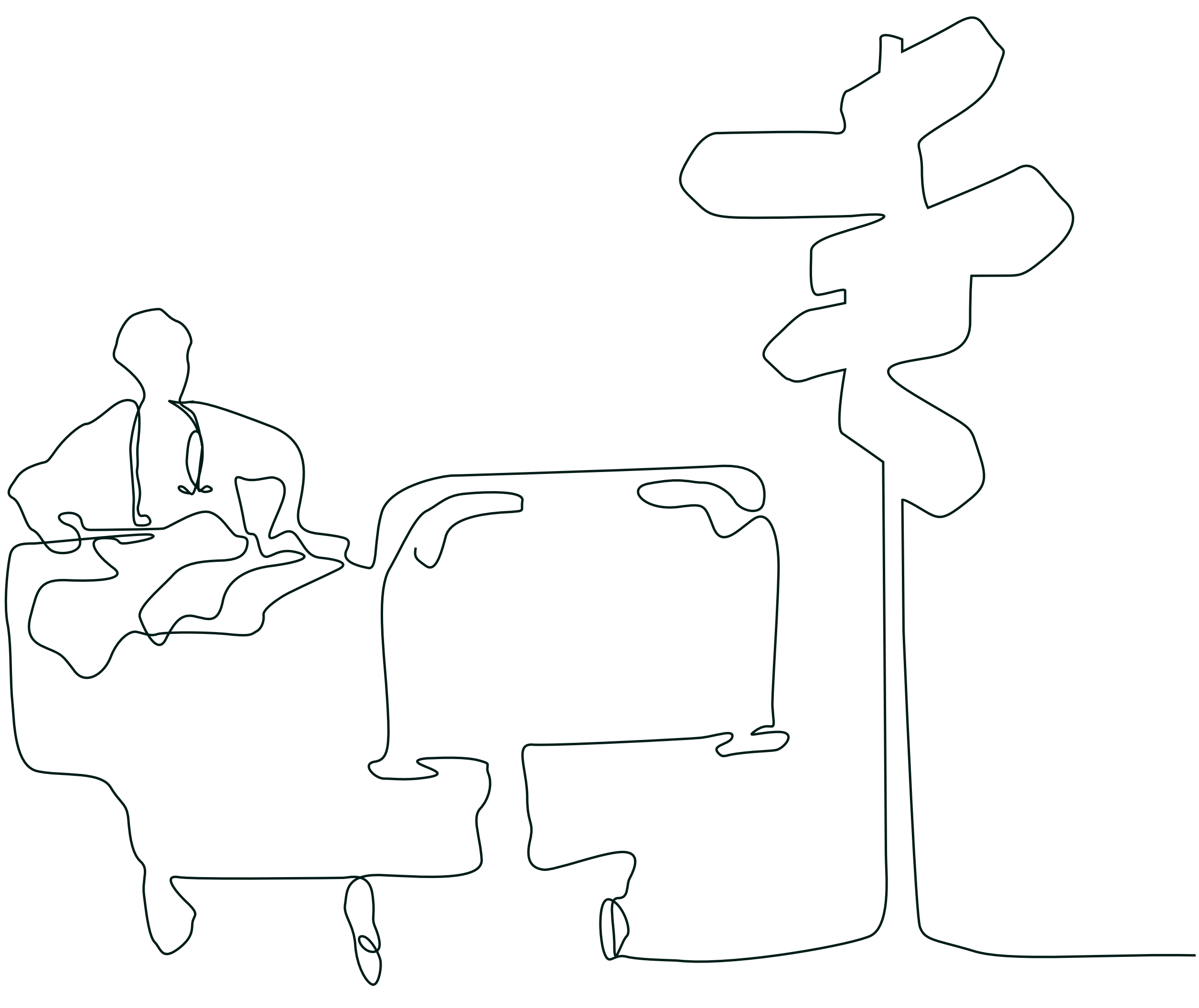
THE ASSIGNMENT OF CLINICAL DEPARTMENTS TO WARDS



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In collaboration with

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The assignment of clinical departments to wards

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Preface

This thesis is the result of my Industrial Engineering and Management graduation assignment, which I have been working on for the past seven months. This assignment gave me the opportunity to apply mathematics to a case study in Deventer Ziekenhuis. For me this was the perfect combination between abstract mathematics and adding value to society by optimizing healthcare processes.

There are a few people I would like to thank for their help and support during my graduation assignment. First of all, I want to thank the colleagues of Deventer Ziekenhuis. They offered me a warm welcome, but most of all they inspired me with their open, passionate and driven mindset. I also want to thank Twan. His advice but most of all his company made this project much more fun.

Deventer Ziekenhuis is an outstanding hospital regarding capacity management and I am very grateful that Machteld supervised me. She gave me insight in practical challenges. Thank you Machteld! Erwin and Gréanne, I would like to thank you for your supervision. During every meeting you showed me your trust in my research and that helped me to challenge myself. I really enjoyed working with you.

The beautiful front page of this thesis is created by my cousin Carlijn Philips. She helped me visualizing the integration and flexibility of healthcare processes which play an equally important role as the abstract mathematics. Thank you Carlijn!

Finally, I want to thank my friends and family. Special thanks for Frank, his care and professional LaTeX skills helped me to succeed this project and made this report look much more sophisticated, and for my parents, who gave me their unconditional support.

Enjoy reading my thesis!

Juliët
Deventer, October 2019

Abstract

General wards play a crucial role in hospitals. If no beds are available, no patients can be admitted. Elective admissions have to be postponed and emergency patients are sent to other hospitals. However, having a large number of available beds is inefficient. Hence it is important to limit discrepancy between the demand (patients requesting a bed) and the supply (available beds).

The assignment of clinical departments to wards influences this discrepancy. We identify a research gap: no model has been developed before that takes the distinction between single and shared rooms in wards into account and concentrates empty beds. However, both aspects are crucial when aiming to limit the discrepancy between demand an supply in general wards.

We present a first approach for assigning clinical departments to wards that takes the distinction between single and shared rooms into account and concentrates empty beds. In particular we consider a case study of Deventer Ziekenhuis (DZ).

Case study description

DZ aims to assign as many patients as possible to their preferred ward and at the same time use resources of wards efficiently. DZ aims to have a maximum blocking probability of 10%. However, currently [redacted]% of the clinical departments does not meet this standard. Partially this is caused by a high demand for single rooms.

Additionally, the management of DZ experiences changes in the arrival rate and length of stay of patients due to developments in medical treatment. The average length of stay for a hip replacement for example, decreased the past years due to new surgery methods. As a result the demand for beds per clinical department changes and this effects the bed occupancy of wards. Hence, the current assignment of clinical departments to wards needs to be evaluated.

In order to guarantee a maximum blocking probability of 10% and to respond to (future) trends, the assignment of clinical departments to wards is studied.

Approach

We propose a mixed integer linear program (MILP) to assign clinical departments to wards. This MILP uses the Erlang loss formula to determine the required number of beds per ward and takes the distinction between single and shared rooms and the variation in arrival rate into account. The objective of this MILP is to minimize the number of required beds given a maximum blocking probability, and maximize the fulfillment of preferences including the concentration of empty beds.

The MILP is successfully implemented in AIMMS and solved optimally using the CPLEX 12.8 solver. The computation time for extensive instances is less than five minutes.

Using the MILP, an optimal assignment is determined for six configurations. The configurations differ in preferences, arrival rate, length of stay or blocking probability in order to measure the effect of different input values.

Results

The optimal assignments for the six configurations show that insufficient capacity is available to guarantee a maximum blocking probability of 10% for all clinical departments. Assigning a clinical department to multiple wards or blocking a shared room to serve as a single room reduces the blocking probability and solves this problem.

The results also show that the fulfillment of proximity preferences related to wards in DZ can be improved by implementing one of the proposed optimal assignments. However, validation shows that adjustments are necessary, both to the model and to the data collection, in order to increase reliability of the results.

Value for science

To the best of our knowledge, we are the first to present a model for assigning clinical departments to wards that takes the distinction between single and shared rooms into account, concentrates empty beds and does not require a preprocessing step for taking the variation in arrival rate into account. This model can be solved optimally and the computation time is less than five minutes for extensive instances.

Value for practice

The Assignment Model proposed in this paper supports decision making in DZ. The model determines the required number of single and shared rooms given a maximum blocking probability. Additionally, the model determines an optimal assignment of clinical departments to wards with a minimum number of required beds given a maximum blocking probability, and a maximum fulfilment of proximity preferences. The results also showed the bottlenecks regarding the assignment of clinical departments to wards in DZ. DZ will use this insight when evaluating the assignment in general wards.

In DZ there is no consensus about the basic principles regarding the preferences and assumptions in general wards. Therefore DZ first has to formulate joint basic principles and make compromises. The proposed model can be used during this process as a supporting tool. For each of the proposed principles a corresponding optimal assignment can be determined.

The Assignment Model can also be applied to other care units in the hospital or even outside the area of healthcare. Examples are assignments of offices, school classes and chocolate bars.

Management samenvatting

Het Deventer Ziekenhuis (DZ) ervaart **een stijgende discrepantie tussen het aantal benodigde bedden en het aantal beschikbare bedden op verpleegafdelingen**. Het verminderen van deze discrepantie is van groot belang om de zorg toegankelijk en betaalbaar te houden.

De toewijzing van specialismen aan verpleegafdelingen beïnvloedt deze discrepantie. Als de vraag naar bedden op een verpleegafdeling groter is dan het aanbod, kunnen patiënten niet worden opgenomen op hun voorkeursafdeling. Als het aanbod van bedden op een verpleegafdeling groter is dan de vraag, worden verpleegkundigen inefficiënt ingezet.

De volgende vraag staat centraal in deze casestudy:

Wat is de optimale toewijzing van specialismen aan verpleegafdelingen in DZ?

We presenteren als eerste een aanpak voor het toewijzen van specialismen aan verpleegafdelingen waarbij rekening wordt gehouden met het onderscheid tussen een- en meerpersoonskamers en de concentratie van lege bedden. De resultaten van deze casestudy ondersteunen DZ bij de strategische besluitvorming omtrent verpleegafdelingen.

Omschrijving casestudy

DZ heeft op dit moment vijf algemene verpleegafdelingen in gebruik en maakt onderscheid tussen 23 specialismen. Elk specialisme is toegewezen aan één verpleegafdeling, dit is de voorkeursafdeling. DZ streeft er naar om zo min mogelijk patiënten te weigeren op hun voorkeursafdeling en tegelijkertijd middelen efficiënt te gebruiken. DZ streeft naar een maximale weigerkans van 10%. **Momenteel voldoet [redacted]% van de specialismen echter niet aan deze norm.** Gedeeltelijk wordt dit veroorzaakt door een grote vraag naar eenpersoonskamers.

Om een maximale weigerkans van 10% te garanderen en te reageren op (toekomstige) trends in aankomstfrequentie en ligduur van patiënten, wordt de toewijzing van specialismen aan verpleegafdelingen onderzocht.

Aanpak

We stellen een gemengd geheeltallig lineair programma (MILP) op om de optimale toewijzing van specialismen aan verpleegafdelingen te bepalen. Dit MILP gebruikt de Erlang-verliesformule om het benodigde aantal bedden per verpleegafdeling te bepalen. De opgestelde MILP maakt onderscheid tussen een- en meerpersoonskamers en de variatie in aankomstfrequentie van patiënten. Het doel van dit MILP is om **het aantal benodigde bedden te minimaliseren gegeven een maximale weigerkans, en de vervulling van voorkeuren, waaronder de concentratie van lege bedden, te maximaliseren.**

Het MILP is met succes geïmplementeerd in AIMMS en kan optimaal worden opgelost met behulp van de CPLEX 12.8-solver. De rekentijd voor grote instanties is minder dan vijf minuten.

Met behulp van het MILP wordt een optimale toewijzing bepaald voor zes configuraties. De configuraties verschillen in voorkeuren, aankomstsnelheid, verblijfsduur of weigerkans om het effect van verschillende initiële waarden te meten.

Resultaten

De optimale toewijzingen voor de zes configuraties laten zien dat er op dit moment onvoldoende capaciteit beschikbaar is in DZ, om een maximale weigerkans van 10% voor alle specialismen te garanderen. **Het toewijzen van een specialisme aan meerdere verpleegafdelingen of het blokkeren van een meerpersoonskamer om als eenpersoonskamer te dienen maakt het mogelijk om een weigerkans van 10% te garanderen voor alle specialismen.**

De resultaten laten ook zien dat de vervulling van voorkeuren met betrekking tot verpleegafdelingen in DZ, kan worden verbeterd door een van de voorgestelde optimale toewijzingen te implementeren. Uit validatie blijkt echter dat aanpassingen nodig zijn, zowel aan het model als aan de gegevensverzameling, om de betrouwbaarheid van de resultaten te vergroten.

Conclusie en aanbevelingen

Het toewijzingsmodel opgesteld in deze casestudy **helpt DZ bij de strategische besluitvorming** omtrent verpleegafdelingen en is **multifunctioneel**. Het model kan bepalen wat het benodigde aantal een- en meerpersoonskamers is, gegeven een maximale weigerkans. Bovendien bepaalt het model een optimale toewijzing van specialismen aan verpleegafdelingen die het benodigde aantal bedden minimaliseert en de vervulling van voorkeuren maximaliseert. De resultaten tonen ook de knelpunten met betrekking tot de optimale toewijzing van specialismen aan verpleegafdelingen in DZ. Dit inzicht neemt DZ mee bij het herinrichten van de verpleegafdelingen.

In DZ bestaat geen consensus over de uitgangspunten met betrekking tot de voorkeuren en aannames op algemene verpleegafdelingen. Daarom moet DZ eerst gemeenschappelijke uitgangspunten formuleren en besluiten welke compromissen moeten worden genomen. Ons model kan tijdens dit proces worden gebruikt ter ondersteuning van de besluitvorming. Per verzameling van uitgangspunten kan een nieuwe optimale toewijzing worden bepaald.

Voor zover wij weten, zijn wij de eerste die een model presenteren voor het toewijzen van specialismen aan verpleegafdelingen dat rekening houdt met het onderscheid tussen een- en meerpersoonskamers, lege bedden concentreert, en geen voorbereidende stap vereist voor het meenemen van de variatie in aankomstfrequentie van patiënten. Dit model kan optimaal worden opgelost en de rekentijd is minder dan vijf minuten voor grote instanties.

Het toewijzingsmodel kan ook worden toegepast op andere zorgeenheden in het ziekenhuis of zelfs buiten de gezondheidszorg. Voorbeelden zijn toewijzingen van kantoren, schoolklassen en **chocoladerepen**.

Contents

List of abbreviations

Abbreviation	Definition
ALOS	Average length of stay
C	Clinical admission
CCU	Coronary care unit
D	Day treatment
DZ	Deventer Ziekenhuis
ED	Emergency department
EHH	First cardiac aid
FTE	Full-time equivalent
IC	Intensive care
LOS	Length of stay
MILP	Mixed Integer Linear Program
O	Outpatient clinic admission
OR	Operating room
SONCOS	Stichting Oncologische Samenwerking
Q1	Quarter 1 (January to March)
Q2	Quarter 2 (April to June)
Q3	Quarter 3 (July to September)
Q4	Quarter 4 (October to December)
Clinical departments	
ANAE	Anaesthesiology
CAR	Cardiology
ENT	Ear, nose and throat surgery
DER	Dermatology
GAST	Gastroenterology
GER	Geriatrics
GYN	Gynaecology
INT	Internal medicine
NEPH	Nephrology
NEU	Neurology
ONC	Oncology
OPH	Ophthalmology
ORA	Oral surgery
ORT	Orthopaedics
PLAS	Plastic surgery
PUL	Pulmonary medicine
RHEU	Rheumatology
SUR	Surgery
TRAU	Traumatology
URO	Urology

1 Introduction

This study focuses on the assignment of clinical departments to wards in Deventer Ziekenhuis (DZ). Section 1.1 describes the context of this study, Section 1.2 contains the motivation of this study, Section 1.3 describes the problem and Section 1.4 describes the research objective.

1.1 Context description

DZ is a medium sized general public hospital located in Deventer. More than 2000 people work at DZ (1690 FTE) and in 2018 approximately 24.000 patients were admitted to DZ. Passion, transparency and patient centred care are core values of DZ.

The function of wards is to facilitate care for patients that due to their medical condition are not able to go home. DZ has three types of wards for admission of patients: dedicated wards, general wards and a ward for day treatment. Dedicated wards include intensive care (IC), coronary care unit (CCU), first cardiac aid (EHH), pediatric ward and obstetric ward. Each ward has a fixed number of beds. In total 364 beds are available in DZ.

This study focuses on general wards. Appendix A provides an overview of the general wards in DZ and the current assignment of clinical departments to wards. DZ has single, double and triple rooms for patients. Furthermore, the general wards have different sizes.

1.2 Motivation of research

DZ aims to assign as many patients as possible to their preferred ward and at the same time use the resources of wards efficiently. The management of DZ experiences changes in the arrival rate and length of stay (LOS) of patients due to developments in medical treatment. The average length of stay (ALOS) for a hip replacement for example, decreased the past years due to new surgery methods. As a result the demand for beds per clinical department changes and this effects the bed occupancy of wards.

In order to respond to (future) trends in the arrival and LOS of patients, the management of DZ wants to know how to assign clinical departments to wards taking into account the blocking probability of wards, variability in bed occupancy, and standards.

1.3 Problem description

The management of DZ experiences variability in bed occupancy. This makes the resource capacity planning of wards complex. The demand, patients requesting a bed, fluctuates per day. This makes it difficult to estimate the required supply, that is the required number of beds and nurses per ward. Every ward has a fixed number of beds, however a bed is is only available if it is staffed. The hospital has a fixed nurse to patient ratio.

If the demand is larger than supply, patients cannot be admitted at their preferred ward. This can either be a shortage of available beds in general wards or a shortage of single rooms. As a result the workload of nurses increases since they have to take care of patients beyond their specialization. Moreover, physicians have to visit multiple wards to check their patients. If this holds for all wards, the hospital will temporary stop admitting patients, this happens rarely in DZ. If the demand is smaller than supply, resources are not used efficiently.

The variability of demand has three causes:

- Natural fluctuation: The arrival of emergency patients is variable. If we assume that only the patient's medical condition determines the discharge moment, also the LOS of patients fluctuates naturally. As a result the number of arriving emergency patients and the LOS of patients varies per day. Natural fluctuation cannot be influenced by human interventions.
- Artificial fluctuation: The arrival of elective patients is planned. However, most clinical departments do not take the bed occupancy of wards into account when planning an elective patient. As a result the number of arriving elective patients varies per day.
- Trends: Developments in medical treatment influence the arrival and ALOS of patients. As a result the demand per clinical department changes.

Note that only the demand of elective patients can be influenced. Since the natural fluctuation and trends cannot be influenced it is important to respond to this variability.

The management of DZ determines the supply. They decide how many beds are available for admission. There are some limitations since the hospital has a fixed number of beds and a fixed number of single rooms. Moreover, nurses work in shifts so extra supply cannot be arranged at any moment. Nurses prefer to know their work schedule some weeks in advance. Hence nurses dislike being informed a short time in advance about the cancellation or planning of a shift. We conclude that the supply can be influenced by the management, except for some limitations.

> *The core problem of this study is the discrepancy between demand and supply in the wards.*

This study focuses on how supply can adapt to the trend in demand. Specifically this study concerns the assignment of clinical departments to wards. The effect of the planning of elective patients on the discrepancy between demand and supply in wards is out of the scope of this research since a lot of research has already been done in this field (Cardoen et al. (2010); Levine et al. (2015)).

Additionally, the management of DZ faces another challenge. Stichting Oncologische Samenwerking (SONCOS) states that from the first of January 2022 at least one half of the number of nurses taking care of an oncology patient, needs to be specialized in oncology. Currently oncology patients are spread over various wards. This means that a large number of nurses needs to be specialized in oncology in order to comply with the SONCOS standard. Therefore the management of DZ also wants to know what the advantages and disadvantages are of placing all oncology patients in the same ward.

Appendix B provides a problem bundle. This problem bundle elaborates the above-mentioned problems and shows the cause-effect relationships.

1.4 Research objective

The research objective is to develop a model for assigning clinical departments to wards in order to find a trade-off between the blocking probability and efficient use of resources and to meet standards. Moreover, we aim to take future trends into account to not only provide a solution for the current situation but also for future scenarios.

Based on this research objective the following research questions are formulated:

1. What are the characteristics of the current inflow and outflow of patients in general wards?

Observations and interviews with various stakeholders are used to identify the characteristics of the current admission and discharging process in general wards. Chapter 2 describes these characteristics.

2. What is the current strategic level performance of the general wards in DZ?

Chapter 2 describes the performance indicators and the current strategic level performance of the general wards in DZ. The performance indicators are defined based on context analysis. Data analysis is used to measure the current performance.

3. Which models for assigning clinical departments to wards are described in literature?

A literature review is performed to discuss relevant literature and to define research gaps. The results of this literature review are presented in Chapter 3.

4. How can the assignment of clinical departments to wards be modelled?

The results of Chapter 2 and 3 are used to formulate an assignment model. This model is introduced in Chapter 4.

5. How does the model perform?

In Chapter 5 experiments are performed using data of DZ. Various configurations are studied to measure the impact of different input values on the optimal assignment of general wards.

6. How can the Assignment Model be implemented in DZ?

Chapter 6 discusses practical implications related to results of this research. Chapter 7 summarizes the findings of this research, discusses the results and gives recommendations for further research.

2 Context analysis

This chapter provides a context analysis of the general wards in DZ. Section 2.1 provides an overview of the stakeholders of wards, Section 2.2 describes the process of admission and discharge in general wards, Section 2.3 describes the planning and control in general wards, Section 2.4 describes the performance indicators and shows their current performance and Section 2.5 provides a conclusion.

2.1 Stakeholders

Stakeholders play an important role in processes and determine the objectives. The following four groups are the stakeholders of wards:

- **Patients**
  A patient stays in a ward if he is unable to go home due to his medical condition. Patients are categorized by clinical departments. Admitted patients can be divided in two groups: elective patients and emergency patients. Some patients require a single room due to their medical condition.
- **Nurses**
  Nurses take care of the medical condition of patients. General nurses are specialized in one or multiple clinical departments and are allocated at a particular ward. Flexible nurses work for all clinical departments and can be called up if there is a shortage of nurses. Every shift one nurse is the shift coordinator. This nurse coordinates the nurses during the shift.
- **Physicians**
  Physicians determine the medical policy and check the medical condition of patients in wards. The frequency of these visits depends on the diagnosis and medical condition of the patient and the schedule of the physician. Physicians are specialized in a clinical department and only check patients from their own department.
- **Management**
  Every ward has an operational manager. This manager takes care that daily processes are ran successfully and efficiently. Additionally, this manager determines together with the head of admissions how many beds are available in the ward for the current day.

2.2 Process description

Admission and discharge of patients determine the demand for beds in general wards. In order to understand the context of general wards it is therefore important to study the process of admission and discharge of patients. This section provides a description of the admission and discharge processes.

2.2.1 Admission

Patients are categorized by clinical department. Each clinical department is assigned to a ward. Since there are more clinical departments than wards, clinical departments share wards.

It is preferred to admit patients at the ward assigned to the clinical department of their responsible medical specialist. By concentrating similar patients it is possible to offer specialized care and potentially decrease the risk of mistakes and increase patient satisfaction. If a patient cannot be admitted to its preferred ward, the management aims to admit the patient to a ward similar to its preferred ward. The probability of refusing an admissions is called the *blocking probability*. A patient that is not placed in its preferred ward is called an *outlier*. If a patient can not be admitted to any ward in the hospital the patient is sent to another hospital.

Some patients require a single room due to their medical condition. The number of single rooms is limited, therefore this condition can also result in outliers.

Figure 1 provides a schematic overview of the inflow of patients in general wards. The connections between the different departments represents both long and short time periods. The connection between the outpatient clinic and the general wards for example, concerns a long time period in case of an elective patient and a short time period in case of an emergency patient.

Some patients get surgery in other hospitals, which explains the external department in Figure 1. Patients that receive day treatment and are unable to go home are temporary admitted to the general ward, this explains the day treatment in Figure 1.

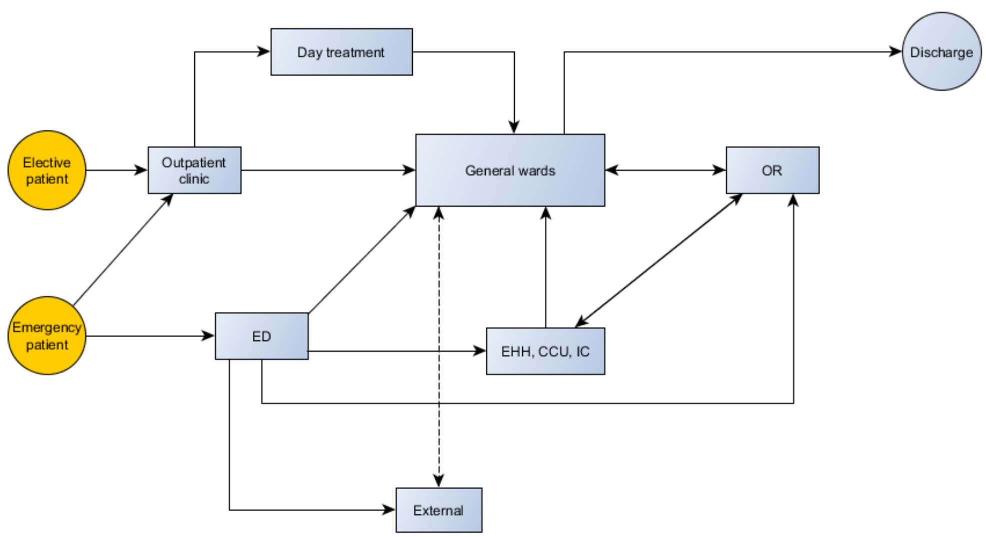

Figure 1: Schematic overview of the inflow of patients in wards.

Figure 2 provides a schematic overview of the admission process of an elective patient. If the physician prescribes an hospital admission, the patient has to contact the admission officer. The officer plans the admission date. If a surgery is needed, the admission date is planned based on the surgery schedule. If a medical examination is needed, the admission date is planned based on the medical examination schedule. Otherwise, the admission date is planned based on preferences of the patient. Only a few clinical departments take the occupancy of wards into account when planning admissions. By default each patient is planned at its preferred ward.

A day before the admission date, staff from the ward calls the patient to inform him about the time of admission. If the patient undergoes surgery, the time is determined by the management of the operating rooms. If the patient needs medical examination, this determines the arrival time. Otherwise the time is determined by the staff from the ward. At the day of admission the coordinator of the ward assigns the patient to a specific bed.

Figure 3 provides a schematic overview of the admission process of an emergency patient. If an emergency patient needs to be admitted in the hospital, an officer of the admission department allocates the patient. The officer checks which wards have beds available and aims to assign the patient to the preferred ward. If the patient is assigned to a ward, the officer contacts the coordinator of this ward. The coordinator then assigns the patient to a specific bed.

Often it is known in advance if a patient requires a single room. The admission officer or staff from the ward will make sure that the patient is assigned to a single room. If no single rooms are available a patient has to wait or a shared room is blocked such that it functions as a single room.

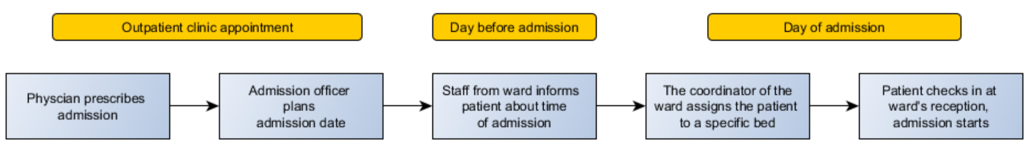

Figure 2: Schematic overview of the admission process of an elective patient

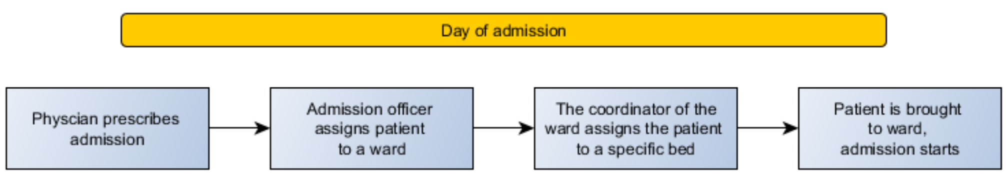

Figure 3: Schematic overview of the admission process of an emergency patient

2.2.2 Discharge

If a patient is admitted to the hospital a discharge date is suggested based on the patient's diagnosis. During the stay in hospital nurses and physicians update this date if necessary. A liaison nurse organizes aftercare if needed. Not only the medical condition but also the provision of aftercare determines if a patient can be discharged.

2.3 Resource planning

The resource planning concerns the planning of beds and nurses. This section describes the strategic, tactical and operational planning of available beds.

2.3.1 Strategic resource planning

The strategic planning of available beds concerns the assignment of beds to wards and the assignment of clinical departments to wards. In principle every ward has a fixed number of beds, however due to the layout of wards it is possible for a ward to increase its capacity by taking over rooms from a neighboring ward. Moreover, it is also possible to decrease the capacity of a ward for a longer period by closing beds. This is called a *reduction period*. During this period, fewer treatments are planned, and as a consequence fewer beds are required in the wards. The periods of reduction are determined once a year and are based on historical data, national holidays, and special circumstances.

The management of DZ determines the assignment of clinical departments to wards. This decision is based on historical data and experience and does not happen on a frequent base since a change in the assignment of clinical departments to wards has many implications for staff and logistical processes. Not all clinical departments can share a ward due to differences in provision of care. It is for example not preferred to assign surgical and non-surgical departments to the same ward.

2.3.2 Tactical resource planning

Based on the strategic resource planning, historical data and the nurse to patient ratio, the schedule for nurses is planned three months in advance. The management of DZ aims to predict the bed occupancy a week in advance to be able to adjust the number of planned nurses. However, the bed occupancy prediction for one week in advance currently is not very accurate due to discharge dates that are not updated on time. Additionally, a high number of planned admissions or an intended closure of beds also gives rise for adjusting the number of planned nurses in advance.

2.3.3 Operational resource planning

Generally the closure of eight beds in one ward corresponds with cancelling one nurse shift. Due to this rule the management aims to concentrate empty beds. This is not only to use resources efficiently but also to deal with a shortages of nurses.

From Monday to Friday, every morning the managers of the wards meet together with the head of admissions to discuss the bed occupancy of the wards for that day. During this meeting the expected number of admissions and discharges is shared. Based on this information, the reduction period, and the assignment of clinical departments to wards, it is decided how many beds will be available for admission that particular day. Based on this decision, the planned number of nurses is adjusted. During the weekend, the weekend manager decides how many beds will be available for admission.

2.4 Current performance

This section provides a definition of the performance indicators and their current performance.

2.4.1 Performance indicators definitions

In collaboration with the management of DZ, with the objective efficient use of resources and offering high quality of care in mind, the following performance indicators are formulated:

- **Bed occupancy**
  In order to measure the efficiency of use of resources, the bed occupancy is chosen as performance indicator. The bed occupancy for a ward is defined as follows:

  $$\frac{\text{Occupied capacity in time period } T}{\text{Available capacity} \times \text{time period } T} \cdot 100\%$$

  The occupied capacity in time period T is defined as the sum of the LOS of all patients occupying a bed in time period T. Preparing a bed for a new admission costs time, this is not taken into account. Additionally, closed beds are measured as available capacity. Hence, the available capacity is overestimated and therefore the actual bed occupancy is higher. However, we assume that the pattern approximates the actual pattern in bed occupancy.

  The management of DZ aims for a bed occupancy of 80%.

- **Throughput**
  Throughput is measured as the number of patients in a specified time period that occupied a bed in the ward. The throughput is a measure for the availability of care in a hospital. Only analyzing the bed occupancy rate is not sufficient since a high bed occupancy rate does not necessarily indicate a high throughput.

  The throughput is measured per clinical department for time period T. We expect a higher throughput for surgical clinical departments than internal medicine departments due to a lower ALOS.

- **Blocking probability**
  Outliers could potentially increase the risk of mistakes and therefore reduce the quality of care. Hence the blocking probability is chosen as a performance indicator for quality of care. It should be mentioned that not all outliers are evenly disapproved. For example, assigning a patient from the orthopedics department to a ward assigned to the traumatology department is preferred over assigning this patient to a ward assigned to the internal medicine department.

  The blocking probability is measured per clinical department for time period T. An admission is a refused admission if the first day of the admission took place in a not preferred ward. The first day of the admission is most important since during this day the treatment plan is setup.

  The management of DZ aims for a maximal blocking probability of 10%.

- **Proximity preference**
  DZ has some preferences concerning the assignment of clinical departments to wards.

It is for example preferred to locate internal medicine clinical departments close to each other since the type of required care is similar. It is also preferred to place clinical departments related to surgery close to the operating rooms. In this study we take the preference for clinical department and ward combinations and the preference for combinations of clinical departments into account. Additionally, we specify which ward is preferred for concentrating empty beds.

The proximity preferences are approximated by interviewing various stakeholders. The measurement of the current fulfilment of proximity preferences is given in Chapter 5. Since the proximity preferences are not measured before, the management of DZ can not give a target value for the fulfilment of proximity preferences.

2.4.2 Zero measurement of performance

The current performance is measured based on data from 2016 to 2018 from the Finance, Control and Information department of DZ. This department extracts their data from HiX, the hospital information system.

- **Bed occupancy**

Figure 4 shows the average bed occupancy per general ward from 2016 to 2018. General ward E2 is not shown in this figure since currently no clinical admissions take place in this ward.

The bed occupancy increases each year from quarter three to quarter one due to a yearly influenza epidemic in the winter. Due to national summer holidays, less elective surgeries are planned during summer and therefore the bed occupancy decreases in quarter two and three.

In 2016 and 2017 outpatient clinic chemotherapy took place in ward A2. A number of rooms in ward A2 was reserved for these treatments. Since these treatments take place during the day, these rooms were not occupied during the night. This explains the difference in bed occupancy for ward A2 compared to the other general wards.

No conclusions can be drawn from the difference in bed occupancy for wards B2, C2, D2 and G2 since this difference is very small. Additionally, the exact value of the bed occupancy is only an indication as mentioned in Section 2.4.1.

Figure 5 shows that in 2018, 24% of the bed occupancy took place in single rooms and 76% of the bed occupancy took place in shared rooms. This ratio is similar to the ratio in 2016 and 2017. However this ratio is not equal to the ratio in available bed capacity as can be seen in Figure 5. This matches the experience of the management of DZ that single rooms in general wards are subject to increasing stress. [redacted]

Each clinical department has a demand for beds in single rooms. Figure 6 shows the bed occupancy if all no blocking occurs. This figure shows that the clinical departments that are assigned to the general wards A2 and B2 have a higher demand for beds in single rooms compared to the general wards C2, D2 and G2. However, all general wards have approximately the same number of single rooms.

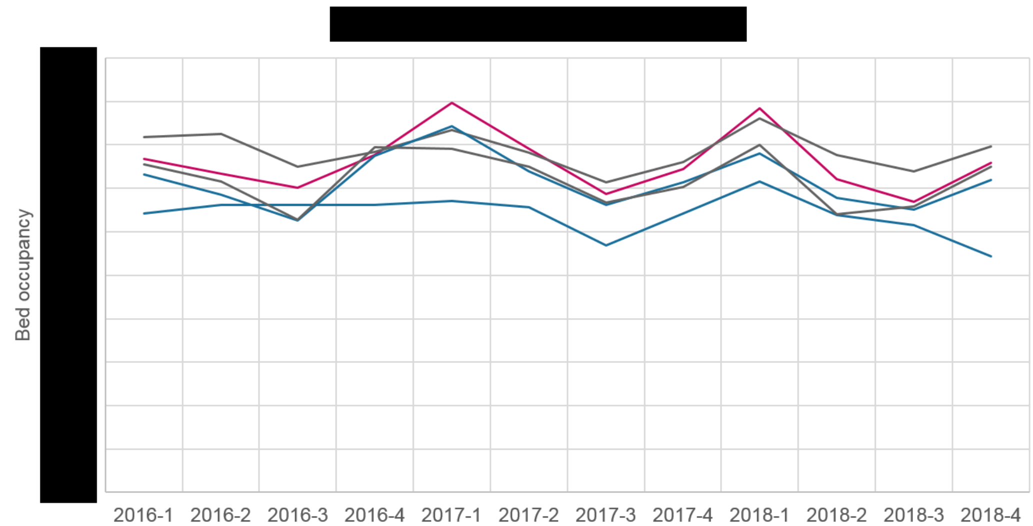

Figure 4: Bed occupancy per general ward from 2016 to 2018 (HiX Deventer Ziekenhuis, $n = 66661$)

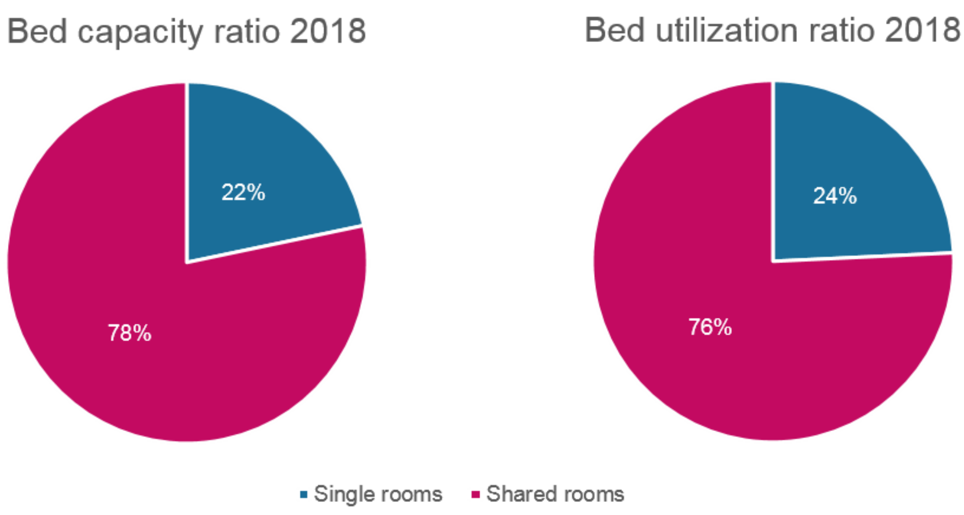

Figure 5: Bed capacity ratio and bed utilization ratio for beds in single and shared rooms based on the total LOS in general wards in DZ in 2018 (HiX Deventer Ziekenhuis, $n = 23319$)

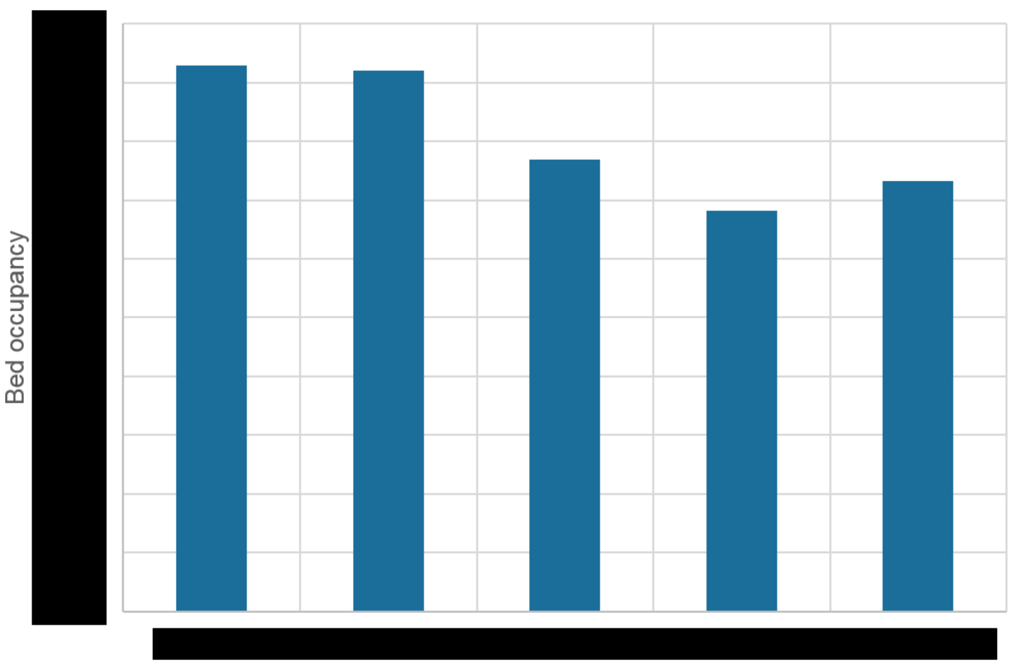

Figure 6: Theoretical distribution of bed occupancy in single rooms per general ward if no blocking occurs (HiX Deventer Ziekenhuis, 2016 to 2018, $n = 9775$)

- **Throughput**

In total 66.661 patients were admitted in general wards in DZ from 2016 to 2018. This equals 44% of all admission in DZ. Figure 7 shows that there is an increase in the number of admissions in general wards from 2016 to 2018. Figure 8 shows the trend in admissions per clinical department. Especially the day treatment and the clinical admissions of the oncology department experience an increase in the number of admissions in the last three years. The surgery department experiences a decrease in the number of admissions since the LOS of treatments decreases and therefore more patients are treated in day treatment.

Figure 9 and 10 show that the number of admissions varies during the year, especially for the admissions in single rooms. There is also a variation in arrivals during the days of the week as can be seen in Figure 11. Elective admissions mainly take place during work days. The oral surgery department has most admissions on Wednesday.

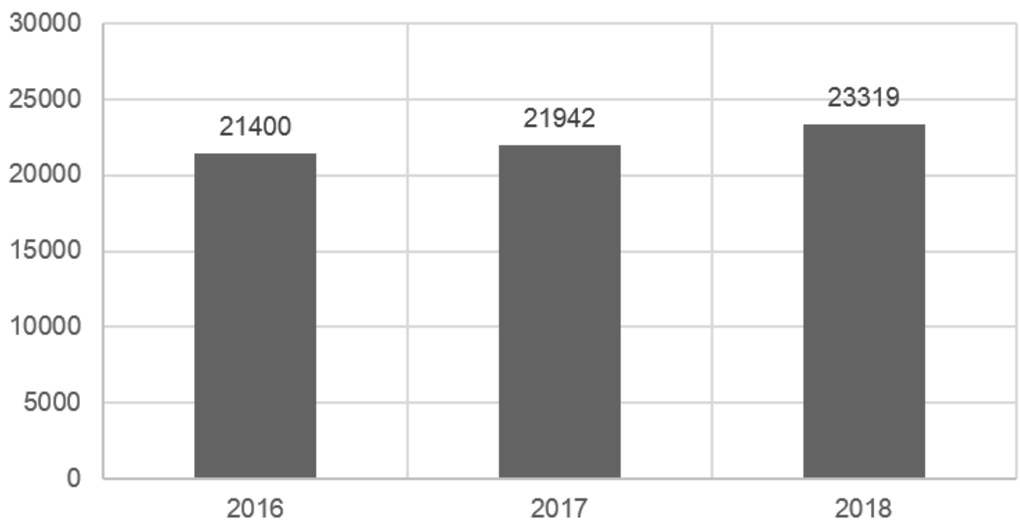

Figure 7: Number of admissions in general wards per year (HiX Deventer Ziekenhuis)

Tables 2 and 3 present the number of admissions, ALOS, Gini coefficient and the average number of occupied beds per day per clinical department in shared rooms and single rooms respectively.

The surgery department has the highest number of beds occupied per day in shared rooms. The internal medicine department has the highest number of beds occupied per day in single rooms as can be seen in Table 3.

In shared rooms, the neurology department has the highest Gini coefficient. In single rooms, the plastic surgery department has the highest Gini coefficient. This means that these departments have the highest variation in LOS of patients.

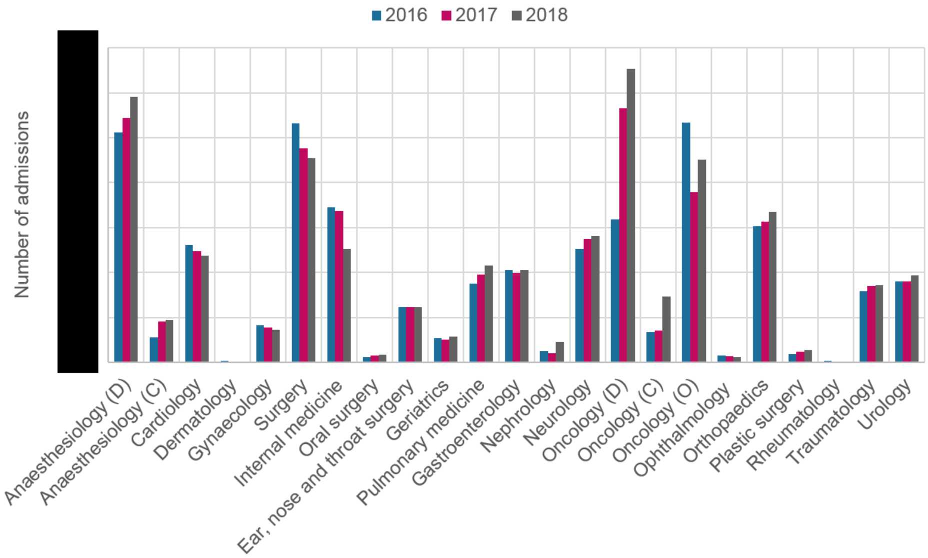

Figure 8: Number of admissions in general wards per clinical department per year (HiX Deventer Ziekenhuis, $n = 66661$)

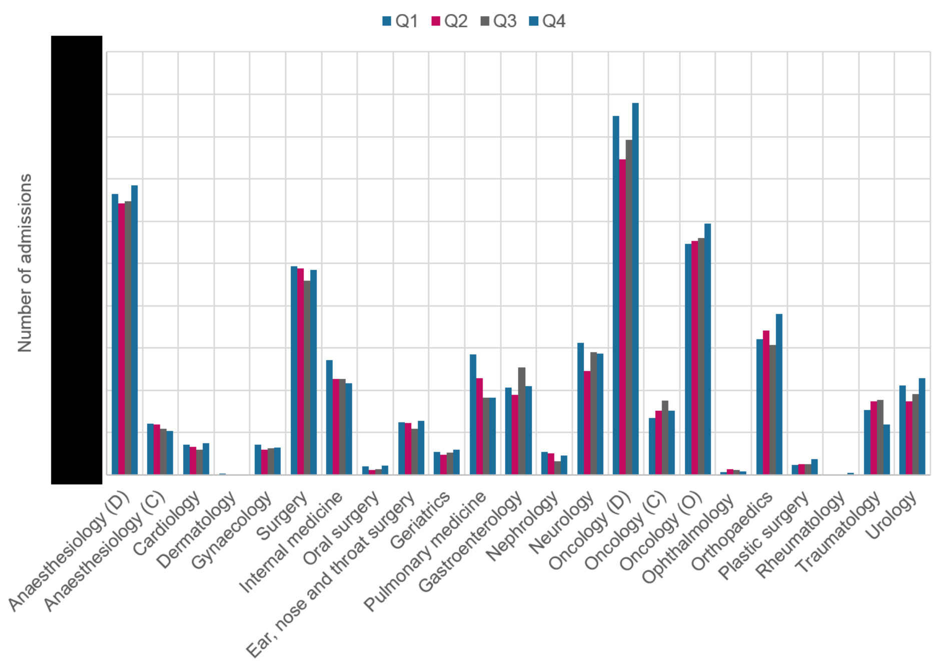

Figure 9: Number of admissions in shared rooms per quarter per clinical department (HiX Deventer Ziekenhuis, 2018, $n = 19382$)

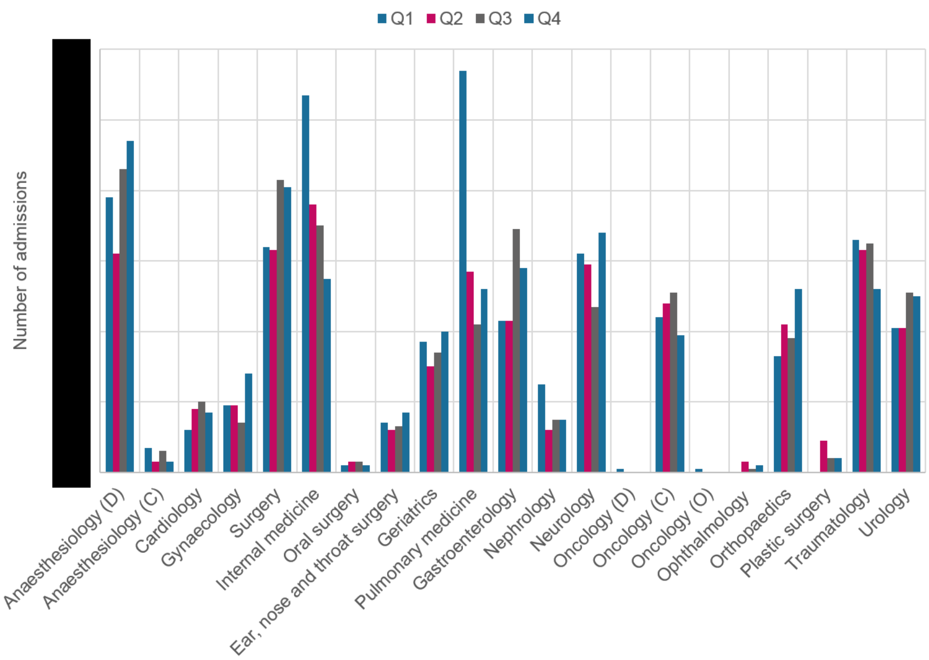

Figure 10: Number of admissions in single rooms per quarter per clinical department (HiX Deventer Ziekenhuis, 2018, $n = 2874$)

Table 2: Admissions in shared rooms per clinical department in 2018 (HiX Deventer Ziekenhuis, $n = 19448$)

CONFIDENTIAL

Table 3: Admissions in single rooms per clinical department in 2018 (HiX Deventer Ziekenhuis, $n = 3252$)

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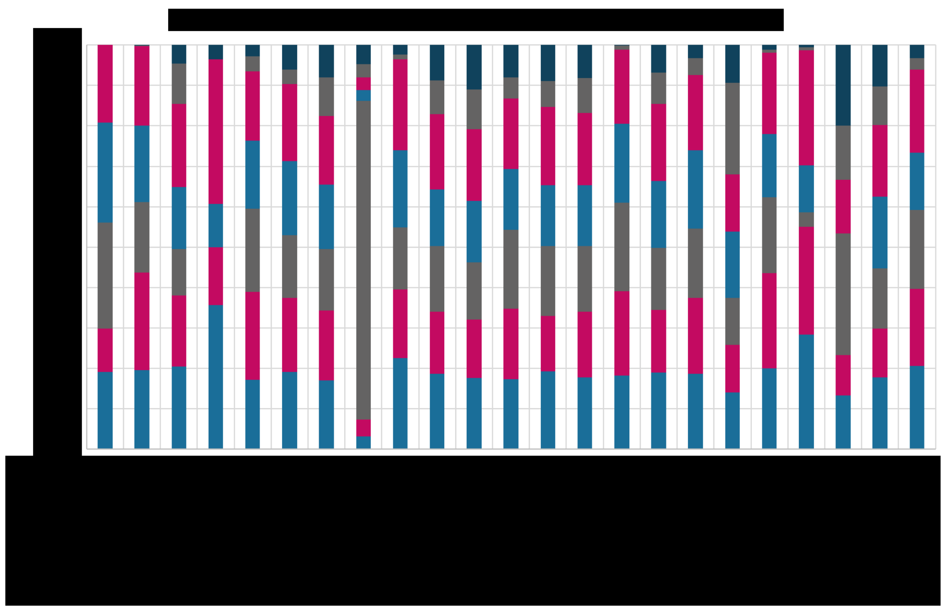

Figure 11: Ratio patient arrivals on week days (HiX Deventer Ziekenhuis, 2016 to 2018, $n = 66661$)

- **Blocking probability**

The blocking probability for each clinical department in 2018 is shown in Figure 12. DZ aims to have a maximum blocking probability of 10%. [redacted]

In 2018 no clinical admissions were refused in DZ due to a shortage of available beds. Hence we assume that if a clinical admission is refused at its preferred ward it can be assigned to another ward in the hospital.

Figure 13 shows that the blocking probability for the internal medicine, geriatrics and gastroenterology department varies over the year. The high blocking probability in the first quarter of 2018 is caused by an influenza epidemic. Due to this epidemic the throughput of patients was very high and as a result more admissions were refused.

Figure 14 shows that for most clinical departments the blocking probability decreased over the past three years. No particular policy is implemented that explains this decrease, however the awareness for outliers is raised in the past years. Still many clinical departments do not meet the objective of DZ.

[redacted]

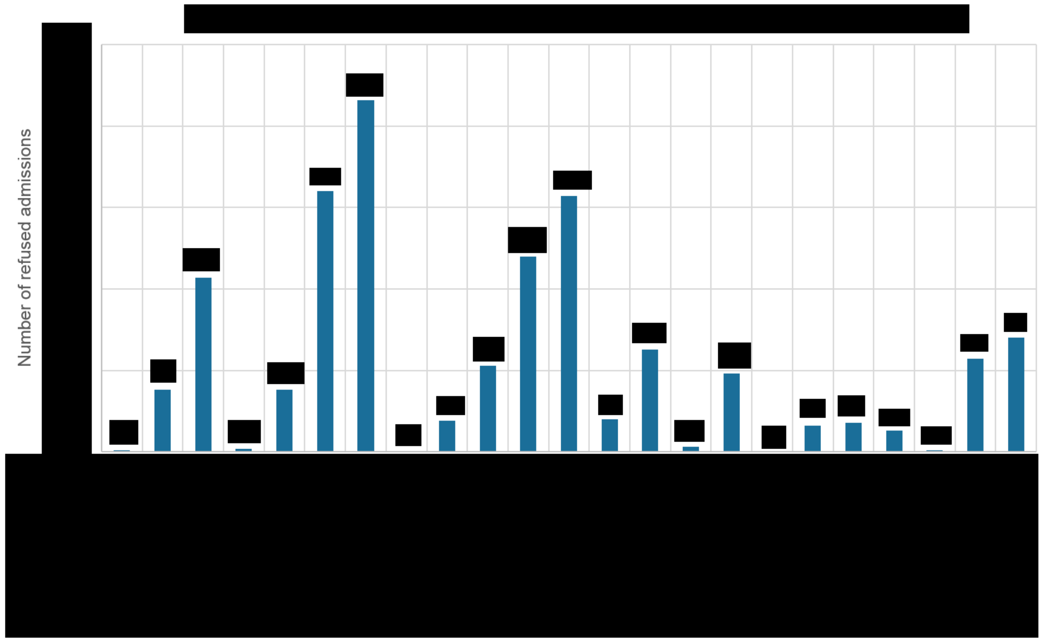

Figure 12: Admissions refused at their preferred ward in 2018 per clinical department (HiX Deventer Ziekenhuis, $n = 23319$)

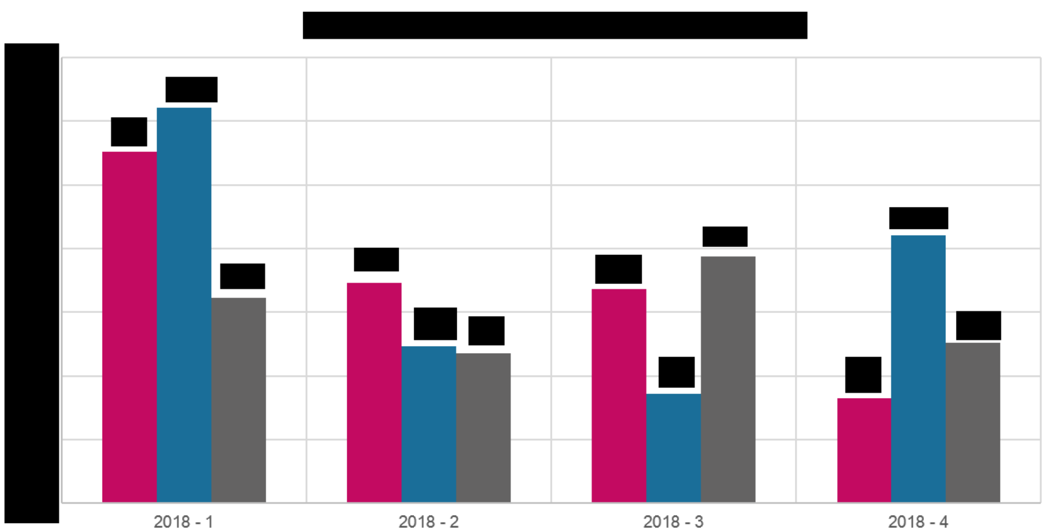

Figure 13: Percentage of admissions refused at their preferred ward in 2018 per quarter for the internal medicine department, the geriatrics department and the gastroenterology department (HiX Deventer Ziekenhuis, $n = 2574$)

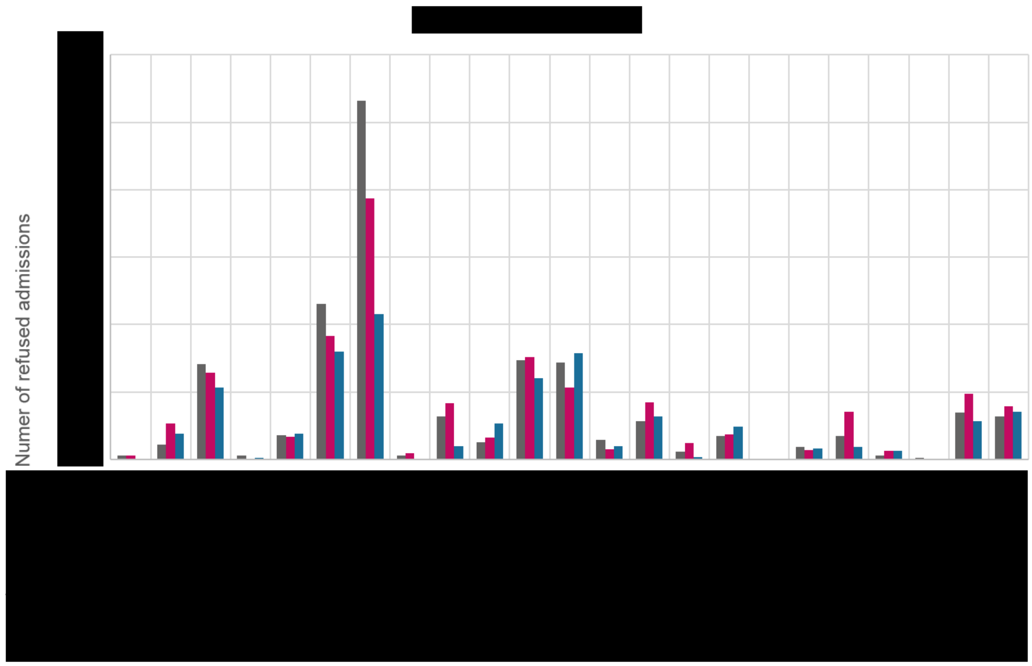

Figure 14: Number of admissions refused at their preferred ward per year per clinical department (HiX Deventer Ziekenhuis, 2016 to 2018, $n = 4376$)

- **Proximity preference**

The preferences are measured by individual and group interviews with the (medical) management of the general wards. Appendix C describes the setup of these interviews. We conclude the following from the these interviews:

- There is a clear preference to locate internal medicine departments close to each other and to locate surgery departments close to each other. However, within the group of internal medicine departments and surgery departments there are different preferences for combinations. This depends on different opinions about medical expertise and work pressure.

- Currently E2 is not in use for clinical admissions, however this ward is close to the operating rooms. Therefore stakeholders want to know if it is possible to open E2 for clinical admissions and close another ward.

- Stakeholders prioritize the preference for combinations of clinical departments. On the second place comes the preference for combinations of wards and clinical departments. Concentrating empty beds is also important, however not as important as the other preferences.

2.5 Conclusions

The characteristics of general wards are described by its stakeholders and the admission and discharge process. Important stakeholders of wards are patients, nurses, physicians and management. The admission office organizes admissions both for elective and emergency patients and strives to assign patients to their preferred wards. For every patient that is admitted an expected discharge date is set. If necessary this date is updated by physicians or nurses. If the medical condition of the patient is sufficient and aftercare is organized a patient is discharged.

A bed is available for admission if it is staffed. The strategic resource planning concerns the assignment of beds to wards and the assignment of clinical departments to wards. The tactical resource planning concerns the planning of nurses. The operational planning concerns the daily alignment of demand and supply.

DZ strives to offer high quality care and use resources efficiently therefore the bed occupancy, throughput, blocking probability and proximity preferences are chosen as performance indicators.

Due to a yearly influenza epidemic and a yearly reduction period a clear pattern is visible in the bed occupancy of general wards. Unfortunately it is not possible to give a reliable estimate of the bed occupancy due to a lack of data. The bed utilization of single rooms is higher compared to the bed utilization of shared rooms. This matches the experience that single rooms are subject to increasing stress.

In 2018 23319 patients were admitted in the general wards of DZ. From 2016 to 2018 the number of admissions increased by 9%. [redacted]% of the clinical departments exceed the allowed blocking probability of 10% set by DZ. Additionally, improvements can be made in the fulfillment of preferences related to general wards.

Now that we have analyzed the context of the case study, a mathematical model can be developed to reduce the discrepancy between demand and supply in wards by reassigning clinical departments to wards. In Chapter 3, previous work on the assignment of clinical departments to wards is discussed. Chapter 4 describes the mathematical model that we apply to solve the core problem based on the results of Chapter 3.

3 Literature review

This chapter provides an overview of previous work on the assignment of clinical departments to wards. Appendix D provides an overview of the literature search strategy.

Section 3.1 provides an introduction in hospital bed management, Section 3.2 describes models for assigning clinical departments to wards and Section 3.3 concludes the literature review.

3.1 Hospital bed management

Hospital bed management concerns the allocation and provision of beds in hospitals. From 2013 to 2017, 1481 papers were published on Google Scholar, PubMed and Levy Library databases related to bed management, bed planning and bed allocation in hospitals (He, Madathil, Oberoi, Servis, & Khasawneh, 2019). Most papers relate to bed management in the IC or in general wards and present methods for determining the required number of beds. He et al. (2019) identify the following research gaps: few articles consider the entire inpatient flow as a dynamic network, uncertainties in bed management need to be better predicted and there is a lack of standardization in prioritizing inpatients during the admission process.

Mathematical programming, Markov models, queuing theory and simulation are modeling techniques often used in hospital bed management (He et al., 2019). Simulation models are used for detailed processes and for obtaining average performance. Mathematical programming is used for optimizing allocations of beds. Markov models are used for determining the stationary distribution. Queuing theory is used for determining the capacity or stationary distribution of a single ward (van de Vrugt, Schneider, Zonderland, Stanford, & Boucherie, 2018).

Holm, Lurds and Dahl (2013), Bahadori, Teymourzadeh and Kazemi (2017) and Landa, Sonnessa, Tànfani and Testi (2018) provide examples of case studies related to hospital bed management. However, in general there is not much literature on integrating operation research models related to hospital bed management in practice. Moreover it is not clear to what extent these models are actually implemented in practice (van de Vrugt et al., 2018). We conclude there is a gap between research and practice.

3.2 Assignment of clinical departments to wards

This section describes the benefits of assigning combinations of clinical departments to wards and describes the various models that are available for determining an optimal assignment.

3.2.1 Benefits of combining clinical departments

Green and Nguyen (2001), de Bruin, Bekker, van Zanten and Koole (2010) and Bekker, Koole and Roubos (2017) studied the benefits of assigning a combination of clinical departments to one ward. Green and Nguyen (2001) show that combining clinical departments may reduce the number of required beds. However, they also show that combining clinical departments with different admission priorities, length of stays (LOSs) and demand can lead to an increase in the number of required beds given a specified blocking probability. In their study they recommend to reserve a number of beds for each clinical department. De Bruin et al. (2010)

show that by combining clinical departments both an acceptable blocking probability and economical viable occupancy rate can be realized. Bekker et al. (2017) show that specifically small scale systems can benefit from combining clinical departments. For large scale systems a little flexibility is sufficient to benefit from most of the economies of scale. To deal with different admission priorities, LOSs and demand they propose a threshold type of control.

Besides combining clinical departments, Kortbeek, Braaksma, Burger, Bakker and Boucherie (2015) recommend to introduce flexible staffing policies to effectively respond to variability in demand. The flexible policies involve the employment of float nurses for whom it is decided at the start of a shift in which specific care units they will work.

3.2.2 Models

Van Essen, van Houdenhoven and Hurink (2015), Bekker et al. (2017) and Hübner, Walther and Kuhn (2018) formulate models for assigning clinical departments to wards. All these models follow a set partitioning modeling approach. In this approach a mixed integer linear model is formulated that combines clinical departments and allocates ward capacity to these combinations. The method for determining the required number of beds for different combinations of clinical departments differs per model. Moreover, the models use different hard and soft constraints.

Van Essen et al. (2015) use the Erlang loss formula to determine the bed requirements of combinations of clinical departments given a maximum blocking probability, the expected number of admissions and expected LOS. This approach is based on the method developed by De Bruin et al. (2010). The objective of Van Essen et al. (2015) is to minimize the maximum number of clinical departments in one combination, to minimize the walking distance between wards assigned to the same combination, and to maximize the preferences of departments located close to central facilities. Since the problem Van Essen et al. (2015) formulate, is strongly NP-hard they propose two heuristics solution approaches.

The model formulated by Bekker et al. (2017) is similar to the model formulated by Van Essen et al. (2015). With this model Bekker et al. (2017) test four policies: separate wards, simple merging, earmarking beds and threshold policies. These policies are compared with optimal policies. Unlike Van Essen et al. (2015), Bekker et al. (2017) take different levels of priorities for clinical departments into account.

Unlike the models of Van Essen et al. (2015) and Bekker et al. (2017), the model of Hübner et al. (2018) takes weekly and monthly seasonality effects into account, and provides a time-efficient solution method. Van Essen et al. (2015) assume that the patient elective arrivals are evenly distributed during weekdays. However, this is generally not the case according to Hübner et al. (2018). They propose a method that determines the bed requirements per combination of clinical departments by convoluting the probability distribution functions of the occupancy levels of clinical departments within the combination, for a specified time period. The day with the highest bed requirements within the observed time period, and the specified blocking probability determine the required number of beds. As a consequence, combinations of departments that provide a balancing effect with regard to overall bed occupancy require a smaller number of beds compared to other combinations of departments, and are therefore more likely to be chosen.

In order to provide a time-efficient solution method, Hübner et al. (2018) first carry out a preprocessing step. In this step a set of feasible department combinations is attained. Aim of this step is to reduce the solution space and as a consequence reduce the computation time. The set of feasible department combinations and the corresponding bed requirements together with staff, distance and cost parameters are used as input for the mixed integer linear model.

Hübner et al. (2018) take the trade-off in savings into account. Parameters related to costs for beds and costs for pooling are included in the model. Their objective is to minimize the total costs.

The research of Van Essen et al. (2015), Bekker et al. (2017) and Hübner et al. (2018) have some limitations. Van Essen et al. (2015), Bekker et al. (2017) and Hübner et al. (2018) do not address a trend in the arrival rate or LOS of patients. However, this trend is visible as mentioned in Chapter 1. Reallocating clinical departments is an intensive process and therefore it is preferred to limit the number of reallocations. Hence, it is important to study expected trends and to take these trends into account to limit the number or reallocations in the future.

Additionally, the distinction between single and shared rooms is not taken into account by Van Essen et al. (2015), Bekker et al. (2017) and Hübner et al. (2018). As described in Chapter 1, a shortage of single rooms causes refused admissions. Hence the blocking probability is underestimated if no distinction is made between single and shared rooms.

Also, the models of van Essen et al. (2015), Bekker et al. (2017) and Hübner et al. (2018) do not concentrate empty beds. In order to increase efficient use of resources it is not only important to limit the number of required beds. It is also important to concentrate empty beds such that shifts of nurses can be canceled. If empty beds are spread over different wards, no shifts can be canceled due to a minimum nurse to patient ratio. Hence, there is no efficiency benefit.

3.3 Conclusion

From 2013 to 2017, 1481 papers were published on Google Scholar, PubMed and Levy Library databases about hospital bed management (He et al., 2019). Although Green and Nguyen (2001), de Bruin et al. (2010) and Bekker et al. (2017) clearly describe the benefits of assigning combinations of clinical departments to wards, the number of papers related to the assignment of clinical departments to wards is limited. Only three papers propose a model for determining the assignment of clinical departments to wards: Van Essen et al. (2015), Bekker et al. (2017) and Hübner et al. (2018). Van Essen et al. (2015) and Bekker et al. (2017) use the Erlang loss formula to determine the bed requirements for combinations of clinical departments. Hübner et al. (2018) convolute the probability distribution functions of the occupancy levels of clinical departments to determine the bed requirements. All three proposed models use a mixed integer linear program to determine the optimal assignment of clinical department to wards.

However, we identify a research gap. The models of Van Essen et al. (2015), Bekker et al. (2017) and Hübner et al. (2018) consider the current patient case mix and do not take trends in arrival rate or LOS into account. Moreover, no distinction is made between single and shared rooms and empty beds are not concentrated. As a result, the blocking probability is underestimated and the efficiency benefit will be smaller.

In Chapter 4, we propose a model for assigning clinical departments to wards taking into account the distinction between single and shared rooms, the variation in arrival rate, and concentrating empty beds. In Chapter 5, different configurations are studied to analyze the effect of different preferences on the assignment of clinical departments to wards.

4 Mathematical model

This chapter describes the model selection and introduces the Bed Requirements Model and the Assignment Model. Section 4.1 describes the model selection, Section 4.2 describes the Bed Requirements Model and Section 4.3 describes the Assignment Model.

4.1 Model selection

Based on the problem description we propose a mathematical model that assigns clinical departments to wards. A mathematical model is able to evaluate different configurations and to find or approximate an optimal solution in a very efficient way. However a mathematical model is an approximation of reality and therefore the results of experiments have to be interpreted carefully.

In Chapter 3, three models are introduced for the assignment of clinical departments to wards. Since we are not interested in different policies for the assignment of wards, we do not use the model of Bekker et al. (2017). The model of Hübner et al. (2018) uses the probability distribution function of the occupancy levels of clinical departments to determine the required number of beds per combination of clinical departments. Since no reliable data is available of the occupancy levels of clinical departments, this model is not used. Hence, the model of Van Essen et al. (2015) is used as a starting point for our model. Additionally, the model is extended to take the distinction between single and shared rooms into account, to take the variation in arrival rate into account and to concentrate empty beds.

In the model of Van Essen et al. (2015), the Erlang loss formula is used for determining the required number of beds per combination of clinical departments. This method is explained in Section 4.2. The mixed integer linear program (MILP) used for assigning clinical departments to wards is formulated in Section 4.3.

4.2 Bed Requirements Model formulation

The required number of beds in a ward depends on the arrival rate λ and the LOS $\frac{1}{\mu}$ of the clinical departments that are assigned to that ward. If the arrival rate and LOS of patients are deterministic, $\frac{\lambda}{\mu} = \rho$ beds are occupied. Since the number of admissions varies per day and the LOS varies per patient, more than ρ beds are required to be able to admit most patients. However, the number of required beds has to be very large in order to admit all patients. This is undesirable, since in this case a large number of beds will be empty most of the time, and hence resources will be used inefficiently. Therefore, we aim to find the minimum number of required beds given a blocking probability that is acceptable for DZ.

The Erlang loss model determines the blocking probability B given the arrival rate λ, the LOS $\frac{1}{\mu}$ and the number of available beds x. Recall that the average number of occupied beds equals $\rho = \frac{\lambda}{\mu}$. The blocking probability can be calculated with the following equation:

$$B(\rho, x) = \frac{\rho^x / x!}{\sum_{k=0}^{x} \rho^k / k!} \tag{1}$$

The Erlang loss model has the following assumptions, which are also discussed by Van Essen et al. (2015):

- The arrival of patients follows a Poisson distribution. According to Van Essen et al. (2015) it is not necessary that the arrival of patients exactly follows a Poisson distribution since the variability in arrivals is in generally well captured by this distribution.
- The LOS of patients is independent and identically distributed and follows a general distribution. This assumption holds since the LOS distributions are determined from historical data.
- Patients who cannot be admitted at the assigned ward are transferred to another hospital. This assumption does not hold in DZ. Patients who cannot be admitted at the assigned ward are admitted to another ward. This has to be taken into account when interpreting the results.
- The system is in stationary equilibrium. We can assume our system is in stationary equilibrium since the considered problem is on the strategic level.

Equation (1) can be used to determine the required number of beds given a specified blocking probability, arrival rate and ALOS. Equation (2) can be used to calculate the average number of occupied beds for a combination C of clinical departments, where λ_d is the arrival rate for clinical department d and $\frac{1}{\mu_d}$ is the ALOS for patients of clinical department d.

$$\rho = \sum_{d \in C} \frac{\lambda_d}{\mu_d} \tag{2}$$

The goal is to find the smallest number of beds x for which the blocking probability is smaller or equal to the specified blocking probability. To be able to find the relation between the required number of beds x and the average numbers of occupied beds ρ, it is necessary to calculate equation (1) for a large set of instances and to select only the instances that result in the specified blocking probability. The pseudo code for this algorithm is presented in Appendix E. Figure 15 shows the results for blocking probabilities $B = 10\%$ and $B = 6\%$. A high blocking probability requires fewer beds than a low blocking probability since a larger buffer of beds is required.

Figure 15 shows that the relation between the required number of beds x and the average numbers of occupied beds ρ is represented by a step function. To be able to model this in our MILP, we split the occupancy levels in intervals $i \in I$. If the occupancy level of a combination C falls within interval i, n_i beds are required to ensure that the specified blocking probability is not exceeded.

4.3 Assignment Model formulation

We propose a MILP to determine the optimal assignment of clinical departments to wards and to evaluate different configurations. The MILP decides which clinical department is assigned to which ward. The MILP distinguishes hard and soft constraints, representing prerequisites and preferences related to wards respectively. The objective is to maximize the fulfillment of preferences given a specified blocking probability. These preferences are

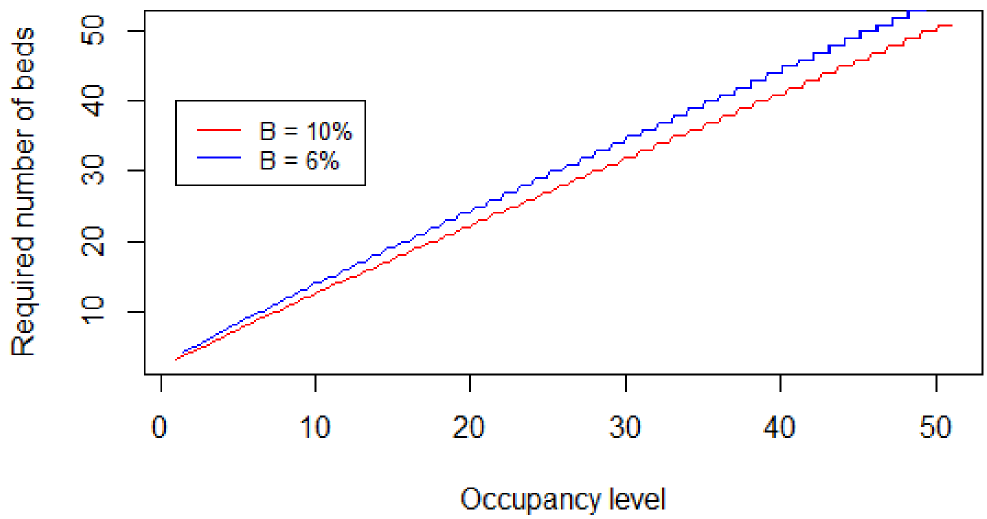

Figure 15: Stepfunction representing the relation between the required number of beds x and the average numbers of occupied beds ρ for a specified blocking probability B, based on Van Essen et al.(2015)

related to efficient use of resources and quality of care. An overview of the sets, indices, variables and parameters used in the MILP is given in Table 4.

Table 4: Overview of the sets, indices, variables and parameters of the proposed MILP

Indices and sets	**Definition**	**Range**
$d, e \in D$	Set of clinical departments	
$w, v \in W$	Set of general wards	
$i \in I$	Set of intervals	

Decision variables	**Definition**	**Range**
$X_{d,w}$	Binary variable indicating whether department d is assigned to ward w (1) or not (0)	Binary
V_w	Variable indicating the required number of beds for ward w	Integer

Auxiliary variables	**Definition**	**Range**
$Y_{w,i}$	Binary variable indicating whether interval i is selected for ward w (1) or not (0)	Binary
$Z_{d,e,w}$	Binary variable indicating whether both departments d and e are assigned to ward w (1) or not (0)	Binary

Parameters	**Definition**	**Range**
$a_{d,e}$	Indicator whether department d and e can share the same ward (1) or not (0)	Binary
$b_{d,w}$	Indicator whether department d is allowed to be assigned to ward w (1) or not (0)	Binary
$k_{d,e}$	Indicator whether department d and e are a combination of shared and single admissions for the same clinical department (1) or not (0)	Binary
$l_{w,v}$	Indicator whether ward w and v are a combination of shared and single rooms for the same ward (1) or not (0)	Binary
$o_{d,e}$	Indicator whether department d and e are the same clinical department but represent another time period (1) or not (0)	Binary
$p_{w,v}$	Indicator whether ward w and v are the same ward but represent another time period (1) or not (0)	Binary
c_w	Capacity of ward w	Integer
λ_d	Arrival rate of department d	Non-negative
$\frac{1}{\mu_d}$	ALOS for patients of department d	Non-negative
m_i	Right endpoint of interval i	Non-negative
n_i	Required number of beds in interval i	Non-negative
$f_{d,e}$	Indicates the preference of department d to be assigned to the same ward as department e	[-1,1]
$g_{d,w}$	Indicates the preference of department d to be assigned to ward w	[-1,1]
h_w	Indicates the preference to concentrate empty beds at ward w (1) or not (0)	Binary
$S1_{min}$	Lower bound for variable $S1$	Free

$S1_{max}$	Upper bound for variable $S1$	Free
$S2_{min}$	Lower bound for variable $S2$	Free
$S2_{max}$	Upper bound for variable $S2$	Free
$S3_{min}$	Lower bound for variable $S3$	Free
$S3_{max}$	Upper bound for variable $S3$	Free
α	Sharing preference weight	Non-negative
β	Assignment preference weight	Non-negative
γ	Concentrate empty beds preference weight	Non-negative

4.3.1 Constraints

The constraints to model the assignment of clinical departments to wards are given below.

Constraint (3) stipulates that each clinical department is assigned to exactly one ward. Constraints (4) ensures that the interval that is selected for the ward, corresponds to a bed occupancy that is greater than or equal to the bed occupancy level of the ward. Constraint (5) stipulates that exactly one interval is selected for each ward. Constraint (6) determines the required number of beds per ward. Constraint (7) stipulates that not more clinical departments are assigned to a ward than the capacity of the ward allows.

Constraints (8) and (9) represent prerequisites related to wards. Constraint (8) stipulates that only clinical departments that are allowed to share a ward are able to share a ward. Constraint (9) stipulates that a clinical department can only be assigned to a ward that is allowed.

$$\sum_{w \in W} X_{d,w} = 1 \quad \forall d \in D \tag{3}$$

$$\sum_{i \in I} Y_{w,i} \cdot m_i \geq \sum_{d \in D} X_{d,w} \cdot \frac{\lambda_d}{\mu_d} \quad \forall w \in W \tag{4}$$

$$\sum_{i \in I} Y_{w,i} = 1 \quad \forall w \in W \tag{5}$$

$$V_w = \sum_{i \in I} Y_{w,i} \cdot n_i \quad \forall w \in W \tag{6}$$

$$V_w \leq c_w \quad \forall w \in W \tag{7}$$

$$X_{d,w} + X_{e,w} - 1 \leq a_{d,e} \quad \forall d, e \in D, w \in W \tag{8}$$

$$X_{d,w} \leq b_{d,w} \quad \forall d \in D, w \in W \tag{9}$$

Each clinical department is split in two subsets. One subset can only be assigned to single rooms and the other subset can only be assigned to shared rooms. Constraints (10) and (11) stipulate that these two subsets are assigned to the same ward, one subset to the single rooms of that particular ward and the other subset to the shared rooms of that particular ward.

$$k_{d,e} \cdot l_{w,v} \cdot (X_{d,w} - X_{e,v}) = 0 \quad \forall d, e \in D, w, v \in W \tag{10}$$
$$k_{d,e} \cdot (1 - l_{w,v}) \cdot (X_{d,w} + X_{e,v}) \leq 1 \quad \forall d, e \in D, w, v \in W \tag{11}$$

To take the variation in arrival rate into account, each clinical department and each ward occurs twice in the set of departments and wards respectively, to represent two different time periods. Constraint (12) and (13) stipulates that if a clinical department is assigned to a particular ward in one time period, this clinical department is also assigned to that particular ward in the other time period. Hence the assignment in both time periods is equal.

$$o_{d,e} \cdot p_{w,v} \cdot (X_{d,w} - X_{e,v}) = 0 \quad \forall d, e \in D, w, v \in W \tag{12}$$
$$o_{d,e} \cdot (1 - p_{w,v}) \cdot (X_{d,w} + X_{e,v}) \leq 1 \quad \forall d, e \in D, w, v \in W \tag{13}$$

Constraints (14), (15) and (16) determine the value of the auxiliary variable $Z_{d,e,w}$, which is required for determining whether two clinical departments are assigned to the same ward.

$$Z_{d,e,w} \leq X_{d,w} \quad \forall d, e \in D, w \in W \tag{14}$$
$$Z_{d,e,w} \leq X_{e,w} \quad \forall d, e \in D, w \in W \tag{15}$$
$$Z_{d,e,w} \geq X_{d,w} + X_{e,w} - 1 \quad \forall d, e \in D, w \in W \tag{16}$$

The soft constraints represent preferences and are given by constraints (17)-(19). Constraint (17) measures the fulfillment of sharing preferences. Constraint (18) measures the fulfillment of assignment preferences. Constraint (19) measures the fulfillment of the concentration of empty beds preference. In DZ only one ward is chosen to concentrate empty wards, hence the parameter h_w equals one for exactly one ward and zero for all other wards. Constraints (20)-(22) scale the preference variables $\tilde{S1}$, $\tilde{S2}$ and $\tilde{S3}$.

$$S1 = \sum_{d \in D} \sum_{e \in D} \sum_{w \in W} Z_{d,e,w} \cdot f_{d,e} \tag{17}$$

$$S2 = \sum_{d \in D} \sum_{w \in W} X_{d,w} \cdot g_{d,w} \tag{18}$$

$$S3 = \sum_{w \in W} (c_w - V_w) \cdot h_w \tag{19}$$

$$\tilde{S1} = \frac{S1 - S1_{\min}}{S1_{\max} - S1_{\min}} \tag{20}$$

$$\tilde{S2} = \frac{S2 - S2_{\min}}{S2_{\max} - S2_{\min}} \tag{21}$$

$$\tilde{S3} = \frac{S3 - S3_{\min}}{S2_{\max} - S3_{\min}} \tag{22}$$

4.3.2 Objective function

The following objective function is used in the model:

$$\max \quad \sum_{w \in W} (c_w - V_w) + \alpha \cdot \tilde{S1} + \beta \cdot \tilde{S2} + \gamma \cdot \tilde{S3} \tag{23}$$

The objective function ensures that the minimum number of required beds is selected and maximizes the fulfillment of the soft constraints. Each soft constraint is given a weight to give each preference a different priority. The value of these weights, α, β and γ, can be determined by the decision makers, the management of DZ in this case. The soft constraints are scaled such that the decision makers do not have to take into account different scales when assigning values to the weights. Therefore weights in the range of 0 to 10 will give the same optimal assignment as weights in the range of 0 to 100. It is also possible to choose a negative weight to prevent the fulfillment of preferences. However, this is not in line with the objective of DZ.

4.4 Conclusion

In this chapter the Bed Requirements Model and the Assignment Model are introduced. Both models are based on the assignment model developed by Van Essen et al. (2015). The Bed Requirements Model uses the Erlang loss formula to determine the bed requirements per combination of clinical departments. The results of this model are used as an input for the Assignment Model. The Assignment Model uses a MILP to determine the optimal assignment of clinical departments to wards taken into account the distinction between single and shared rooms and the variation in arrival rate.

The objective of the proposed MILP is to minimize the number of required beds and to maximize the fulfillment of preferences. The preferences represent combinations of clinical departments, assignments of clinical departments to particular wards and the concentration of empty beds at a particular ward. Each preference is given a weight, which can be determined by decision makers, to be able to specify priorities.

In Chapter 5, the proposed MILP is applied to the case of DZ.

5 Experimentation

The experiments to measure the effect of various initial values, such as proximity preferences and blocking probability, on the performance indicators of wards are described in this chapter. The MILP introduced in Chapter 4, is used to conduct the experiments. The MILP is implemented in AIMMS 4.64 and solved optimally using the CPLEX 12.8 solver. The computation time for the configurations discussed in this chapter is less than five minutes.

Section 5.1 describes the input data for the MILP, Section 5.2 describes the validation of the model, Section 5.3 introduces six configurations and Section 5.4 presents the results of these configurations.

5.1 Input

This section describes the initial values of the sets and parameters that are used as an input for the MILP.

5.1.1 Sets

Clinical departments

Patients are categorized by clinical department. Not all clinical departments that are represent in DZ are included in the experiments. No distinction is made between the general surgery department and the vascular surgery department for example. From data it can not be concluded whether a patient is a vascular surgery patient or a general surgery patient. Additionally, dermatology and rheumatology are not included in the experiments since these departments have a very low arrival rate. In the past three years not more than 30 dermatology patients and 30 rheumatology patients arrived in DZ. Table 5 provides an overview of the clinical departments that are included in the experiments with the corresponding parameters.

Some patients require a single room due to their medical condition. To make sure that these patients are assigned to single rooms, each clinical department is divided into two subsets. One subset represents the patients that require a single room. The other subset represents the patients that do not require a single room.

General wards

In total DZ has six general wards. However, one ward is currently not used for clinical admissions. This ward is included in the input data to be able to test the effect of including this ward on the optimal assignment.

A distinction is made between the single rooms and the shared rooms of a ward. Table 6 provides an overview of the wards that are included in the experiments with the corresponding parameters.

Intervals

The model introduced in Section 4.2 is used to generate a set of intervals for a given blocking probability. This model is implemented in R according to the algorithm described in Appendix E. Each interval represents occupancy levels and corresponds with a required number of beds. The initial blocking probability is 10%. Table 20 in Appendix F provides an overview of the intervals and its initial values.

Table 5: Including clinical departments with corresponding parameters

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Table 6: General wards with corresponding parameters

General ward	**Rooms**	Abbreviation	Capacity
A2	Shared	A2	30
	Single	A2(1)	9
B2	Shared	B2	30
	Single	B2(1)	9
C2	Shared	C2	34
	Single	C2(1)	8
D2	Shared	D2	29
	Single	D2(1)	9
E2	Shared	E2	29
	Single	E2(1)	9
G2	Shared	G2	32
	Single	G2(1)	8

5.1.2 Parameters

Requirements

Sometimes a combination of clinical departments is not allowed to be assigned to the same ward due to medical reasons. It can also hold that a clinical department is not allowed to be assigned to a particular ward. The management of DZ states that in general all clinical departments can be combined and all clinical department can be assigned to all wards. Exceptions are:

- Geriatrics patients or neurology patients are not allowed to be assigned to ward C2 or E2 to reduce the risk of these patients to wander around the hospital. Unlike the other general wards, these wards have two entrances.
- To make sure that the subset of clinical departments that require single rooms can only be assigned to single rooms, it is not allowed to assign this subset to shared rooms. This also holds vice versa.

Capacity

Each ward has a fixed number of beds. A distinction is made between beds in single rooms and beds in shared rooms. Table 6 provides an overview of the capacity per ward. Note that a patient can only be admitted if a bed is staffed. However, the nurse staffing strategy is not in the scope of this research. We assume all beds are staffed.

If insufficient capacity is available to guarantee a maximum blocking probability, the capacity is increased in the model in order to get a solution.

Arrival rate

The arrival rate varies during the year and during the week as described in Chapter 2. From Figure 11 it is clear that most arrivals take place during the week. If the arrival rate is based on all days of the week, the blocking probability will be underestimated during week days and overestimated during weekend days. In order to guarantee a maximum blocking probability throughout the week, we choose to determine the arrival rate based on weekdays. As a consequence the blocking probability will be overestimated for weekend days.

Figure 9 and 10 show that the number of arrivals varies per quarter. Quarter one has most arrivals in total. However, this does not hold for all clinical departments individually. If the arrival rate is based on all four quarters, in each quarter the blocking probability will be underestimated for some clinical departments and overestimated for other clinical departments.

Since most beds are occupied in quarter one (Q1) and quarter four (Q4), we base our solution on the arrival rate in Q1 and Q4. Due to a limitation of computation time it is not possible to take the arrival rate of all four quarters into account.

Table 5 gives the arrival rate per day per clinical department in Q1 and Q4. Data from 2018 is used to determine the arrival rate to focus on the most recent developments. The division between the arrival rate for single rooms and for shared rooms is based on data from DZ. We assume that patients only occupy a single room if it is required for their medical condition. Blocked shared rooms to create single rooms are not taken into account. Therefore the approximated arrival rate of patients that require a single room is underestimated.

Length of stay

We assume that the day of the week and the quarter of the year has no influence on the LOS of patients. Therefore we determine the ALOS of patients based on data from 2018. Table 5 gives the ALOS in days per clinical department.

Preference

As mentioned in Chapter 2, there is a clear preference to locate internal medicine departments close to each other and to locate surgery departments close to each other, however it is ambiguous how the preferences are within these two groups. Experiments show that varying the preferences within the two groups have little influence on the results, since the number of possible combinations are limited due to a fixed capacity and the requirement that clinical departments are not allowed to split up between multiple wards. Therefore in the experiments, we only use the initial values of the parameter $f_{d,e}$, which can be found in Appendix G.

Concerning the preferences for wards, there is a clear preference to locate surgery departments near the operating rooms since these departments have a high throughput and use the operating rooms extensively. There is a preference to assign the nephrology department to ward A2 or B2 since these wards are close to the dialysis department. There is a preference to assign the geriatrics department to ward B2 since ward B2 has wander detection in the floor. The initial values of the parameter $g_{d,w}$ can be found in Appendix H.

Ward A2 is preferred for concentrating empty beds, since this ward is located at the end of the general wards. In this way also the occupied beds in the hospital are concentrated.

Ward G2 is located at the other end of the general wards, however this ward is close to the operating rooms and therefore it is not preferred to concentrate empty beds in this ward.

Weights

Each preferences is given a weight. We initialize the weights for the three preferences based on the preference interviews as described in Chapter 2. Table 7 shows the initial values for the weights.

Table 7: Initial values for the weights α, β and γ

Preference	**Initial value**
Combinations of clinical departments (α)	3
Combination of clinical department and ward (β)	2
Concentrate empty beds (γ)	1

5.2 Validation

Chapter 4 introduces the Bed Requirements Model and the Assignment Model. In this section both models are validated.

5.2.1 Bed Requirements Model

In the Bed Requirements Model the Erlang loss formula is used to calculate the blocking probability given the average number of occupied beds and the number of available beds. In Table 8 the blocking probability calculated with the Erlang loss formula is compared with the percentage of refused admissions per clinical department to validate the Bed Requirements Model. Data from quarter one and four in 2018 is used for this comparison.

Table 8 shows that the blocking probability calculated with the Erlang loss formula differs from the percentage of refused admissions. This has the following reasons:

- The Erlang loss model assumes that the available beds are always staffed. However this is not the case in practice. Hence the blocking probability is underestimated by the Erlang loss formula since the available number of beds is overestimated.
- The Erlang loss model assumes that patients who cannot be admitted at the assigned ward are transferred to another hospital. However in practice the refused patients are assigned to another ward in the hospital. Hence the blocking probability is underestimated by the Erlang loss formula since the arrival rate is underestimated.
- The Erlang loss model assumes that the clinical departments that are assigned to the same ward have the same blocking probability. However, in practice this is not the case. Some patient groups have a higher priority to be assigned to the preferred ward than other patient groups.
- In practice the assignment of patients to wards is more flexible than in the Erlang loss model. If the urgency is high, necessary requirements can be broken in order to provide care. This influences the blocking probability, however this is not incorporated in the Erlang loss model.

As a consequence the results of the Bed Requirements Model have to be interpreted carefully.

Table 8: Percentage of refused admissions per clinical department per quarter (B_{Q1},B_{Q4}) and blocking probability measured with the Erlang loss formula per quarter ($B_{Erlang(Q1)}$,$B_{Erlang(Q4)}$) (HiX Deventer Ziekenhuis, 2018(Q1,Q4), $n = 12116$)

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5.2.2 Assignment Model

The proposed assignments corresponding to the configurations discussed in Sections 5.3 and 5.4 are presented to the management of DZ. According to the management of DZ, who also look at the assignments from a medical perspective, the assignments partially match their preferences. This is expected since due to capacity constraints not all preferences can be fulfilled. It is however the question which preferences are most important and where the compromise must be made. There is no consensus about this. Further research by DZ is necessary in order to formulate a vision regarding the preferences for the assignment of clinical departments to wards. The Assignment Model can be used during this process to determine the optimal assignment for various preference configurations.

5.3 Configurations

This sections describes six configurations. For each of these configurations an optimal assignment is determined. All these configurations use the input as described in Section 5.1 unless otherwise indicated. The results of these experiments can be found in Section 5.4.

1. <u>Current assignment</u>
   Recall from Chapter 2 that some clinical departments have a blocking probability that is larger than 10%. In this configuration the required number of beds per ward is calculated for the current assignment of clinical departments to wards that guarantees a maximum blocking probability of 10%. How many extra beds are necessary in order to meet this standard?

2. <u>Sufficient available capacity?</u>
   In this configuration preferences are not taken into account when determining an optimal assignment. Is sufficient capacity available to guarantee a maximum blocking probability of 10% for all clinical departments? Additionally, this configuration gives insight in the minimum number of required beds.

3. <u>Blocking probability 6%</u>
   The management of DZ allows a maximum blocking probability of 10%. However, the management of DZ also wants to know how many extra beds are required to guarantee a maximum blocking probability of 6%.

4. <u>No clinical admissions at ward E2</u>
   Ward E2 is currently not used for clinical admissions. If the management of DZ decides to allow clinical admissions at ward E2, this ward needs to be redesigned in order to accommodate clinical admissions and this brings rebuilding costs. Therefore we first look at the configuration in which ward E2 is not used for clinical admissions.

5. No clinical admissions at ward C2
Ward E2 and G2 are located closest to the operating rooms. In this configuration we allow no clinical admissions at ward C2 such that the admissions of ANAE(D), ONC(D) and ONC(O) can take place at ward C2 and E2 can be used for clinical admissions that require surgery. This reduces the walking distance of nurses. Another advantage, patients who are in fasting state for surgery do not need to pass the staff restaurant if they are assigned to ward E2 or G2. Additionally, the surgical departments with the smallest ALOS are assigned to E2 since this ward is more appropriate for short stays. Since ward C2 is least preferred for clinical admissions, this ward is chosen to be closed for clinical admissions.

6. Concentrate all clinical oncology patients
To reduce the number of required nurses specialized in oncology in order to comply to the SONCOS standard, this configuration concentrates all clinical oncology patients. This configuration uses different arrival rates and LOSs, since in this configuration the oncology department also includes oncology patients from other clinical departments. For example, currently in DZ an oncology patient with lung cancer can be registered as a pulmonary medicine patient instead of an oncology patient. In this configuration this patient is registered as an oncology patient. Hence in this configuration the oncology clinical department has a larger arrival rate than in the other configurations.

5.4 Results

This section describes for each of the configurations introduced in Section 5.3 the optimal assignment. The blocking probability and the fulfillment of proximity preferences is given per configuration. The approximated bed occupancy and throughput per configuration are shown in Appendix I and are not discussed in this section. As mentioned in Chapter 2, the bed occupancy is underestimated, therefore no conclusions can be drawn from the calculated bed occupancy.

1. Current assignment

Table 9 shows the assignment for configuration 1, this is the current assignment of clinical departments to wards in DZ. The corresponding required number of beds is shown in Figure 16. The objective value of this configuration is 5.

From the results of configuration 1 we conclude the following:

- In order to guarantee a maximum blocking probability of 10% ward B2 and C2 require extra capacity. Ward A2 and G2 can use a double room as a single room to solve the shortage of single rooms in Q1 and Q4 respectively.

Table 9: Assignment of clinical departments to wards for configuration 1: Current assignment

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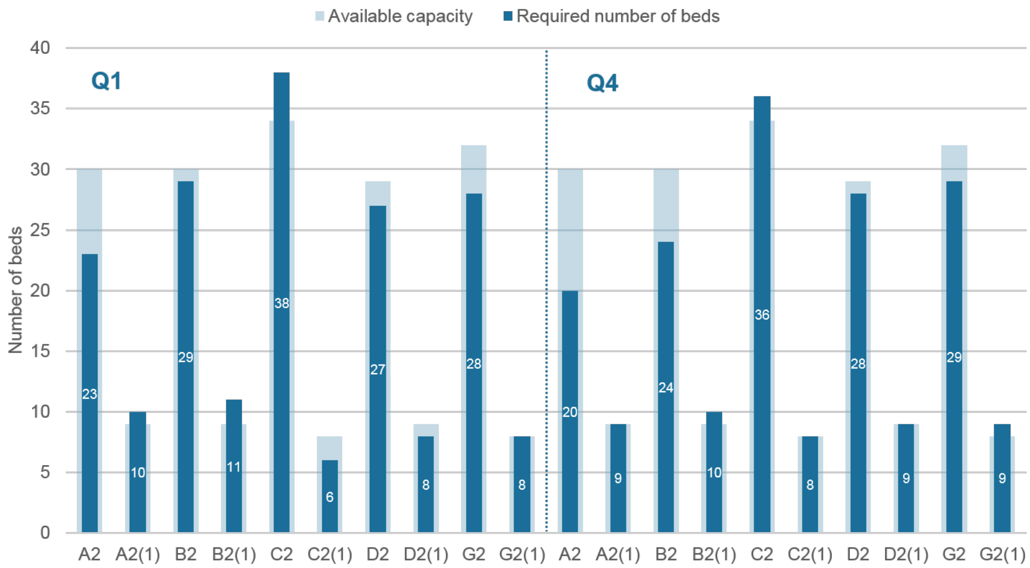

Figure 16: Required number of beds for configuration 1: Current assignment

2. Sufficient available capacity?

Table 10 shows the optimal assignment for configuration 2. The corresponding required number of beds is shown in Figure 17. The objective value of this configuration is 1.

From the results of configuration 2 we conclude the following:

- There is insufficient capacity to guarantee a blocking probability of 10% for all clinical departments without assigning a clinical department to multiple wards.
- In Q1 ward D2 has a shortage of one single bed. The shortages in ward B2 in Q1 and ward G2 in Q4 can be solved by blocking a double room for a single room. The shortage in ward C2 in Q1 can be solved by using single rooms for patients that not necessarily require a single room.
- The proposed assignment of this configuration does not match the preferences of the stakeholders. This can also be seen in the objective value, which is very low compared to the other configurations.

Table 10: Optimal assignment of clinical departments to wards for configuration 2 Sufficient available capacity?

A2	**B2**	**C2**	**D2**	**E2**	**G2**
ANAE(C) CAR ONC(C) GER	INT NEU	SUR NEPH ORA OPH	PUL GAST URO	ANAE(D) ONC(D) ONC(O)	GYN TRAU ENT ORT PLAS

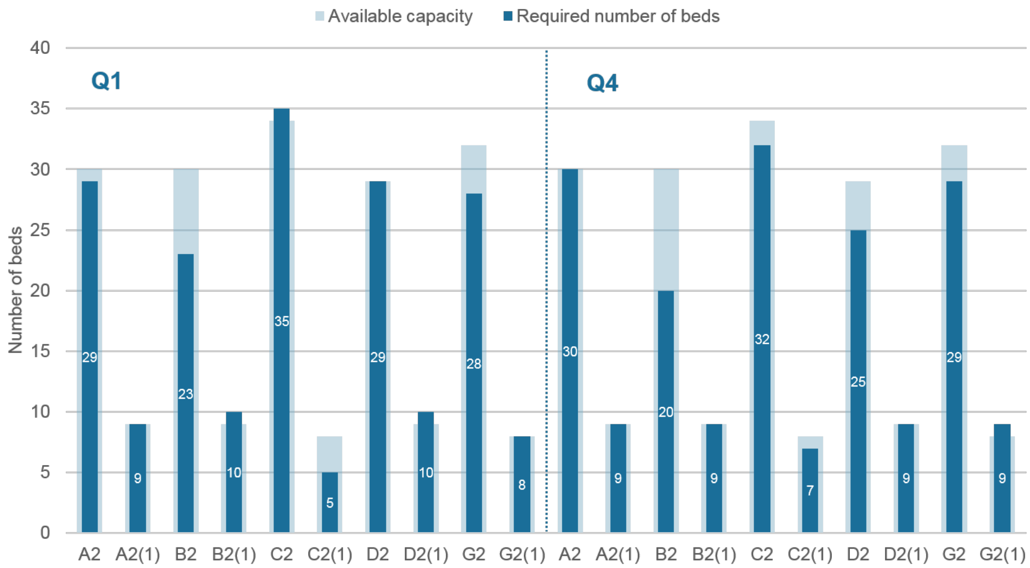

Figure 17: Required number of beds for configuration 2 Sufficient available capacity?

3. Blocking probability 6%

Table 11 shows the optimal assignment for configuration 3. The corresponding required number of beds is shown in Figure 18. The objective value of this configuration is 5.81.

From the results of configuration 3 we conclude the following:

- There is insufficient capacity to guarantee a blocking probability of 6% for all clinical departments.
- Even if it is allowed to assign a clinical department to multiple wards, there is still a shortage of approximately 5 beds in single rooms and 2 beds in shared rooms.

Table 11: Optimal assignment of clinical departments to wards for configuration 3 Blocking probability 6%

A2	**B2**	**C2**	**D2**	**E2**	**G2**
ONC(C) GER PUL	ANAE(C) CAR NEPH NEU	INT ORT	SUR	ANAE(D) ONC(D) ONC(O)	GYN TRAU ORA ENT GAST OPH PLAS URO

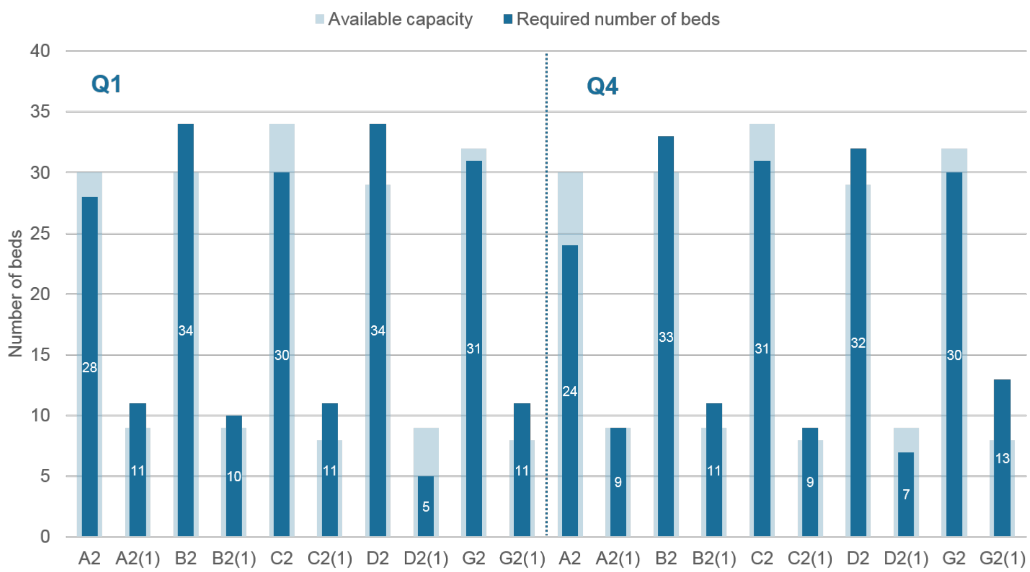

Figure 18: Required number of beds for configuration 3 Blocking probability 6%

4. <u>No clinical admissions at ward E2</u>

Table 12 shows the optimal assignment for configuration 4. The corresponding required number of beds is shown in Figure 19. The objective value of this configuration is 5.33.

From the results of configuration 4 we conclude the following:

- It is necessary to assign a clinical department to multiple wards in order to have a maximum blocking probability of 10% for all clinical departments if ward E2 is closed for clinical admissions.
- In Q1 ward G2 can use a double room for a single room to solve the shortage, however this is not sufficient in Q4. The single room that is available in ward D2 in Q4 can be used to solve this shortage, however this results in outliers.
- We propose to assign the vascular surgery department that is included in the surgery department, to ward A2 to concentrate vascular patients. The exact bed occupancy of this department is unknown, however the management of DZ expects that it is possible to fit this group in ward A2. This solves the shortage of beds in ward C2 in Q1 and Q4.
- The proposed assignment of this configuration largyly matches the preferences of the stakeholders.

Table 12: Optimal assignment of clinical departments to wards for configuration 4 No clinical admissions at ward E2

A2	B2	C2	D2	E2	G2
CAR NEU	INT NEPH GER	ANAE(C) SUR ONC(C)	GYN URO ORA ENT OPH LONG PLAS	ANAE(D) ONC(D) ONC(O)	TRAU GAST ORT

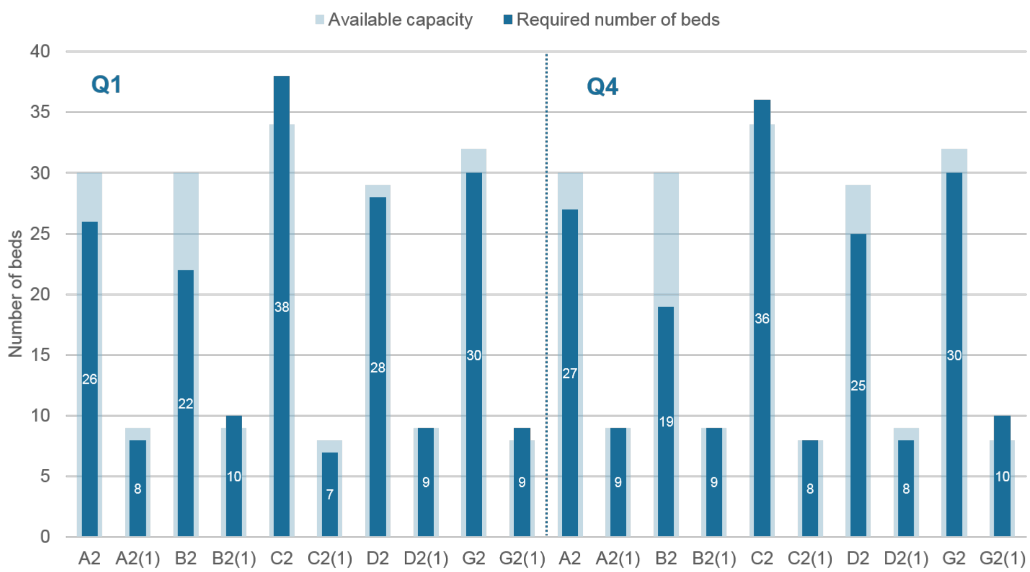

Figure 19: Required number of beds for configuration 4 No clinical admissions at ward E2

5. No clinical admissions at ward C2

Table 13 shows the optimal assignment for configuration 5. This configuration has as a restriction that URO, OPH, PLAS, GYN, ENT and ORA are assigned to E2 and TRAU, ORT ans SUR to G2. This distinction is based on ALOS. The corresponding required number of beds is shown in Figure 20. The objective value of this configuration is 5.67.

From the results of configuration 5 we conclude the following:

- Ward G2 has an extreme shortage of beds. Hence, it is necessary to assign a clinical department to multiple wards in order to have a maximum blocking probability of 10% for all clinical departments if ward C2 is closed for clinical admissions.
- We suggest to split the general surgical department. The vascular surgery patients, for example, can be assigned to ward D2 since cardiology and neurology patients require similar care. Additionally, within the general surgery department a distinction can be

made between short and long stay patients. However, further data analysis must be carried out in order to determine the bed occupancies of these groups.

- The proposed assignment of this configuration largely matches the preferences of the stakeholders.

Table 13: Optimal assignment of clinical departments to wards for configuration 5 No clinical admissions at ward C2

A2	**B2**	**C2**	**D2**	**E2**	**G2**
ONC(C) PUL GAST	ANAE(C) INT NEPH GER	ANAE(D) ONC(D) ONC(O)	CAR NEU	URO OPH PLAS GYN ENT ORA	TRAU ORT SUR

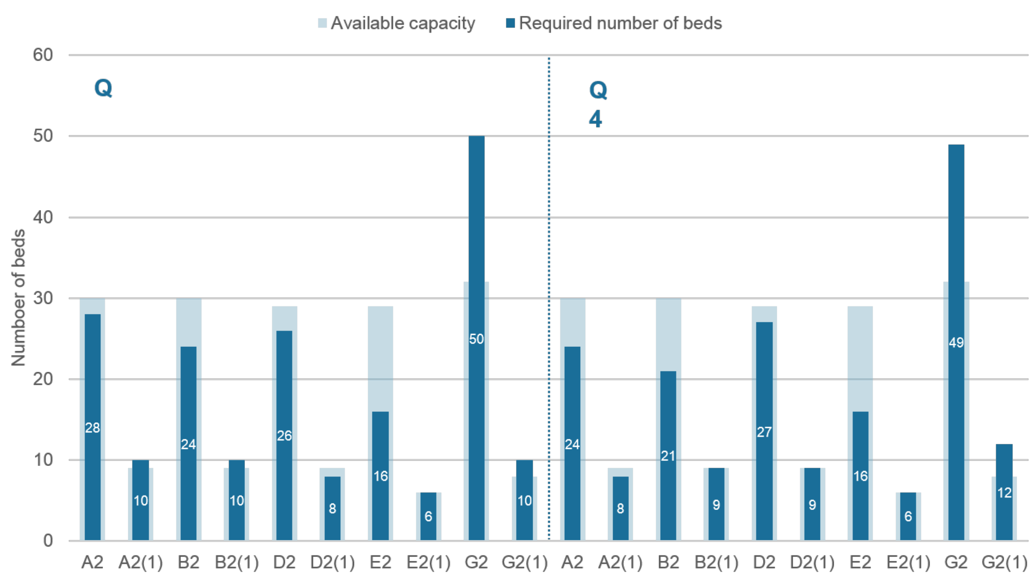

Figure 20: Required number of beds for configuration 5 No clinical admissions at ward C2

6. Concentrate all clinical oncology patients

Table 14 shows the optimal assignment for configuration 6. The corresponding required number of beds is shown in Figure 21. The objective value of this configuration is 6.12.

From the results of configuration 6 we conclude the following:

- It is necessary to assign a clinical department to multiple wards in order to have a maximum blocking probability of 10% for all clinical departments in Q4 if all oncology patients are concentrated.
- In Q4 ward G2 has a shortage of one bed in a single room even if available double rooms in ward G2 are blocked for single rooms.

- In Q4 ward C2 has a shortage of two beds.
- In Q1 sufficient capacity is available for the proposed assignment of this configuration if 1 double room in ward A2, B2 and G2 is blocked for a single room and if ward C2 uses 1 single room for a patient that not necessarily requires a single room.
- The proposed assignment of this configuration shows that by allowing a shortage of three beds, it is possible to concentrate all clinical oncology patients in one ward.

Table 14: Optimal assignment of clinical departments to wards for configuration 6 Concentrate all clinical oncology patients

A2	**B2**	**C2**	**D2**	**E2**	**G2**
INT	CAR	SUR	GER	ANAE(D)	GYN
PUL	NEPH	ONC(C)	ORT	ONC(D)	URO
	NEU		ANAE(C)	ONC(O)	TRAU
					GAST
					ORA
					ENT
					OPH
					PLAS

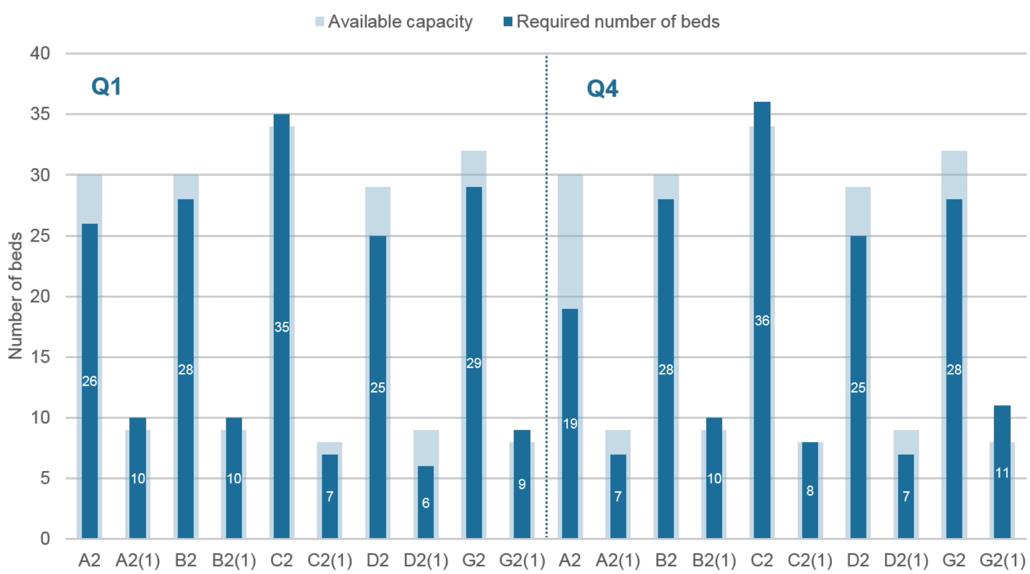

Figure 21: Required number of beds for configuration 6 Concentrate all clinical oncology patients

5.5 Conclusion

This chapter described six configurations and their performance. The MILP introduced in Chapter 4, is used to determine the optimal assignment per configuration. The performance of the six configurations is summarized in Table 15.

From configuration 2 we conclude that currently insufficient capacity is available in DZ to guarantee a blocking probability of 10%. However by splitting up a clinical department and blocking a double room for a single room, the shortage of beds can be solved. This is not possible if the maximum allowed blocking probability is 6% as shown by the results of configuration 3.

Configurations 4, 5 and 6 present three possible assignments of clinical departments to wards for DZ. Configuration 5 shows that insufficient bed capacity is available to close ward C2 for clinical admissions and to concentrate the clinical departments with the lowest ALOS in one ward. However the advantage of configuration 5 is that walking distance is reduced and patients in fasting state do not need to pass the staff restaurant. Moreover, the management of DZ expects that in the future more surgical admissions can be handled in day treatment and hence the bed occupancy of surgery departments in general wards decreases. Additionally, assigning the general surgery department to three wards reduces the shortages of available beds. Configuration 5 offers an opportunity to optimize processes in wards by concentrating clinical departments based on their ALOS.

Configuration 6 is preferred over configuration 4 as can be seen by the level of fulfilment of proximity preferences. Also configuration 6 has the advantage of concentrating oncology patients such that less specialized oncology nurses are required to meet the SONCOS standard. Hence, concentrating oncology patients results in bed occupancies of clinical departments that are favourable for combining clinical departments.

The validation of the Bed Requirements Model shows that the results have to be interpreted carefully. Adjustments are necessary in order the increase the reliability of the results.

Table 15: The blocking probability and level of fulfilment of proximity preferences for the six configurations

configuration	**Blocking probability**	**Proximity preferences**
1. Current assignment	10%	5
2. Sufficient available capacity?	10%	1
3. Blocking probability 6%	6%	5.81
4. No clinical admissions at E2	10%	5.33
5. No clinical admissions at C2	10%	5.67
6. Concentrate all clinical oncology patients	10%	6.12

6 Practical implications

The implementation of the results of this study has practical implications. This chapter describes these implications. Section 6.1 describes prerequisites for the implementation of the Assignment Model. Section 6.2 describes the short term practical implications and Section 6.3 describes the long term practical implications. Section 6.4 concludes this chapter.

6.1 Prerequisites

The data used for the context analysis is incomplete. The arrival rate for single rooms is underestimated since it is not known how many shared rooms are blocked to serve as a single room. Additionally, it is not known which patients are classified as oncology patients and need specialized care in order to comply to the SONCOS standard. This study underestimates the number of oncology patients due to the absence of this classification.

If the management wants to use the Assignment Model to determine a new assignment in order to reduce the stress on single rooms and to comply to the SONCOS standard, the data gathering should be expanded. All patients that require a single room must be registered and all patients that are oncology patients must be classified as oncology patients.

The context analysis shows that 12% of the admissions in 2016 to 2018 had a reallocation between two general wards. However, from data it is not clear why these reallocations took place and which policy drives these reallocations. Human interventions influence the blocking probability. In order to minimize blocking probability, it is necessary for the management of DZ to identify the policy that drives the reallocations. Which ward is optimal to reallocate a patient?

During the feedback sessions, it became clear that currently their is no consensus about the basic principles for the assignment of clinical departments to wards. It is clear that a separation between surgical and internal departments is preferred, however the preferences within these two groups are not clear. Due the fixed capacity of wards, not all preferences can be fulfilled and a compromise must be made. We advise DZ to continue the discussion about preferences in order to find a consensus. During this process, the Assignment Model can be used to determine the optimal assignment for various preference configurations.

6.2 Short term implications

Changing the assignment of clinical departments to wards requires reorganisation of multiple processes. For each of the stakeholders of wards the required reorganisation is described below.

- **Patients**
  Patients may need to be reallocated to other wards if the assignment of clinical departments to wards changes. This reallocation needs to be carried out carefully, to not hinder the provision of care for patients. The proposed Bed Requirements Model can be used when making the reallocation plan, for example by determining in which order the clinical departments must reallocate.

  Additionally, the route descriptions for the clinical departments need to be adjusted such that patients can find their ward.

- **Nurses**
  Nurses from a clinical department collaborate with nurses from the clinical departments that are assigned to the same ward. If the assignment of clinical departments to wards changes, the composition of these multidisciplinary teams changes. The management of DZ needs to support the new multidisciplinary teams in order to encourage collaboration. Additionally, the distance towards central facilities such as the operating rooms and emergency departments may change due to a reallocation of their clinical department. As a consequence the travel time to central facilities may increase or decrease and this has to be taken into account in the work planning of nurses.
- **Physicians**
  Due the a new assignment physicians may need to change their route in order to visit patients from their clinical department. This could effect the travel time of physicians and as a consequence their working pressure.
- **Management**
  The management of DZ needs to direct the implementation of the new assignment of clinical departments and wards. Besides supporting the nurses and physicians in the reorganisations also the cleaning, catering and provisioning staff need to be informed and their processes need to be evaluated in order to determine whether reorganisation is necessary.

6.3 Long term implications

If a new assignment of clinical departments to wards is beneficial for DZ, the management should consider to evaluate the assignment of clinical departments to wards on a regular base. We advise the management to incorporate this evaluation in the yearly strategic planning and to use the Assignment Model proposed in this study to determine an optimal assignment for updated input values.

Additionally we advise DZ to maintain a flexible design in the general wards such that general wards can be used for all clinical departments. Rebuilding a ward such that it is specifically designed for a particular clinical department, makes it much more expensive to reassign clinical departments to wards.

6.4 Conclusion

If the management of DZ wants to implement the results of this study, they have to take into account practical implications. These practical implications can be divided into prerequisites and short term and long term implications.

In order to rely on the results of the Assignment Model introduced in this study, DZ requires registration of patients that require a single room and classification of oncology patients. Additionally, rules need to be formulated for reallocating patients such that the influence of human interventions on the blocking probability is minimized.

Currently their is no consensus about the preferences for the assignment of clinical departments to wards. We advise DZ to develop a consensus and to use the Assignment Model in this process to determine the optimal assignment for various preference configurations.

The short term practical implications include implications for patients, nurses, physicians and the management. The proposed Assignment Model can be used during the reallocation process to determine in which order the clinical departments must be reallocated.

The long term practical implications include the embedding of the assignment of clinical departments to wards in the structural planning and maintaining a flexible design in general wards.

In the next chapter additional recommendations are given for DZ and the results of this study are discussed.

7 Conclusions and recommendations

This chapter contains the conclusions of this research and gives recommendations for DZ. Section 7.1 describes the conclusions of this research and its added value for science and practice. Section 7.2 contains the discussion and recommendations and describes further research.

7.1 Conclusions

Recall the objective of this research:

> *Develop a model for assigning clinical departments to wards in order to find a trade-off between the blocking probability and efficient use of resources, taken into account standards and future trends.*

We successfully developed a model based on the Assignment Model of Van Essen et al. (2015) that assigns clinical departments to wards. The Erlang loss formula is used to determine the required number of beds given a maximum allowed blocking probability. A MILP is used to determine the optimal assignment taking into account the distinction between single and shared rooms, the variation in arrival rate and the concentration of empty beds. The MILP aims to minimize the number of required beds and maximize the fulfillment of preferences related to combinations of clinical departments and combinations of clinical departments and wards.

The results show that insufficient capacity is available in DZ to guarantee a maximum blocking probability of 10%. However by assigning a clinical department to two wards and by blocking double rooms to serve as single rooms, the shortage of beds can be solved.

The results also show that the fulfilment of proximity preferences in DZ related to general wards, can be increased by changing the assignment of clinical departments to wards. Closing ward C2 offers opportunities to reduce walking distance and concentrate patients based on length of stay, however currently insufficient capacity is available to close ward C2. This may change in the future, if the ALOS of patients from surgery departments decreases and if the general surgery deparment is assigned to multiple wards.

However, currently their is no consensus about the preferences for the assignment of clinical departments to wards in DZ. Developing a consensus is an iterative process, for which in each step various preferences configurations must be evaluated. In each iteration the optimal assignment of the preference configuration can be determined using the Assignment Model proposed in this study. Hence, the Assignment Model is a supporting tool for decision making in DZ.

Concentrating oncology patients does not only reduce the number or required specialized oncology nurses, but also increase the fulfillment of proximity preferences. This is an attractive configuration for DZ.

7.1.1 Value for science

Models for assigning clinical departments to wards have been developed before by Van Essen et al. (2015), Bekker et al. (2017) and Hübner et al. (2018). However, to the best of our knowledge, we are the first to develop an assignment model that takes into account the distinction between single and shared rooms and concentrates empty beds. Additionally, our method for taking the variation of arrival rate into account does not require a prepossessing step. This is different than the method proposed by Hübner et al. (2018).

7.1.2 Value for practice

DZ can use the results of this study to support decision making related to the assignment of clinical departments to wards. The results can be used to measure the effect of concentrating empty beds. Additionally, the results inventories the number of required single and shared rooms given a maximum allowed blocking probability. Also, the Assignment Model can be used to evaluate various preference configurations.

The results in this study clearly showed the bottlenecks regarding the optimal assignment: insufficient capacity, high demand for single rooms and seasonal patterns. DZ will use this insight in the strategic planning of wards.

The proposed model for assigning clinical departments to wards can can be expanded to also take into account specialized wards and day treatment. The model can also applied to assign clinical departments to outpatient clinics.

It is also possible to apply the proposed model to other areas. The model can for example be used to assign departments to offices within a company building or university or to assign school classes to classrooms. Moreover, the model can be used to determine the optimal assignment for assigning pieces of a chocolate bar to your colleagues taking into account (your) preferences.

7.2 Discussion

The validation of the Bed Requirements Model shows that the approximated blocking probability does not correspond with the current blocking probability. The blocking probability is underestimated since the model assumes all beds are open for admissions and patients who are refused at their preferred ward are transferred to another hospital. However, the blocking probability is also overestimated, since the relation between the bed occupancy and required number of beds is approximated with intervals. The blocking probability on weekend days is also overestimated, since only weekdays are taken into account in our solution. Also, in practice more flexibility regarding the assignment of patients is allowed than modelled in this study.

Adjustments are necessary in order the increase the reliability of the results. At this moment the Assignment Model can be used to evaluate different assignments, preferences and blocking probabilities for the general wards, in order to support decision making. However, extra research is necessary if the results need to be implemented in practice.

The model can be improved by adjusting the ALOS of patients such that bed preparation time is also taken into account. This increases the demand for beds and hence increases the accuracy of the approximation of available bed capacity.

A simulation offers the possibility to measure the effect of assigning refused patients to others ward in the hospital on the bed occupancy and blocking probability of wards. By simulating the general wards, taken into account the assignment proposed by the Assignment Model, and applying a strategy for reallocating refused patients to other wards, this can be achieved. Another option is to increase the arrival rate of patients, based on the number of refused patients per ward.

In order to increase the accuracy of the approximated intervals in the Bed Requirements Model, we recommend to increase the step size of the bed occupancy. However, this also increases computation time.

We recommend DZ the following in order to improve the results of the proposed models:

- Register patients according to the classification applied to general wards. For example, now a nephrology patient is classified as a internal medicine patient in the data. However, in general wards there is a distinction between internal medicine and nephrology patients. Based on other statistics we determined which patients are nephrology patients and which patients are internal medicine patients, however this is an approximation. Therefore we recommend to apply the classification of clinical departments in general wards also to the data.
- Register which patients require a single room and register when shared rooms are blocked to serve as a single room. Now, we underestimated the demand for single rooms since blocked shared rooms where not taken into account.
- Classify oncology patients in order to measure precisely the arrival rate and length of stay of oncology patients for the compliance to the SONCOS standard. Now the number of oncology patients is underestimated since no classification is used.

Besides adjusting the assignment of clinical departments to wards, other adjustments are possible to decrease the discrepancy between demand and supply in wards.

- The results in this study focuses on the strategic planning of general wards. However, in order to decrease the discrepancy between demand and supply in wards it is necessary to study flexible staffing policies on a tactical level. How many specialized nurses and how many flexible nurses must be deployed to use resources efficiently?
- Artificial fluctuation influences the discrepancy between demand and supply in wards. The discrepancy can be decreased if the schedule of elective admissions takes the bed occupancy of wards into account. Currently only the operating room schedule is taken into account when planning an elective patient. Hence, we recommend to study the impact of the operating room schedule on the bed occupancy of general wards.
- Currently admissions and discharges of elective patients mostly take place at the same time. Since both these processes take a lot of time, this results in a high workload for nurses. Also, elective patients have to wait to be admitted or are admitted in other wards, if a scheduled discharge did not take place yet. Hence we advise to study optimal scheduling of admissions and discharges to balance the workload of nurses and decrease waiting time and reallocations of patients.

- Aftercare influences the LOS of patients. For example, if no nursing home has capacity to admit a patient that requires aftercare, the LOS in the hospital is extended. Also, a discharge of a patient requires discharge papers from the physician. Additionally a taxi is sometimes necessary. If the physician does not have the discharge papers ready in time or if the taxi has delay, the patient cannot leave the hospital and this effects the admissions of new patients. Hence, we recommend to optimize the organization of aftercare to improve the discrepancy between demand and supply in wards.

The admissions of some elective patients take place in a temporary admission room if no beds are available before the surgery. After the surgery the patient is assigned to a bed in the ward. Since the patient changes from room, the personal belongings of the patient also have to be reallocated. Currently the nurses reallocate these belongings. Before the surgery, the belongings are brought to the storage of the ward and with stickers it is specified which patient owns the belongings. After the surgery, a nurse needs to find the belongings of the patient in the storage and brings them back to the patient. This costs a lot of time and space in the storage. We advise DZ to urge patients to bring a minimal amount of personal belongings, place them in a bag and hang the bag on the patient's bed. In this way nurses do not have to reallocate the belongings.

Most hospitals have a fixed nurse to patient ratio in general wards and this is questionable. New admissions and discharges take most time. Therefore it is expected that clinical departments with a high throughput need to have more nurses compared to clinical departments with a lower throughput. Hence, we advise to consider different nurse to patient ratios when modeling general wards.

The SONCOS standard states that at least halve of the nurses that take care of an oncology patient, needs to be specialized in oncology. It is not clear which problem the new SONCOS standard tries to solve.

The standard applies to all oncology patients: oncology patients that require surgery, chemotherapy, immunotherapy or another treatment and oncology patients that are admitted for observation. The nurse specialization in oncology however, focuses on chemotherapy. One can question whether an oncology patient that needs surgery and not chemotherapy, needs a nurse specialized in oncology. This particular patient needs a nurse specialized in wound care. Hence, it is questionable whether concentrating all oncology patients improves the quality of care for all oncology patients or increases efficiency if besides nurses specialized in oncology also other nurse specializations are necessary. Additionally, concentrating specialized oncology nurses can also be a threat for patients of other clinical departments that are not diagnosed with cancer but require similar care.

In this research we approached the organisation of general wards from the capacity perspective. One can also look at the organisation of care in general wards. Why are patients concentrated by clinical department and not for example on ALOS? Why are nurses specialized in one clinical department? In order to optimize the quality of care in general wards, we recommend to study these questions and compare alternatives.

In this research only two different time periods were taken into account to account for the variation in arrival rate. The model can be expanded by taken for example the average arrival rate of all four quarters into account. However, it is necessary to model this in an efficient way to prevent long computation time.

The results show that shared rooms need to serve as a single room and vice versa to have a feasible assignment. In this study these adjustments were calculated by hand. We recommend to expand the model such that the model also determines how many and which shared rooms should be blocked to serve as a single room and how many and vice versa.

References

Bahadori, M., Teymourzadeh, E., & Kazemi, R. (2017). Mathematical modeling for bed allocation in a military hospital. *Journal of Military Medicine*, *19*(4), 390–399.

Bekker, R., Koole, G., & Roubos, D. (2017). Flexible bed allocations for hospital wards. *Health care management science*, *20*(4), 453–466.

Cardoen, B., Demeulemeester, E., & Beliën, J. (2010). Operating room planning and scheduling: A literature review. *European journal of operational research*, *201*(3), 921–932.

de Bruin, A. M., Bekker, R., Van Zanten, L., & Koole, G. (2010). Dimensioning hospital wards using the erlang loss model. *Annals of Operations Research*, *178*(1), 23–43.

Green, L. V., & Nguyen, V. (2001). Strategies for cutting hospital beds: the impact on patient service. *Health services research*, *36*(2), 421.

He, L., Madathil, S. C., Oberoi, A., Servis, G., & Khasawneh, M. T. (2019). A systematic review of research design and modeling techniques in inpatient bed management. *Computers & Industrial Engineering*, *127*, 451–466.

Holm, L. B., Lurås, H., & Dahl, F. A. (2013). Improving hospital bed utilisation through simulation and optimisation: with application to a 40% increase in patient volume in a norwegian general hospital. *International journal of medical informatics*, *82*(2), 80–89.

Hübner, A., Kuhn, H., & Walther, M. (2018). Combining clinical departments and wards in maximum-care hospitals. *OR Spectrum*, *40*(3), 679–709.

Hübner, A., Walther, M., & Kuhn, H. (2016). Approach to clustering clinical departments. In *Health care systems engineering for scientists and practitioners* (pp. 111–120). Springer.

Kortbeek, N., Braaksma, A., Burger, C. A., Bakker, P. J., & Boucherie, R. J. (2015). Flexible nurse staffing based on hourly bed census predictions. *International journal of production economics*, *161*, 167–180.

Landa, P., Sonnessa, M., Tànfani, E., & Testi, A. (2018). Multiobjective bed management considering emergency and elective patient flows. *International Transactions in Operational Research*, *25*(1), 91–110.

Levine, W. C., & Dunn, P. F. (2015). Optimizing operating room scheduling. *Anesthesiology clinics*, *33*(4), 697–711.

van de Vrugt, N., Schneider, A., Zonderland, M., Stanford, D. A., & Boucherie, R. (2018). Operations research for occupancy modeling at hospital wards and its integration into practice. In *Operations research applications in health care management* (pp. 101–137). Springer.

van Essen, J. T., van Houdenhoven, M., & Hurink, J. L. (2015). Clustering clinical departments for wards to achieve a prespecified blocking probability. *OR spectrum*, *37*(1), 243–271.

A Map of the general wards in DZ

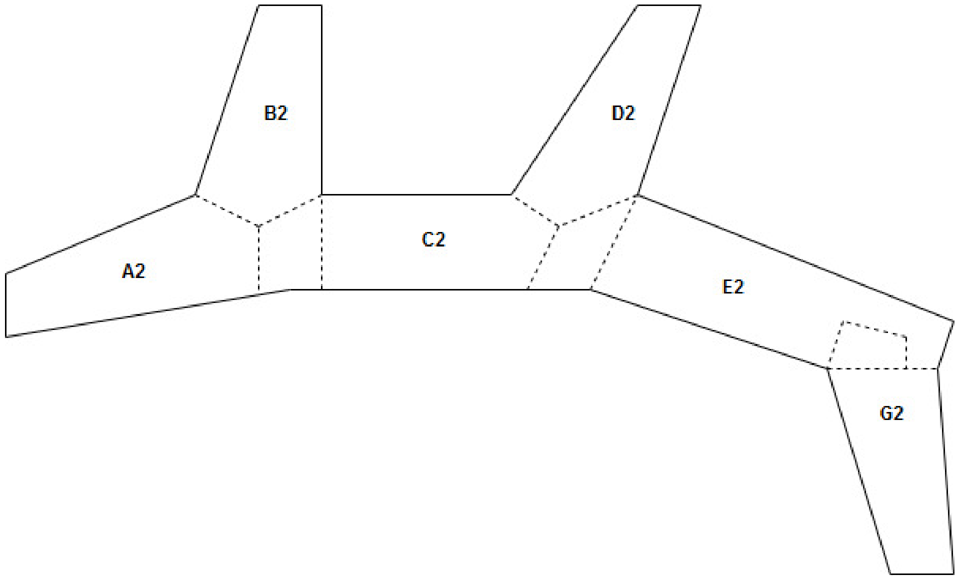

Figure 22: Map of general wards in DZ. All general wards are located at the second floor of DZ.

Table 16: The current assignment of clinical departments to wards in DZ

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B Problem bundle

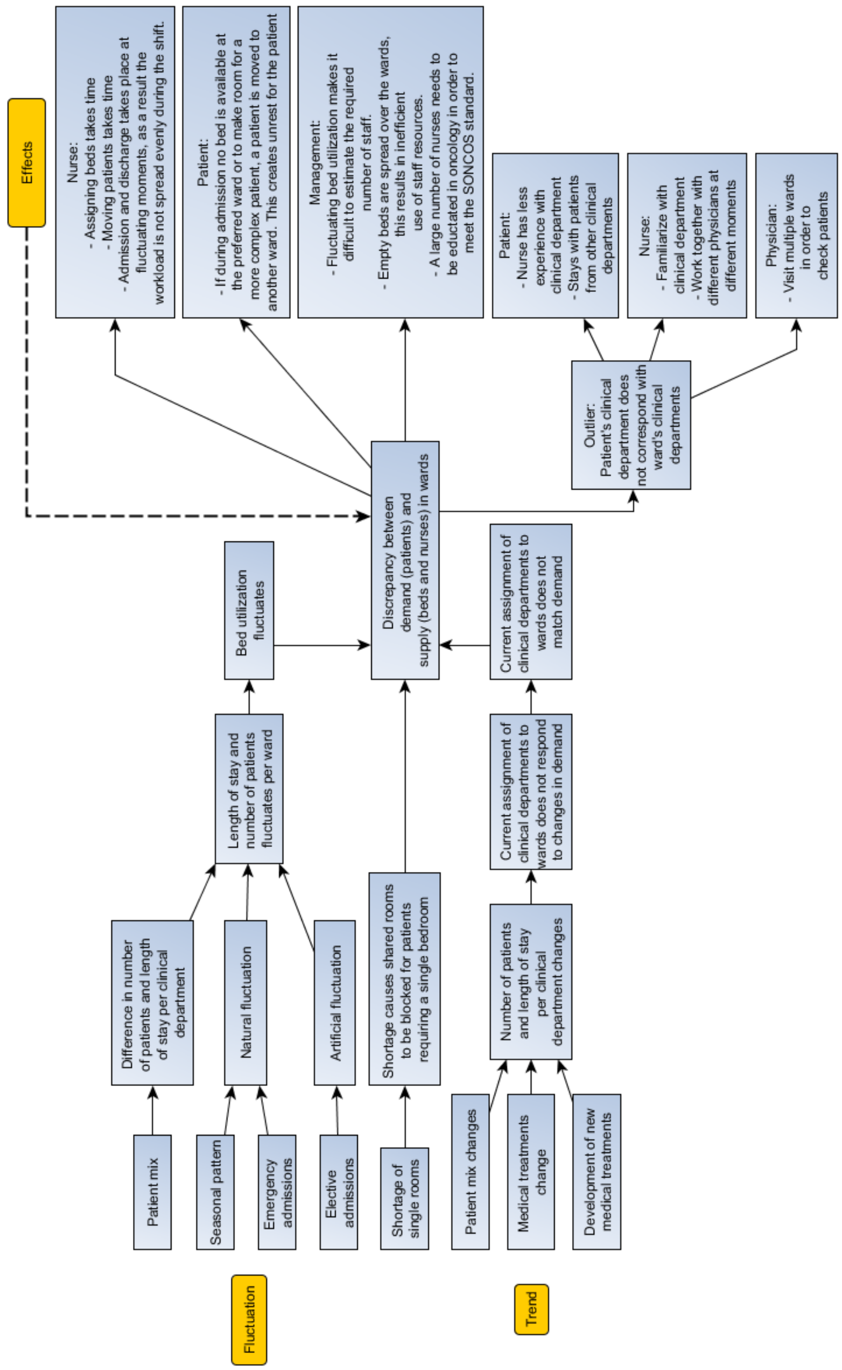

Figure 23: Problem bundle

C Preference interview setup

In order to measure the preferences for the assignment of clinical departments to wards, interviews were held with various stakeholders such as the managers of the wards and the manager of admissions. The setup of these interviews is described in this appendix.

The setup of the preference interviews consist of two phases. In the first phase all participating stakeholders are interviewed individually to prevent the participants from influencing each other. In the second phase the outcomes of the first phase are presented in a group interview to feedback the results. Appendix C.1 describes phase one and Appendix C.2 describes phase two.

C.1 Phase one: Individual interviews

During the individual interviews each participant is asked to elaborate on their preferences for the assignment of clinical departments to wards. The preferences are divided in the following three preference perspectives:

- Preference for combinations of clinical departments
- Preference for clinical department and ward combinations
- Preference for a ward for concentrating empty beds

The preference for combinations of clinical departments mostly relates to nursing expertise. If clinical departments with a similar nursing expertise are located close to each other, the nurses from these clinical departments can support each other. The preference for clinical department and ward combinations mostly relates to proximity preferences. Some wards are located closer to the operating rooms than others, for example.

Besides, the participants were also asked to weight the different preferences. Which preference is most important and how do the different preferences relate to each other?

In total five stakeholders were interviewed individually including two ward managers, the admission manager, the head of patient logistics and the head of the general wards. Although all these participants have a role as a manager, they also looked at the preferences from a medical perspective. Most of these managers have a background as a nurse.

Unfortunately it was not possible to interview patients to measure their preferences for the assignment of clinical departments to wards. According to the complaints officer, no complaints were registered in the last three years regarding the assignment of clinical departments to wards. Hence we assume that the preferences mentioned by the managers also match the preferences of the patients since these preferences are also leading principles for the current assignment.

Based on the outcomes of the individual interviews, various preference configurations are derived.

C.2 Phase two: Group interview

During the group interview the preference configurations derived from the individual interviews are presented. Aim of the group meeting is to check if the results of the individual interviews are interpreted correctly. Additionally, an optimal assignment for each of the preference configurations is presented. The participants of the group interview are asked to assess these assignments.

In total six stakeholders participated in the group interview including four ward managers, the head of admissions and the head of patient logistics.

Based on the outcomes of the group interview, the preference configurations were adjusted.

D Literature search strategy

As a starting point for the literature search we used the paper of Van Essen et al. (2015). To the best of our knowledge, they are the first to formulate a model that explicitly assigns clinical departments to wards with a fixed capacity. Citations and references of this paper were included in the literature search.

Additionally a search on Scopus was carried out. Table 17 provides an overview of the search terms and exclusion criteria. Table 18 provides an overview of the included papers.

Table 17: Overview of search terms in Scopus and exclusion criteria

Search terms	**Scope**	**Date**	**Number of papers**
“bed allocation”	Article title, Abstract, Keywwords	12-04-2019	59
(“bed blocking” OR “refused admissions”) AND “hospital”	Article title, Abstract, Keywwords	12-04-2019	42
(“bed occupancy” OR “bed utilization”) AND “ward”	Article title, Abstract, Keywwords	12-04-2019	365

Exclusion criteria	**Motivation**
- Papers published before 2009	Focus on recent developments
- Papers focused on a specific department in the hospital such as the IC or emergeny department	Focus on general wards
- Papers focused on specific patient groups	Focus on general wards

Table 18: Overview of included papers from the literature search

Search	Included papers	Context
Citation Van Essen et al. (2015)	(Hübner, Walther, & Kuhn, 2016)	Assignment model
	(Hübner, Kuhn, & Walther, 2018)	Assignment model
References Van Essen et al. (2015)	(Green & Nguyen, 2001)	Benefits of clustering clinical departments
	(de Bruin, Bekker, Van Zanten, & Koole, 2010)	Erlang loss model
Scopus search	(He et al., 2019)	Literature review on inpatient bed management
	(van de Vrugt et al., 2018)	Operation research for hospital wards
	(Holm, Lurås, & Dahl, 2013)	Case study in Norwegian hospital
	(Bahadori, Teymourzadeh, & Kazemi, 2017)	Case study in a military hospital
	(Landa, Sonnessa, Tànfani, & Testi, 2018)	Case study in Italian hospital
	(Bekker, Koole, & Roubos, 2017)	Assignment models
	(Kortbeek, Braaksma, Burger, Bakker, & Boucherie, 2015)	Flexible staffing policies

E Pseudo code Bed Requirements Model

Algorithm 1 and 2 contain the pseudo code of the Bed Requirements Model introduced in Chapter 4. Table 19 explains the abbreviations used in algorithm 1 and 2.

Table 19: List of abbreviations used in pseudo code

Abbreviation	**Definition**
ρ	Bed occupancy
$\rho_{\max}$	Maximum allowed bed occupancy
Δ_ρ	Step size $(\rho_{i+1} - \rho_i)$
λ	Patient arrival rate
μ	Service rate
x	Number of available beds
$x_{\max}$	Maximum number of available beds
B	Maximum allowed blocking probability

Algorithm 1 Bed Requirements Model (Part A)

function ERLANG LOSS FORMULA(λ,μ,x)
$\triangleright$ *This function uses the Erlang loss formula to calculate the blocking probability given the arrival rate, service rate and available number of beds.*
    $\rho = \lambda/\mu$
    Numerator $= \rho^x$
    Denominator $= 0$
    for i in $1 : x$ **do**
        Denominator $=$ Denominator $+ \rho^i/i!$
    end for
    Blocking.Probability $=$ Numerator/Denominator
    return Blocking.Probability
end function

function BLOCKING PROBABILITIES($\rho_{\max}$, Δ_ρ, $x_{\max}$)
$\triangleright$ *This function creates a matrix with blocking probabilities. These blocking probabilities are calculated for different instances, taken into account the maximum bed occupancy, the precision and the maximum number of beds. The calculation is based on the Erlang loss formula.*
    nrow $= \rho_{\max}/\Delta_\rho$
    ncol $= x_{\max}$
    Blocking.Probabilities $=$ matrix(nrow, ncol)
    $\rho = 1$
    for i in 1:nrow **do**
        for j in 1:ncol **do**
            Blocking.Probabilities$[i, j]$ $=$ ERLANG LOSS FORMULA(ρ, j)
            $\rho = 1 + i \cdot \Delta_\rho$
        end for
    end for
    return Blocking.Probabilities
end function

function FIND BLOCKING COMBINATIONS(B, $\rho_{\max}$, Δ_ρ, $x_{\max}$)
$\triangleright$ *This function creates a matrix that contains all combinations of bed occupancy and required number of beds, that result in the specified blocking probability. Each new combination (B, ρ, x) is added to the matrix.*
    nrow $= 0$
    ncol $= 3$
    Blocking.Combinations $=$ matrix(nrow, ncol)
    Blocking.Probabilities $=$ BLOCKING PROBABILITIES($\rho_{\max}$, Δ_ρ, $x_{\max}$)
    for i in 1:($\rho_{\max}/\Delta_\rho$) **do**
        for j in 1:$x_{\max}$ **do**
            if Blocking.Probabilities$[i, j]$ $==$ B **then**
                Add (B, $1 + i * \Delta_\rho$, j)) to Blocking.Combinations
            end if
        end for
    end for
    return Blocking.Combinations
end function

Algorithm 2 Bed Requirements Model (Part B)

function CREATE INTERVAL TABLE(B, $\rho_{\max}$, Δ_ρ, $x_{\max}$)
▷ *This function creates an interval table for a specified blocking probability, using the Find Blocking Combinations function. The first column contains the required number of beds, the second and third column represent the left and right endpoints of the bed occupancy interval respectively.*

    Blocking.Combinations = FIND BLOCKING COMBINATIONS(B, $\rho_{\max}$, Δ_ρ, $x_{\max}$)
    nrow = $x_{\max}$
    ncol = 3
    Interval.Table = matrix(nrow,ncol)
    Interval.Table[,1] = c(1:$x_{\max}$)
    Interval.Table[,2] = rep.int(100, $x_{\max}$)
    for i in 1:nrow(Blocking.Combinations) **do**
        x = Blocking.Combinations[i,3]
        ρ = Blocking.Combinations[i,2]
        if $\rho <$ Interval.Table[x,2] **then**
            Interval.Table[x,2] = ρ
        else
            if $\rho >$Interval.Table[x,3] **then**
                Interval.Table[x,3] = ρ
            end if
        end if
    end for
    return Interval.Table

end function

function APPROXIMATE INTERVAL TABLE(B, $\rho_{\max}$, Δ_ρ, $x_{\max}$)
▷ *The interval table contains gaps, this function approximates the total length of the intervals such that there are no gaps. The right endpoint of the previous row is taken as the left endpoint of the current row (+0.01). This is possible since the 10 % blocking probability is an upper bound for the blocking probability.*

    Approximate.Interval.Table = CREATE INTERVAL TABLE(B, $\rho_{\max}$, Δ_ρ, $x_{\max}$)
    for i in 2:nrow(Approximate.Interval.Table) **do**
        Approximate.Interval.Table[i,2] = Approximate.Interval.Table[i-1,3] + 0.01
    end for
    return Approximated.Interval.Table

end function

F Intervals Bed Requirements Model

Table 20: Bed occupancy intervals with required number of beds given a 10% blocking probability [Data from Bed Requirements Model implemented in R]. Interval 51 is added in order be able to provide an interval for all possible combinations of clinical departments.

Interval number	Right endpoint	Required number of beds
1	0.00	0
3	1.03	3
4	1.94	4
5	2.86	5
6	3.79	6
7	4.73	7
8	5.68	8
9	6.64	9
10	7.62	10
11	8.61	11
12	9.60	12
13	10.61	13
14	11.62	14
15	12.64	15
16	13.67	16
17	14.70	17
18	15.74	18
19	16.78	19
20	17.82	20
21	18.87	21
22	19.92	22
23	20.97	23
24	22.02	24
25	23.08	25
26	24.14	26
27	25.21	27
28	26.27	28
29	27.34	29
30	28.41	30
31	29.47	31
32	30.55	32
33	31.62	33
34	32.69	34
35	33.77	35
36	34.84	36
37	35.92	37
38	37.00	38
39	38.08	39

40	39.16	40
41	40.24	41
42	41.33	42
43	42.41	43
44	43.49	44
45	44.58	45
46	45.66	46
47	46.75	47
48	47.84	48
49	48.93	49
50	50.01	50
51	500.00	500

G Initial value of preference for combinations of clinical departments

Table 21: Initial value $f_{d,e}$ (part A)

	ANAE(C)	ANAE(D)	CAR	GYN	SUR	TRAU	INT	NEPH	ONC(C)	ONC(D)
ANAE(C)	0	0	0	0	0	0	0	0	0	0
ANAE(D)	0	0	0	0	0	0	0	0	0	0
CAR	0	0	0	0	0	0	0	1	0	0
GYN	0	0	0	0	0	0	0	0	0	0
SUR	0	0	0	0	0	1	0	0	0	0
TRAU	0	0	0	0	1	0	0	0	0	0
INT	0	0	0	0	0	0	0	0	0.5	0
NEPH	0	0	1	0	0	0	0	0	0	0
ONC(C)	0	0	0	0	0	0	0.5	0	0	0
ONC(D)	0	0	0	0	0	0	0	0	0	0
ONC(P)	0	0	0	0	0	0	0	0	0	0
ORA	0	0	0	1	0	0	0	0	0	0
ENT	0	0	0	1	0	0	0	0	0	0
GER	0	0	0	0	0	0	1	0	0.5	0
PUL	0	0	0	0	0	0	1	0	0.5	0
GAST	0	0	0	0	0.5	0.5	0	0	0.5	0
NEU	0	0	1	0	0	0	0	1	0	0
OPH	0	0	0	1	0	0	0	0	0	0
ORT	0	0	0	0	1	1	0	0	0	0
PLAS	0	0	0	1	0	0	0	0	0	0
URO	0	0	0	0.5	0.5	0.5	0	0	0	0

Table 22: Initial value $f_{d,e}$ (part B)

	ONC(O)	ORA	ENT	GER	PUL	GAST	NEU	OPH	ORT	PLAS	URO
ANAE(C)	0	0	0	0	0	0	0	0	0	0	0
ANAE(D)	0	0	0	0	0	0	0	0	0	0	0
CAR	0	0	0	0	0	0	1	0	0	0	0
GYN	0	1	1	0	0	0	0	1	0	1	0.5
SUR	0	0	0	0	0	0.5	0	0	1	0	0.5
TRAU	0	0	0	0	0	0.5	0	0	1	0	0.5
INT	0	0	0	1	1	0	0	0	0	0	0
NEPH	0	0	0	0	0	0	1	0	0	0	0
ONC(C)	0	0	0	0.5	0.5	0.5	0	0	0	0	0
ONC(D)	0	0	0	0	0	0	0	0	0	0	0
ONC(O)	0	0	0	0	0	0	0	0	0	0	0
ORA	0	0	1	0	0	0	0	1	0	1	0.5
ENT	0	1	0	0	0	0	0	1	0	1	0.5
GER	0	0	0	0	1	0	0	0	0	0	0
PUL	0	0	0	1	0	0	0.5	0	0	0	0
GAST	0	0	0	0	0	0	0	0	0.5	0	0
NEU	0	0	0	0	0	0	0	0	0	0	0
OPH	0	1	1	0	0	0	0	0	0	1	0.5
ORT	0	0	0	0	0	0.5	0	0	0	0	0.5
PLAS	0	1	1	0	0	0	0	1	0	0	0.5
URO	0	0.5	0.5	0	0	0	0	0.5	0.5	0.5	0

H Initial value of preference for combinations of clinical department and ward

Table 23: Initial value $g_{d,w}$

	A2	B2	C2	D2	E2	G2
ANAE(C)	0	0	0	0	0	0
ANAE(D)	0	0	0	0	0	0
CAR	0	0	0	0	0	0
GYN	0	0	0	0	1	1
SUR	0	0	0	0	0	1
TRAU	0	0	0	0	1	1
INT	0	0	0	0	0	0
NEPH	0	1	0	0	0	0
ONC(C)	0	0	0	0	0	0
ONC(D)	0	0	0	0	0	0
ONC(O)	0	0	0	0	0	0
ORA	0	0	0	0	1	1
ENT	0	0	0	0	1	1
GER	0	1	0	0	0	0
PUL	0	0	0	0	0	0
GAST	0	0	0	0	0	0
NEU	0	0	0	0	0	0
OPH	0	0	0	0	1	1
ORT	0	0	0	0	1	1
PLAS	0	0	0	0	1	1
URO	0	0	0	0	1	1

I Bed occupancy and throughput per configuration

Table 24: Throughput and bed occupancy in days for configuration 1

	Q1					Q4				
	A2	**B2**	**C2**	**D2**	**G2**	**A2**	**B2**	**C2**	**D2**	**G2**
Bed occupancy shared rooms	67%	90%	108%	83%	80%	59%	72%	101%	88%	84%
Throughput shared rooms	20.07	26.98	36.84	24.17	25.74	17.83	21.66	34.18	25.45	26.96
Bed occupancy single rooms	81%	88%	50%	57%	67%	64%	75%	71%	65%	72%
Throughput single rooms	7.32	7.94	3.96	5.17	5.38	5.72	6.76	5.67	5.89	5.77

Table 25: Throughput and bed occupancy in days for configuration 2

	Q1					Q4				
	A2	**B2**	**C2**	**D2**	**G2**	**A2**	**B2**	**C2**	**D2**	**G2**
Bed occupancy shared rooms	90%	68%	98%	93%	90%	94%	59%	88%	79%	93%
Throughput shared rooms	26.89	20.39	33.41	27.08	26.02	28.31	17.76	30.03	22.95	27.04
Bed occupancy single rooms	71%	84%	35%	84%	62%	72%	71%	57%	68%	70%
Throughput single rooms	6.37	7.55	2.76	7.55	5.55	6.47	6.40	4.54	6.10	6.29

Table 26: Throughput and bed occupancy in days configuration 3

	Q1					Q4				
	A2	**B2**	**C2**	**D2**	**G2**	**A2**	**B2**	**C2**	**D2**	**G2**
Bed occupancy shared rooms	77%	99%	75%	101%	81%	64%	95%	77%	93%	79%
Throughput shared rooms	23.08	29.72	25.66	29.40	25.93	19.25	28.50	26.10	27.09	25.13
Bed occupancy single rooms	79%	67%	90%	24%	91%	56%	81%	70%	38%	106%
Throughput single rooms	7.13	6.00	7.19	2.16	7.30	5.01	7.25	5.62	3.43	8.49

Table 27: Throughput and bed occupancy in days for configuration 4

	Q1 **A2**	**B2**	**C2**	**D2**	**G2**	Q4 **A2**	**B2**	**C2**	**D2**	**G2**
Bed occupancy shared rooms	80%	65%	108%	90%	86%	81%	56%	102%	77%	88%
Throughput shared rooms	23.93	19.60	36.72	26.00	27.53	24.23	16.72	34.69	22.21	28.24
Bed occupancy single rooms	59%	82%	49%	73%	82%	68%	69%	63%	55%	94%
Throughput single rooms	5.34	7.38	3.94	6.54	6.59	6.15	6.20	5.01	4.95	7.49

Table 28: Throughput and bed occupancy in days for configuration 5

	Q1 **A2**	**B2**	**D2**	**E2**	**G2**	Q4 **A2**	**B2**	**D2**	**E2**	**G2**
Bed occupancy shared rooms	86%	73%	94%	104%	83%	86%	62%	94%	97%	88%
Throughput shared rooms	25.88	21.80	27.22	30.19	26.41	25.88	18.53	27.38	28.24	28.23
Bed occupancy single rooms	80%	83%	64%	24%	86%	80%	69%	73%	40%	96%
Throughput single rooms	7.18	7.46	5.73	2.16	6.84	7.18	6.24	6.59	3.63	7.65

Table 29: Throughput and bed occupancy in days for configuration 6

	Q1 **A2**	**B2**	**C2**	**D2**	**G2**	Q4 **A2**	**B2**	**C2**	**D2**	**G2**
Bed occupancy shared rooms	80%	86%	99%	79%	83%	56%	84%	102%	79%	81%
Throughput shared rooms	23.99	25.78	33.64	22.99	26.45	16.67	25.29	34.69	23.02	25.92
Bed occupancy single rooms	82%	76%	49%	41%	82%	49%	76%	59%	50%	106%
Throughput single rooms	7.37	6.80	3.92	3.69	6.58	4.45	6.87	4.73	4.46	8.46