The assessment of pooling intensive care and high care units at the neonatology department of Wilhelmina Kinderziekenhuis

Master's thesis – A. Oude Weernink

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Preface

Giving birth to a child is said to be one of the most beautiful moments in live. However, not all parents are lucky to give birth to a healthy child. What would you think would happen if there are severe complications during the pregnancy? Or what if someone gives birth to their child way to early? In both cases the new-born will need extensive monitoring and will probably be admitted to a neonatology department.

In the past eight months, I had the opportunity to perform my Master′s thesis in an inspiring environment: the neonatology department of Wilhelmina Kinderziekenhuis. At this department new-borns are admitted, born as early as 24 weeks gestation, and they are fighting for their lives. Already at the second day at the department, I had put on a white uniform and I was experiencing the first week at the care units. Immediately, the clinical relevance of this project became clear. Those infants were tiny, and they were covered in all kind of medical equipment, and their parents had the most stressful and emotional time of their lives. Now this project is completed, and I came up with an advice for the neonatology department, I think that this implementing resource pooling will have impact on many parents-to-be.

At first, I want to thank several people that helped me with the content of this report. Gréanne Leeftink, thank you for your support during this project, and giving me the freedom to explore my strengths and weaknesses. I would like to thank Erwin Hans for his critical notes and help me improve my writing in general. I also want to thank Willem de Vries for being so enthusiastic about our discipline and for constantly wanting to understand what I was doing. I would like to thank the personnel of the neonatology department for their hospitality. At last, I want to thank Michel Zeilmaker for providing all necessary files for the data analyses.

I want to thank my family and friends for supporting me as well. Together, we made lots of jokes about me making babies for my simulation model. The past few months were challenging, but you made sure that I continue to be motivated.

Finally, I hope you enjoy reading this report and that you will be inspired by such an extraordinary environment.

Anneloes Oude Weernink, Utrecht, May 2018

Management summary

Background In 2021, the renovation of the neonatology department of Wilhelmina Kinderziekenhuis will start. In the new lay-out, the current intensive care (IC) units and the high care (HC) unit are merged into two large spaces with 32 separate family rooms in total. The department has the choice to either preserve the division of 24 intensive care rooms versus 8 high care rooms, or change their capacity strategy by making all family rooms accessible for both patient types, which is called a total pooling strategy. To make an informed decision, the neonatology department wants to assess the influence of such a strategy change on the number of rejections and the number of patients treated.

Goal and method In this report, we evaluate the current performance of the neonatology department by using three types of mathematical models. We want to validate whether these models are an adequate estimation of current processes and whether they can assess the influence of merging the IC and HC units. Moreover, with the validated models we want to conclude whether merging care units will be beneficial for the performance of the neonatology department of Wilhelmina Kinderziekenhuis.

We make an overview of current processes that are related to admitting, rejecting, transferring and discharging patients. Moreover, we determine the current performance of the department based on available data. The overall performance is defined by the number of patients treated and number of rejections, which are called the key performance indicators (KPI). Since these numbers depend on the available resources, an overview about used bed capacity is made as well.

We evaluate the performance of the current lay-out by using three types of mathematical models: Erlang loss model, workload control systems and a simulation model. With the same models we assess the influence of merging the neonatal units. Based on this information we conclude whether these models are good estimators for the performance of the neonatology department and whether merging the intensive and high care units will be beneficial.

Context analysis The neonatology department has a maximum capacity of 32 beds, of which 24 IC beds and 8 HC beds. Unfortunately, not all beds are open, since the number of open beds is depending on the number of available nurses and the department currently has a shortage of personnel. In 2016, the department was operating with 20 beds on average.

On average, every 11.75 hours an IC patient arrives at the neonatology department. This results in more than 600 patients arriving on a yearly basis. These patients are new-borns, and they are in need of acute and intensive care.

Unfortunately, not all IC patients can be assigned to a bed at the neonatology department, since the number of available beds is limited. When no bed is available for the treatment of a new patient, the patient is rejected. In 2016, 93 patients were rejected, which is 12.5% of all

IC arrivals. There is one patient population that has the highest probability of being rejected: the multiple births. In 2017, around 50% of all rejections were patients part of a multiple birth. This is caused by that patients part of a multiple birth all have to be admitted to a bed, or they are rejected when not enough beds are available.

When a patient no longer needs the intensive care, the patient can be either transferred to the HC unit or to a peripheral hospital. 84% of the IC patients is transferred to a peripheral hospital, and 16% of all IC patients is transferred to the HC unit.

Results In this thesis, multiple types of results are generated. At first, results are given for assessing the effect of resource pooling at the neonatology department. Secondly, results of the comparison of the three models are given. With the Erlang loss model, the PAC model, and the simulation model, we generated results that showed that total resource pooling will be beneficial for the neonatology department.

In case of the Erlang loss model, 24 IC beds result in a rejection probability of 15% for IC patient, and 8 HC beds result in a rejection probability of 13%. Both probabilities are higher than the rejection rate of 2016: 12.5%. However, when the resource are pooled into 32 beds and a combined arrival rate and service rate is calculated, we found a rejection probability of only 6%.

By assessing the influence of resource pooling with the PAC model, the waiting time for patient was eliminated. With using 28 beds the expected waiting time was 5.38 hours with the no-pooling strategy. In case of the total pooling strategy the expected waiting time is 0.00 hours.

Afterwards, a simulation model was made and the performance of the department was assessed with this model. We conclude that the positive effects of resource pooling are larger with a smaller number of open beds. On average the number of rejections were decreased with 30%.

Conclusion and recommendation Based on the results found by analysing historical data, by performing calculations with the Erlang loss model and PAC model, and by simulating the department, we conclude that total resource pooling reduces the number of rejections and increases the number of admissions. Therefore, we suggest that the neonatology department of Wilhelmina Kinderziekenhuis should build 32 identical family rooms, which can treat both IC and HC patients. In this way, the neonatology department will be able to treat as many patients as possible with their limited capacity. Moreover, the financial benefit of resource pooling is significant, since by pooling 18 IC beds and 6 HC into 24 universal beds, the income of the department increases with €1,588,651.

We also have two types of recommendation: for the neonatology department and for further research. We recommend that the department should build 32 identical family rooms to make resource pooling possible. Moreover, we think that further research in applying workload control systems in healthcare could be beneficial.

Management samenvatting

Achtergrond In 2021 zal de verbouwing van de neonatologie afdeling van het Wilhelmina Kinderziekenhuis van start gaan. Na de verbouwing zullen de huidige intensive care (IC) units en de high care (HC) unit vervangen worden door twee grote ruimtes met daarin in totaal 32 familiekamers. Nu staat de afdeling voor de keuze om de capaciteitsstrategie hetzelfde te houden en 24 van deze kamer toe te wijzen aan IC patiënten en 8 aan HC patiënten, of de strategie kan zo aangepast worden dat alle kamers beschikbaar zijn voor zowel IC als HC patiënten. Dit laatste wordt ook wel *resource pooling* genoemd. Om een weloverwogen beslissing te maken, wil de afdeling eerst weten wat de invloed van deze aanpassing zal zijn op het aantal weigeringen en het aantal opnames.

Doel en methode In dit onderzoek evalueren wij de huidige prestaties van de neonatologie afdeling met behulp van drie wiskundige modellen. Wij willen bevestigen dat deze modellen gebruikt kunnen worden om een adequate schatting te maken van de huidige situatie en dat deze modellen de invloed van het samenvoegen van de twee zorg units kunnen bepalen. Daarnaast willen we concluderen of het samenvoegen van de IC en HC units voordelig zal zijn voor de prestatie van de neonatologie afdeling van het Wilhelmina Kinderziekenhuis.

We maken een overzicht van de huidige process omtrent het opnemen, weigeren, overplaatsen en ontslaan van patinten. Daarnaast bepalen we de huidige prestaties op basis van beschikbare data. Het aantal weigeringen en het aantal opnames bepalen de prestatie van de afdeling en daarom worden dit de kritieke prestatie-indicatoren (KPI) genoemd. Deze indicatoren zijn afhankelijk van de beschikbare middelen en daarom is er ook een overzicht gemaakt van de bed capaciteit.

Daarna evalueren we de prestatie van de afdeling op basis van drie wiskundige modellen: Erlang verlies model, PAC model en een simulatiemodel. Deze modellen worden ook gebruikt om het samenvoegen van de neonatale units te modeleren en de invloed ervan vast te stellen. Op basis van deze informatie concluderen we of deze modellen een goede schatting zijn voor de prestaties en of *resource pooling* een gunstige strategie is voor de neonatologie afdeling van het Wilhelmina Kinderziekenhuis.

Context analysis De maximumcapaciteit van de neonatologie afdeling is 32 bedden, waarvan er 24 bestemd zijn voor IC patiënten en 8 voor HC patiënten. Helaas worden niet alle bedden benut, omdat het openen van de bedden afhankelijk van de hoeveelheid beschikbare verpleegkundigen en de afdeling momenteel kampt met een personeelstekort. In 2016 waren er gemiddeld 20 bedden in gebruik per dag.

Gemiddeld gezien arriveert er elke 11.75 uren een IC patiënt op de neonatologie afdeling. Dit resulteert in meer dan 600 IC patiënten die per jaar arriveren. Deze patiënten zijn pasgeboren en hebben acute en intensieve zorg nodig.

Helaas, kunnen niet alle arriverende IC patënten opgenomen worden op de neonatologie afdeling van het Wilhelmina Kinderziekenhuis. Het aantal beschikbare bedden is beperkt en wanneer er geen bed meer vrij is, moet de patiënt geweigerd worden. In 2016 werden 93 patënten geweigerd, wat toen 12.5% was van alle gearriveerde IC patënten. Er is één patëntgroep waarbij de kans op weigering groter is dan gemiddeld, namelijk bij de meerlingen. In 2017 waren 50% van alle weigeringen patënten die deel uit maken van een meerling. Als er een meerling arriveert, moet er namelijk voor elke patënt een bed beschikbaar zijn, zodat de gehele meerling opgenomen kan worden, want anders worden alle patënten van die meerling geweigerd.

Als een patënt niet meer op de IC hoeft te zijn, kan de patënt overgeplaatst worden naar de HC unit of naar een perifeer ziekenhuis. Van alle arriverende IC patënten wordt 84% na IC behandeling overgeplaatst naar een perifeer ziekenhuis en de resterende 16% naar een HC bed.

Resultaten In dit onderzoek hebben we meerdere soorten resultaten gegenereerd. Ten eerste zijn er resultaten van de drie modellen wat betreft het *resource poolen*. Ten tweede zijn er resultaten die betrekking hebben op de vergelijking van de drie modellen. Met zowel het Erlang verlies model, als het PAC model, als het simulatiemodel, hebben we resultaten gevonden die laten zien dat het *poolen* van de middelen gunstig is voor de neonatologie afdeling.

In het geval van het Erlang verlies model, resulteert het gebruik van 24 IC bedden in een weigeringskans van 15% voor IC patënten en 8 HC bedden in een weigeringskans van 13% voor HC patënten. Beide kansen liggen hoger dan de kans zoals in 2016, toen was deze kans 12.5%. Als de bedden *gepooled* zijn en er een gemeenschappelijke *arrivalrate* en *service rate* gebruikt wordt, is de weigeringskans 6% voor alle patënten.

Bij het bepalen van de invloed van *resource pooling* met het PAC model, de wachttijd was geëlimineerd. Wanneer er 28 bedden gebruik worden is de verwachte wachttijd 5.38 uren met de *no-pooling* strategie. In het geval van de *total pooling* strategy was de verwachte wachttijd verminderd naar 0.00 uren.

Daarna hebben we een simulatiemodel gemaakt, waarmee ook de prestatie van de afdeling is bepaald als het gebruik maakt van de *total pooling* strategie. We concluderen dat resource pooling grotere voordelen heeft op het moment dat er minder open bedden zijn. Gemiddeld gezien zijn de weigeringen met 30% afgenomen.

Conclusie en aanbevelingen Op basis van de resultaten gevonden met behulp van historische data, de berekeningen met het Erlang verlies model, het PAC model en het simulatiemodel, kunnen wij concluderen dat de prestatie van de afdeling beter is in het geval van de *total pooling* strategie. Het aantal weigeringen en het aantal opnames is in dat geval namelijk toegenomen.

Wij hebben twee soorten aanbevelingen: die voor de neonatologie afdeling en die voor verder onderzoek. Wij bevelen de neonatologie afdeling aan om de familiekamers bij de verbouwing zo in te richten dat de *total pooling* strategie toegepast kan worden. Op deze manier kan de afdeling namelijk zoveel mogelijk patiënten behandelen met de beperkte capaciteit. Verder lijkt het financiële effect van resource pooling ook gunstig te zijn. Bij het *poolen* van 18 IC en 6 IC bedden naar 24 universele bedden, kunnen namelijk 62 extra patiënten behandeld worden en dat levert €1,588,651 extra inkomsten op. Verder bevelen wij aan om meer onderzoek te doen naar de logistiek omtrent de neonatologie, maar om dan ook landelijk te kijken. Daarnaast zou het van toegevoegde waarde zijn om het toepassen van *workload control systems* in de gezondheidssector nogmaals te onderzoeken.

Contents

List of acronyms

CQN	Closed queueing network
FCC	Family centred care
HC	High care
IC	Intensive care
ICU	Intensive care unit
LOS	Length of stay
MC	Medium care
MDA	Mean distribution analysis
NICU	Neonatal intensive care unit
OQN	Open queueing network
PAC	Production authorization card
UMC	Universitair Medisch Centrum
WKZ	Wilhelmina Kinderziekenhuis

Chapter 1

Introduction

This chapter serves as an global introduction for the chapters to follow. Section 1.1 gives background information about the neonatology department of WKZ. The motivation for this research is given in Section 1.2 and in Section 1.3 the problem description is given. Then Section 1.4 gives the main research question and all sub questions.

1.1 Neonatology department of WKZ

The neonatology department forms the birth centre of WKZ, together with the obstetric department. At the birth centre, they focus on pregnancy, birth and post-birth care. Newborns, both born in WKZ as well as born in other hospitals, who need extensive medical observation and treatment are transferred to the neonatology department. The neonatology department consists of three sub departments: intensive care (IC), high care (HC) and medium care (MC). Patients are assigned to a sub department based on their gestational age, weight and the required medical support.

Each sub department has its own bed capacity, which is displayed in Figure 1.1. The IC is located on the second floor and is divided into three units, which all have a maximum of eight beds. Therefore, the maximum number of beds at the IC is 24. The HC unit has a maximum of eight beds and is located on the second floor as well. The MC is based on the third floor, with a maximum capacity of 15 beds.

In order to serve the patients at the neonatology department, the neonatology department annually employs twenty medical specialists, ten physician assistants and 145 nurses[1]. With this personnel about 1200 patients are treated each year[2].

1.2 Research motivation

The information provided in the section above concerns the current situation, as operational in April 2018. In 2021, the neonatology department will be completely rebuilt and will be operating with a different layout. Therefore, the motivation for the analysis is to prepare the neonatology department for the future, in particular for the new situation after rebuilding the department. The department wants to assess whether their current capacity strategy, dedicating beds to patient types, will also be efficient in the rebuilt situation. Therefore, with this project we want to research the performance of the current capacity strategy, which is dedicating a

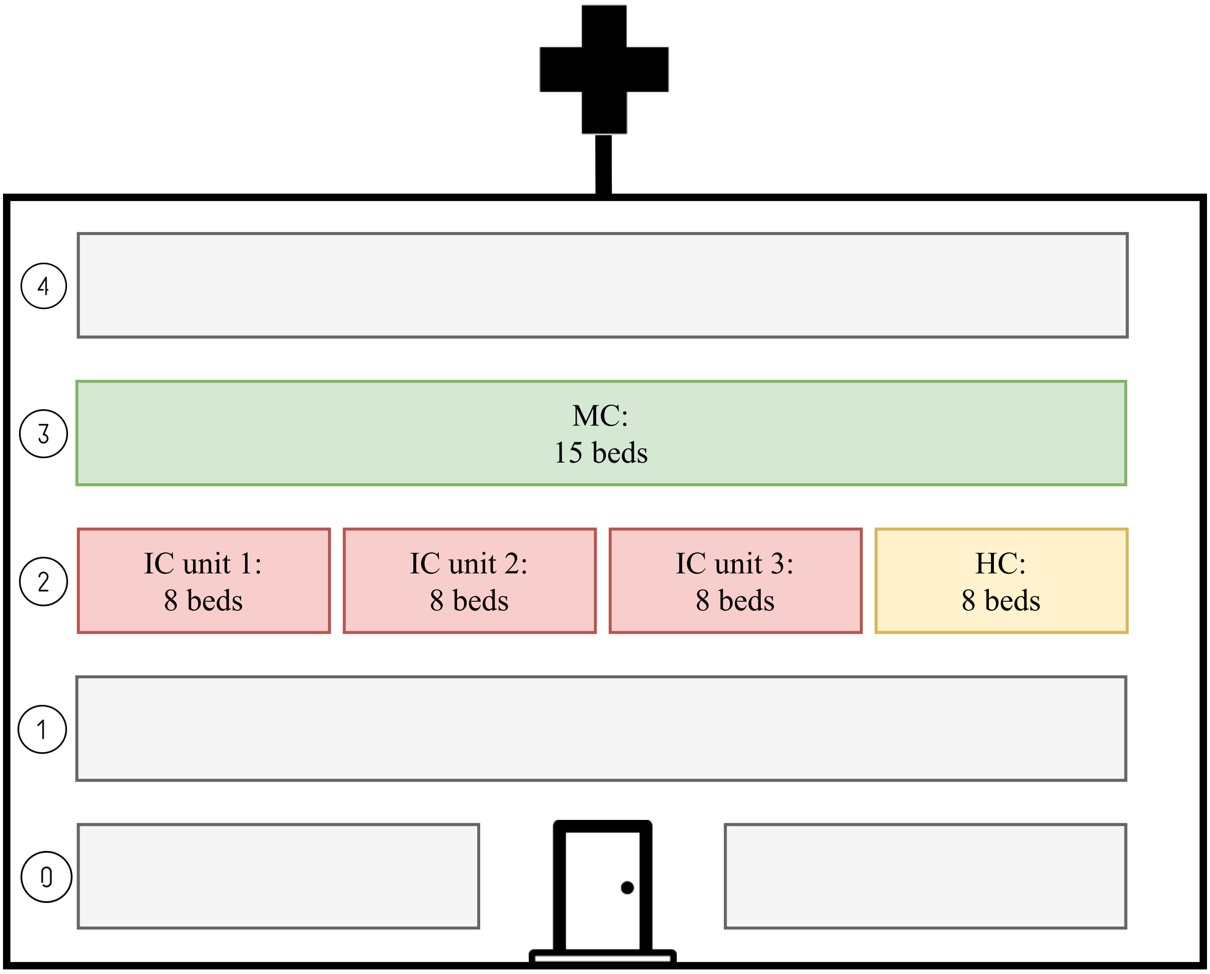

Figure 1.1: Layout of the neonatology department of WKZ

specific number of beds to a certain patient type. Afterwards, we come up with an advise for an optimal strategy for the rebuilt situation. Since, for the neonatology department of WKZ, the performance of such a strategy is quantified by the number of rejected patients, this research aims to reduce the number of rejections with an adjusted capacity strategy.

1.3 Problem description

Currently, the department is struggling with capacity management, in both bed capacity as well as personnel capacity. Questions that arise on a daily basis are: How many available nurses do we have today and in the near future? And how many beds can we serve with these available nurses?

The department is dealing with a personnel problem, since the number of available and qualified nurses has declined the past three years. This leads to the problem of having too few educated nurses, which includes the quality of education and the level of experience. There are three levels of experience: senior nurse, regular nurse and nurse in education. In order to maintain the quality of care a certain qualification of nurses is required, which differs per sub department of the neonatology department. The quality requirements are most extensive at the

IC units and less extensive at the MC unit. On one hand, this results in MC and HC nurses not being allowed to care for IC patients and on the other hand, IC nurses being overqualified to serve MC and HC patients. All these levels and quality requirements result in restrictions for scheduling nurses at all units.

The number of open beds has declined over the past four years as well. A bed is considered to be open for serving patients when enough qualified nurses are available. According to nurses themselves, the declining number of available nurses is the reason that the number of open beds has declined. The average number of open IC beds in 2014 was 21 and in 2017 at a certain point this number was only 17. These four beds cause a decrease of 1460 hospital days at the department. Since the department is paid per occupied bed per day, the decreasing number of hospital days has both a social and a financial effect: more patients have to be rejected and less money is earned.

Nowadays, the department is trying multiple configurations in beds and nurses. However, there is no good estimation of the available capacity and how many patients could be served with it. Therefore, in this research an estimation of the available capacity is made. Based on this estimation, we will also come up with an advice for capacity planning for the rebuilt department, in which the IC and HC units are replaced by 32 separate family rooms. The rebuilding will be further explained in Chapter 2. In the future, the MC unit will be merged with the maternity ward. Therefore, it is decided that the MC unit is left out of scope in this research.

The department suggests that a more controlled patient flow to peripheral hospitals will lead to more available beds. Therefore, the patient transfers will also be investigated in this thesis, and the challenges and opportunities of transferring patients are explained.

1.4 Research questions

Based on the problem description and the research objective, we derive the main research question: what will be the optimal capacity strategy for the neonatology department of WKZ when operating with 32 separate family rooms?

At first, we make an overview of the current performance, current processes, the current capacity strategy, and patient flows within the hospital and between hospitals.

Afterwards, we investigate what type of strategies can be used after rebuilding the department. In order to assess the performance of such a capacity strategy, mathematical models will be used and therefore, we should make an overview of models that can be used for this assessment.

In order to answer the main research question, the aspects of this research are divided into sub questions, which are listed below.

1. How are the admission, discharge and rejection processes regulated in the IC and HC units?

2. What is the current capacity strategy the IC and HC units?

3. What is the current performance of the IC and HC units?

4. What are the current patient flows in the IC and HC units?
5. What mathematical models are often used for assessing capacity strategies?
6. What is the performance of the department in the rebuilt lay-out, considering a no-pooling and a pooling strategy?
7. What actions should the department take to prepare themselves for the future lay-out of the second floor?
8. How can the department stimulate the patient flow to peripheral hospitals?

Questions 1 to 4 are meant for orientation of the current situation at both the IC units and the HC unit. By answering these questions, the current strategy could be compared to possible other strategies as well, as a benchmark.

For assessing the performance of a new capacity strategy, mathematical models will be used. By answering question 5, we will chose a model to make the assessment. The performance of the new capacity strategy is determined with sub question 6.

By answering sub question 7 and 8, we will come up with an advice for a capacity strategy, that can be used in the rebuilt lay-out of the neonatology department of WKZ.

Chapter 2

Context analysis

In order to create the context for this research, semi-structured interviews were conducted and data analyses were performed. The context analysis is based on data of patient admissions between 01-07-2014 and 31-06-2017 are included, unless indicated otherwise.

This context analysis is structured in five components: neonatology department in Section 2.1, current logistical processes in Section 2.2, patient characteristics in Section 2.3, rebuilding of neonatology department in Section 2.4, and a conclusion in Section 2.5.

2.1 Neonatology department of WKZ

The neonatology department of WKZ is one of the ten departments in the Netherlands where a NICU is located. In WKZ, the NICU is specialized in providing neurological care for preterm infants. Parents of patients being admitted at the NICU are experiencing an emotional and stressful period, which can even take several months. The statements above represent the biggest challenges of the neonatology department: admitting as many patients as possible, providing good quality care, and looking after family of patients admitted.

For providing an overview of the environment where this research was conducted, in this section we will explain what type of patients are treated in Section 2.1.1, what type of care is provided in Section 2.1.2, and what the neonatology department currently looks like in Section 2.1.3.

2.1.1 Patient types

Newborns that need intensive care or monitoring, are admitted to the neonatology department. They are categorized based on their gestational age, birth weight and the required medical support. Table 2.1 gives the indication criteria for the IC and HC. A patient should meet one or more of the criteria to be categorized as the corresponding patient type.

The IC criteria are used to assign a newborn to an IC unit at the neonatology department of WKZ. Since the HC unit is used for patients that need intensive monitoring after being treated at an IC unit, the indication criteria for HC are used to discharge patients from an IC bed. With this the IC bed becomes available for new IC patients.

Type of criteria	Admission criteria IC	Admissions criteria HC
Gestational age	Less than 32 weeks	30-32 weeks
Weight	Less than 1000 grams	1000-1200 grams
Medical support	Need for respiratory support, disturbance or threat to vital functions, need for intensive monitoring, antenatal transfer from another hospital.	Patient was IC patient, CPAP/low flow (respiratory support), total parenteral nutrition, central venous catheter, intra-arterial blood pressure measurement, bladder catheter, multiple drug therapy.

Table 2.1: Admission criteria for IC and HC beds

2.1.2 Care provided

Once a patient is categorized as IC patient, the patient is admitted to one of the available IC beds of the department. The newborn stays as long as he or she meet the IC criteria. All types of abnormalities and diseases are treated at the neonatology department. Therefore, neonatologists are intensively collaborating with other paediatric specialists to provide the best care.

2.1.3 Current lay-out

Currently, in April 2018, the department is operating with four care units. In Chapter 1, we already mentioned that three care units are dedicated to IC patients, and that the fourth unit is dedicated to HC patients. All care units are consisting of eight beds. Figure 2.1 shows what such a care unit looks like. In the centre of the unit a station is located with computers for administrative work, which is the base station for personnel. The eight beds are positioned around the central station for a good overview of the unit. Moreover, a unit contains one separate room for isolating one patient. Each bed is surrounded by all type of medical devices and support, as Figure 2.2 shows.

We already mentioned that the hospital stay at the NICU can be a stressful and emotional time for family of the patient. Parents are confronted with everything that happens at the unit and they can only separate themselves from the rest of the unit with a little curtain. Therefore, the biggest drawback of the current lay-out is privacy, which is one of the motivations for building separate family rooms when rebuilding. The rebuilt lay-out will be further explained and discussed in Section 2.4.

2.2 Logistical processes

In this paragraph we explain the relevant logistical processes with respect to patients at the neonatology department. The processes that we assume to be relevant for this research are: the admission, rejection, transfer, and discharge of patients. All these actions are differentiated for the two types of patients of the focus of this research: IC and HC patients.

Figure 2.1: Current layout of an intensive care unit at WKZ, copyright: Wilhelmina Kinderziekenhuis

2.2.1 Admission process

The admissions process can be divided in two types: internal arrival of patients and external arrival of patients. The internal arrivals are patients born in WKZ birth centre and the external arrivals are patients that are born elsewhere.

In case of internal arrival, the neonatology department is informed by the obstetric department when they have patients with chances of giving birth to a premature child and the neonatology department is also aware of the health status of the corresponding children. Based on these prognosis, the neonatology department has to make and keep beds available for these potential patients.

When a potential patient is born elsewhere, the other hospital calls the coordinating medical specialists to discuss the ability of the department to admit this patient. The coordinating medical specialist will further discuss the potential new patient with the coordinating nurse in order to get an overview of the current workforce and the intensity of care of all patients present. Together they decided whether the patient can be admitted to one of the units and to which bed the patient is assigned.

The department concluded that there was too much room for discussion once there are more proposed patients than available beds. Therefore, decisions were made to determine the order of assignment of patients. The priority of assigning a patient is based on the origin region of the patient and the medical condition of the patient.

On average 588 IC patients are admitted to the IC units per year and 115 patients to the HC unit. Most of the HC patients were first treated in one of the IC units and the remaining fraction is discharged from the MC unit of WKZ.

Figure 2.2: One patient bed with all the supporting medical devices, copyright: Wilhelmina Kinderziekenhuis

2.2.2 Rejection process

With limited capacity, it cannot be prevented that patients have to be rejected. Once none or minimal capacity is available, the decision has to be made about admitting a patient or rejecting this patient. This decision is based on multiple factors: number of available beds, number of proposed patients waiting for a bed, whether a patient comes from within or outside the region of WKZ and the number of qualified nurses. Sometimes, it is even decided to open one extra bed for admitting a patient, which is then called an additional bed (in Dutch: overbed).

Unfortunately, insufficient data is available about rejecting IC patients at the neonatology department. In March 2016 the department started monitoring the rejections in more detail, including the date and time of rejection and the reason for rejecting a patient. Rejections for the HC units are not monitored, since these do not occur in practice. When there is no HC bed available, patients stay at an IC bed for an extended time or they are transferred to a peripheral hospital. This leads to IC beds being unnecessarily occupied by HC patients, which can eventually lead to IC patients being rejected.

Based on data from January to November 2017, around 50% of the 123 IC rejections were patients part of a multiple birth. In that period, 26 twins and 3 triplets were rejected. The high rejection probability for multiple births can be explained by that more beds have to be available to assign all patients to a bed. Moreover, when these patients are rejected, all patients of the multiple birth count as an individual rejection. This leads to a fast increasing number of rejections. When comparing the rejected population with the admitted population, we conclude that the chance of rejection is higher for multiple births. The admitted population consists of

16.5% twins and 1.6% triplets. This is not like the fraction of multiple births in the rejected patient groups, of which 50% of the rejections is part of a multiple birth.

2.2.3 Internal transfer process

Transfers between units within the neonatology department are seen as internal transfers, which are transfers within the same hospital. As already described in Section 2.1.1, patients that do no longer need the intensive care, but still need to be monitored extensively, can be transferred to the HC unit. When patients do not need the extensive monitoring, a transfer to the MC unit could be more efficient.

An internal transfer could also be done when the patient health status is becoming worse. Then a patient is admitted to a unit where more intensive care is given. Such a transfer could mean that a patient is readmitted to their original unit.

The reason for transferring patients is categorized in two types: clinical and logistical transfers. Clinical transfers are transfers of patients that are in need of more intensive care, and logistical transfers are transfers that have to be done to make a bed available for a new patient. In case of WKZ, patient transfers from IC to HC are seen as logistical transfers.

Most of the internal transfers at the neonatology department of WKZ are non-medical related transfers, and they are time-consuming. The patient should be administratively be assigned to another bed, all medical support should be temporary paused and this type of transfer is supported by the presence of two nurses. Furthermore, the department prefers that all internal transfers occur in presence of the parents of the transferred patient. In Section 2.3.3 we give an overview of the internal and external transfers.

2.2.4 Discharge process

The discharge process is the most complicated logistical process at the neonatology department. Once a patient's health status has become better and the patient does not need the intensive or high care any more, the patient can be discharged from the department. However, this is depending on multiple stakeholders and these stakeholder are subjected to other restrictions on their turn. In the list below, the stakeholders involved in discharging patients are mentioned, with their corresponding restrictions.

1. Medical specialist - based on the results of laboratory tests and the patient's progress, the medical staff can decide that a patient is ready to be discharged from a unit.

2. Nurse - before a patient can be discharged, the nurse should prepare the transport, and sometimes a nurse should even be available for support during transport.

3. Administration - since most patients leaving the NICU of WKZ are not going home, the medical staff and nurses should make a summary of the hospitalization of the patient and the current health status.

4. Transport - the transport of a patient being discharged is depending on whether the ambulance is available or not. In case of an emergency elsewhere, this will have priority over the infant being discharged, which results in waiting time.

After a patient is discharged and has left the department, the empty bed and the associated medical equipment are extensively cleaned. Hereafter, the empty bed is ready for a new patient to be admitted. At the units they use the so-called Vogelbek method, and with this method the sequence of patients to be discharged is predetermined. With this order, it is prevented that discussions arise at the moment of discharging a patient.

Besides the logistical challenge of discharging a patient, there is also an emotional and psychological aspect. Parents should be highly involved in the whole discharge process, since they often experience the discharge to be all of a sudden. Especially in discharge from NICU, parents assume that they are not ready to leave the NICU yet. They are not confident enough that their child will make it without the intensive care received at the NICU. The emotional aspect of the discharge of patients is not the focus of this research. However, it is still important to mention, since this aspect is often forgotten.

2.2.5 Capacity planning

In Chapter 1 the term 'open bed' was mentioned. A bed is considered to be open, when there is enough qualified personnel to serve this bed. However, open beds are not the same as available beds for new patients. A bed is available once the bed is open and there is no patient already assigned to it. A bed could also be closed, which means that there is not enough personnel to serve that bed. In the situation where a patient needs to be assigned to a bed and there are no available beds, the patient should be rejected. Obviously, this situation should be prevented as much as possible. In 2016, on average 20 patients were being treated at the IC and HC units per day, which means that on average 20 beds are open. This is only 62.5 percent of their maximum capacity. Since being treated at the NICU of WKZ costs 2150 per patient per day, not using all beds causes missed incomes of millions of Euros per year. This calculation is a distorted view of reality, since the number of open beds is currently restricted by the personnel shortage.

At the neonatology department, the nurses are registered to a specific team and such a team is dedicated to one of the units. This results in nurses being dedicated to a single unit in their working shift as well. Nurses are certainly not restricted to only work at this unit and they can assist at other units if necessary.

2.3 Patient characteristics

In the previous sections the patients types, admission process, rejection process, internal transfers, and discharge process are explained. Now, it is important to analyse how these processes and especially the underlying strategies have their influence on patients.

In order to investigate the influence of the strategies at the neonatology department, data analyses were performed. Information is gathered about the number of admissions, rejections, internal transfers and discharges. Not only the number of these processes are looked into, also the distribution of patient arrivals over time is explored. Furthermore, data is analysed about the length of hospital stay of a patient. The patient characteristics are important, since these parameters are used as input parameters in most mathematical models. Supporting figures and explanation of calculations performed in this section can be found in Appendix **??**.

2.3.1 Patient arrival rates

The information about the admissions and discharges is based on data from all admissions between 01-07-2014 and 01-07-2017. For good estimations of the number of admissions in 2014 and 2017, extrapolation was performed. Table 2.2 shows the resulting number of admissions per year.

Year	Total number of admissions	Number of IC admissions	Number of HC admissions
2014	813	685	128
2015	774	626	148
2016	726	651	75
2017	735	656	107

Table 2.2: Number of admissions per year

These numbers do not indicate the distribution of patient arrivals over time. The the arrival rate of patients can be determined by analysing the time between arrivals. This is done for the IC units only, HC unit only and for IC and HC patients as one group. For the last group, the calculated inter-arrival time (IAT) gives the average time between two arbitrary arriving NICU patients.

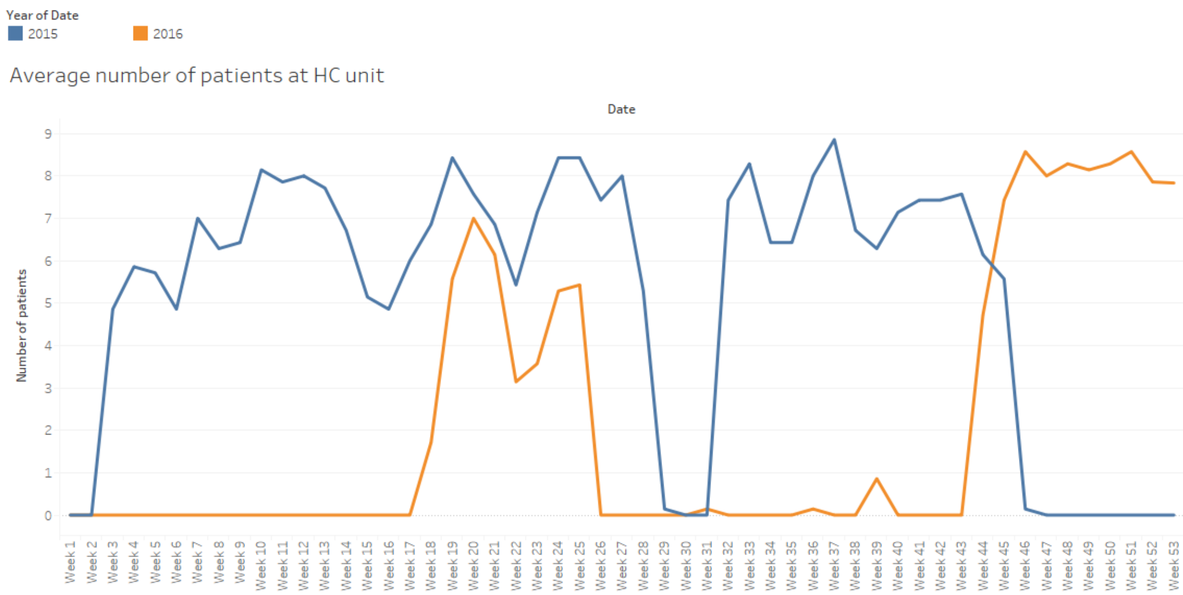

Figure 2.3: The average number of patients present per week at the HC unit in 2015 and 2016

For the IAT the rejections are taken into account as well, since these patients also arrived at the department. Therefore, the calculation of IAT is based on data from March 2016 to November 2017, since for these dates the rejections are registered in more detail. The arrival of a new patient and the readmission of a known patient are treated equally in this study, since the main focus is the arrival of an IC patient. Moreover, for the HC patients it was taken into account that this unit was not open all the time and thus outliers were excluded from these calculations. For example, from week 47 of 2015 to week 17 of 2016 not a single patient was admitted to the HC unit, as Figure 2.3 shows.

Results of the IAT calculations are displayed in Table 2.3. We observe that the standard deviation is bigger than the mean value in all three case. Since we know that inter-arrival times are equal or larger than zero, this implicates that this parameter has a skewed distribution. This phenomenon is discussed more extensively in Chapter 4.

Patient type	Average inter-arrival time (hours)	Standard deviation
IC patients	11.75	12.97
HC patients	51.30	56.13
All patients	10.42	12.14

Table 2.3: Inter-arrival times for IC and HC patients

2.3.2 Patients length of stay

The length of stay of patients was calculated, using data about the moment of admission and the moment of discharge. The length of stay (LOS) was calculated for IC patients, HC patients and the average LOS of the total patient population.

Patient type	Average length of stay (days)	Standard deviation
IC patients	11.87	16.22
HC patients	13.08	14.72
All patients	12.05	15.63

Table 2.4: The length of stay for IC and HC patients

Table 2.4 gives the resulting values for LOS per patient type. Just as with the IAT, with the LOS the standard deviations are larger than the mean values as well. Further explanation of the distribution of the LOS is given in Chapter 4.

2.3.3 Patients flow

From 01-07-2014 to 30-06-2017 1765 admissions were performed at the IC units and 344 admissions were performed at the HC unit. Of those 344 HC admissions, 285 were patients coming from one of the IC units and 59 were patients coming from the MC. There are four possible transfers: IC to HC, HC to IC, IC to somewhere else and HC to somewhere else. Table 2.5 displays the frequency of all these transfers.

Since the department has limited capacity due to shortage in personnel, the department wants to use the open beds for IC patients as much as possible. This can be achieved by transferring IC patients to peripheral hospitals once they do no longer need the care provided in WKZ. However, this causes a higher turnover in patients, and this will lead to an increasing workforce for personnel, since external transfers are time consuming.

Patient's flow	Frequency
IC to HC	0.16 (285/1765)
IC to elsewhere	0.84 (1480/1765)
HC to IC	0.20 (68/344)
HC to elsewhere	0.80 (276/344)

Table 2.5: Patient's flow from IC and HC units

2.4 Rebuilding the neonatology department of WKZ

In 2021, the neonatology department will be operating in a different lay-out. For making an adjusted capacity strategy, which will be successful in the new layout, we first need to understand the motivation for rebuilding the department, and what the department will look like after rebuilding.

WKZ is part of UMC Utrecht, and this hospital has a vision: together for the patient (in Dutch: Samen voor de Patiënt). In this vision family centred care (FCC) plays an important role and this vision also applies to the birth centre of WKZ. Peace and privacy, family participation, safety and hospitality are the key factors of FCC, for the neonatology department of WKZ. This vision is one of the main motivations for rebuilding the department. Individual patient rooms for IC and HC patients are assumed to be of added value in this vision and are expected to be beneficial for patient progress. These rooms are also called family rooms, since family of the patient can visit the newborn in private.

Figure 2.4: Three adjacent family rooms, designed by the company EGM

The neonatology department will get a new layout, in which 32 separate rooms for patients receiving intensive care or high care are built. These rooms will be divided over two large units based on the second floor. These will partly be located where the current IC and HC units are located and one unit is placed at the obstetric department. Figure 2.5 shows the impression of what one family room will look like after the department is rebuilt. Figure 2.4 shows the impression of three adjacent family rooms.

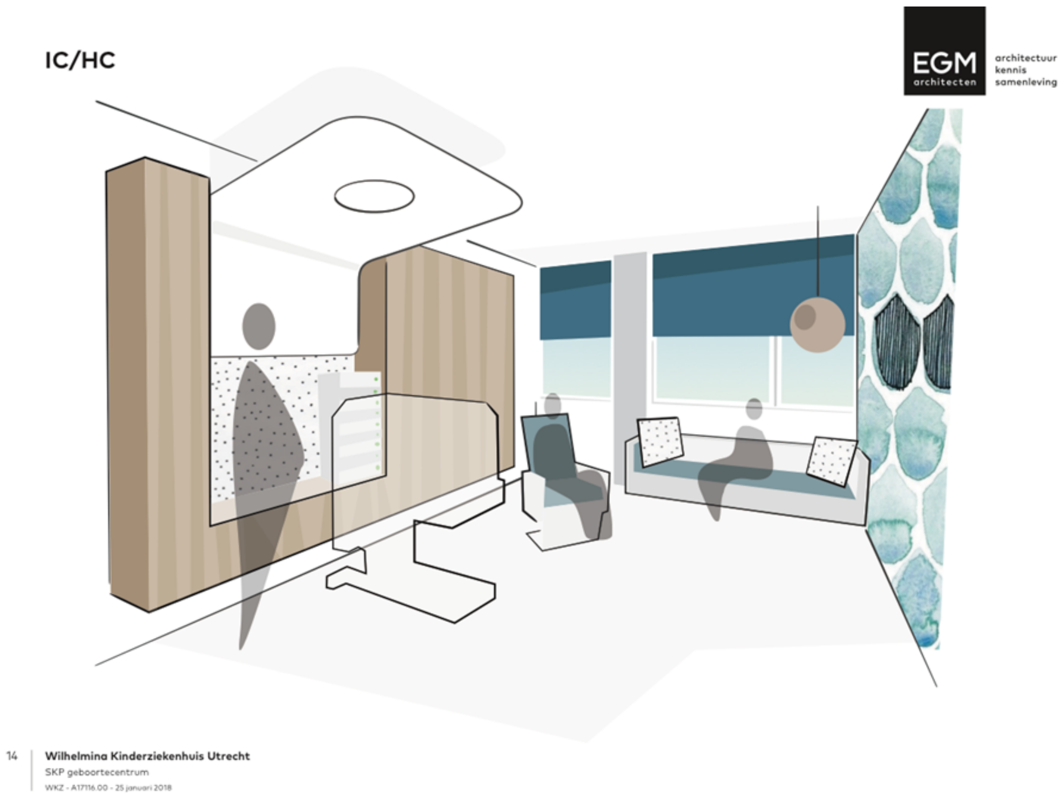

Figure 2.5: Impression of a future family room, designed by the company EGM

2.5 Conclusion

In this chapter, we gave an overview of current processes at the neonatology department and we analysed historical data with respect to patient characteristics. Based on the overview and the data analyses, we are able to answer the first three sub research questions, as described in Chapter 1.

Logistical processes Patients, born in WKZ birth centre or somewhere else, are admitted to the neonatology department based on their medical condition. However, a patient can only be admitted when an appropriate bed is available for treating this patient. When no bed is available treating an IC patient, then the patient is rejected after deliberations of coordinating personnel. Discharging IC patients is often driven by capacity limitations and is depending on the medical conditions of patients. When a patients does no long require an IC or HC treatment, the patient can be discharged from the NICU of WKZ. Many stakeholders are involved in this process and it became clear that this process is hard to manage.

Current capacity strategy In 2016, the neonatology department of WKZ was operating with 20 beds on average. This is only 62.5% of the maximum IC and HC capacity. The number of open beds depends on the number of available nurses and their educational level. Since the neonatology department has a shortage in personnel, the number of open beds is restricted.

Current performance It became clear that the department has a hard time coping with all arriving patients given their limited capacity due to lack of personnel. In 2016, operating with 20 beds on average, 651 IC patients were admitted and 93 patients were rejected in this year. This is 12.5% of all arriving IC patients.

Patient flows Since a limited number of IC beds is available to patients, patients are transferred to peripheral hospitals or to the HC unit once they no longer need the intensive care. More than 84% of the IC patients was discharged from the IC unit to go to a peripheral hospital and 16% of IC patients had to be admitted to an HC bed, after their first IC admission in WKZ.

In conclusion, the results of data analyses correspond with the problem stated in Chapter 1. The department is coping with limited capacity and has to reject patient in 12.5% of all IC arrivals. Given the average LOS of 11.87 days, the 93 rejections in 2016 causes an estimated shortage of 1103.91 hospital days. Since there is a shortage in personnel, the department could not simply open more beds. Therefore, the department should consider a strategy where the number of open beds is used more efficient.

Chapter 3

Literature review

Now the performance of the current situation is known, methods for determining the performance of the future situation had to be found. For this research, we use available literature about pooling hospital beds and mathematical models for determining capacity planning. Appendix **??** describes the detailed literature search method. In this chapter, an overview of included literature is given, divided into three sections: pooling hospital beds in Section 3.1, patient transfers in Section 3.2, and mathematical modelling in Section 3.3. We explain the motivation for reviewing literature about each of these subjects in the corresponding section.

3.1 Pooling hospital beds

After rebuilding the neonatology department, the department will have 32 family rooms instead of having 24 IC beds and 8 HC beds. Therefore, the department can decide whether these rooms will be dedicated to a certain patient type or not and decisions can be made about the maximum number of IC and HC patients. When all family rooms or part of these rooms will be available for both IC and HC patients, there is this strategy called bed pooling.

The term bed pooling is often used in literature to describe the situation of combining multiple departments and then admitting patients to the merged department. The patient population is larger and the number of possible beds is higher, which results in a lower expected rejection rate. The effects of bed pooling are extensively described in literature, of which an overview is given below.

Monks et al.[3] presented a discrete event simulation for determining the effect of co-location and pooling of the acute and rehabilitation units. They concluded that in case of pooling the beds of both units, the probability for delayed admission was reduced for both acute and rehabilitation patients. The reason for this is that no dedicated beds are used or less dedicated beds in case of partial resource pooling. An arriving acute patient can also be assigned to an empty bed that normally would be used for rehabilitation patients and vice versa.

Karsten et al.[4] mentioned that the benefits of resource pooling can be mainly explained by that this principle deals with uncertainty in inter-arrival and services times. Instead of having dedicated servers, all servers or part of the servers, are used as common resources. The main benefits of resource pooling are reduced waiting times for customers to be served. In case of the neonatology department of WKZ, resource pooling is therefore expected to lead to a reduced number of rejections.

Bekker et al. showed different types of resource pooling [5]. They distinguished four types: no pooling, simple pooling, so-called earmarking and the threshold policy. In case of no pooling, all beds are dedicated to a certain patient type. With simple bed pooling all patients share all beds. When applying the so-called earmarking, all patient types share one ward of overflow with fully flexible beds, but each type also has some dedicated beds. The last type of resource pooling was called the threshold policy, in which all beds were used for all patient types. However, a policy was made with a severity based admission sequence. Severe patient are admitted to an available bed, regardless of the number of available beds. Less severe patients are assigned to a bed, when the number of available beds exceeds a predetermined threshold.

The different types of resource pooling as mentioned by Bekker et al.[5] all have their own advantages and disadvantages with regard to specialization of care, and flexibility. One disadvantage, for example, of simple resource pooling is that a multi-skilled medical team is required to treat all different patient types. Bekker et al. state that merging hospital beds of two types of patients does not have to be beneficial for the loss fraction of both types. In case of specialized care, the patient type with the lowest arrival rate will be negatively affected, since they are assigned to a bed according to the First Come First Served principle. They concluded that in general, being flexible with bed allocation is beneficial for coping with the variability in patient arrivals. However, the effect of resource pooling is depended on scale of departments which are pooling their beds.

Vanberkel et al. [6] state that resource pooling is not always efficient and that in some situations it is better to unpool departments. They conclude that some parameters have a correlation with the effect of resource pooling: appointment length, appointment length variation, the arrival rate, and the load of the system.

3.2 Patient transfers

When the neonatology department is rebuilt, decisions have to be made about dedicating rooms to a specific patient type or not, which will also influence the number of internal transports between IC and HC rooms. Imagine that all beds are dedicated to a patient type, once a IC patient does no longer need intensive care, it will be transferred to a HC room to make room for new IC patients. However, when all rooms are universal, no transfers between IC and HC rooms have to be made. Furthermore, decisions can be made about the maximum number of IC and HC patients, as mentioned in the previous section. This will influence the rejection probability, since more IC beds will probably lead to a lower rejection rate. The distributions of rooms to patient types will also have effects on the number of transfers to peripheral hospitals. A small number of HC rooms will lead to a high turnover for HC patients and therefore a high number of transfers to peripheral hospitals. On the other hand, a high number of HC rooms will lead to a low turnover and thus a low number of transfers to peripheral hospitals.

The decisions about dedicating rooms to patient types and determining the maximum number of patients of a certain type are both related to patients transfer. The first decision is about intrahospital transfers, which are transfers within the same hospital. The second decision is about interhospital transfers, which are transfers between two hospitals. For making evidence based decisions, this section gives an overview of available and relevant literature about both intrahospital and interhospital transfers. Besides focusing on the logistical and capacity consequences of these transfers, the outcome of the patient will be discussed as well.

Literature distinguishes non-clinical necessary and clinical necessary transfers, such as a patient being transferred from a regular ward to an ICU. Non-clinical transfers are often logistical necessary transfers. For example, with this type of transfer at the NICU a stable patient is transferred to another nursing ward or another hospital to make the bed available for potential acute patients.

In 2004, Beckmann et al.[7] already concluded that patients undergoing intrahospital transfer are exposed to preventable risks. They mention that approximately 60 percent of the incidents in earlier intrahospital transfers were management related, such as poor communication and lacking set-up of the patient's new environment. The risks identified by Beckmann et al. resulted in negative outcomes, such as patients or relatives displeasure and extended length of stay. These numbers are about adults in the ICU, which had to move from other hospital wards in order to receive intensive care or ICU patients that were discharged to other wards within the hospital. However, these results still show that there are serious effects of an intrahospital transfer, so when these transfers are not clinically necessary, they could better be avoided.

Blay et al.[8] stated that the pressure on hospital beds leads to a higher frequency of intrahospital transfers that are not medically necessary. With pressure of hospital beds, they mean that the bed utilization is high. In this paper they also mention that the phenomenon of the higher transfer frequency with a high bed pressure is the largest in emergency departments and ICUs. In case of a unit where emergency patients are admitted, generally a temporary admissions location is used. Once a suitable bed becomes available, yet an intrahospital transfer will be performed.

Not only intrahospital transfers, also interhospital transfers are known for their effects on patients status and the logistics around these transfers. However, when experienced staff is realized for transferring patient to other hospitals the complications are minimized, as shown by Kulshrestha et al. in 2016 [9]. They say that risk factors for complications during transport are both patient and staff related. For example, unstable patients are more likely to have complications and insufficient preparation of personnel is also a risk factor for complications during or after transport. However, the risk factors mentioned by Kulshrestha et al. are well-known risks and most case the transfer team anticipates on these factors.

Also the time of performing transfers is studied, for example by Morales et al.[10]. They concluded that when a patient is admitted to an ICU during night time there is not a higher mortality rate or longer LOS for this admitted patient, compared to patients admitted during daytime.

Besides the effect of transport on patients, Chen et al.[11] researched the duration of air and ground transport. What is important to mention is that these are trauma transports of patients reported at the emergency centre, so these are not actual interhospital transfers. However, they found high variability in the duration of transports. Waiting for the ambulance to leave and finding a bed and a doctor caused 38 percent of the total duration of the transport. This duration is defined by the moment of initiating transport and the moment of handing the patient over to the other hospital. These results confirm the discussion about patient transfers in Chapter 2 in the section about the discharge process.

3.3 Mathematical modelling of clinical wards

By reason of all changes that will be made in the layout of the neonatology department, a mathematical model will be used to give an estimation of the possible outcomes for multiple scenarios. In operations research groups, mathematical models are often used to for capacity planning in hospitals. In available literature, these models are often used for nursing wards in hospitals, where the arrival of patients is depending on the operating room planning. Also, the ICU and the emergency department are well studied, where acute care patients are admitted. This is also the case at the neonatology department of WKZ.

We review available literature about these mathematical models and we focus at articles that describe an acute care situation. Furthermore, a suggestion is made to use another model for determining the capacity requirements, which is often used in manufacturing, but not in healthcare environments yet. The translation of both types of models to the neonatology department of WKZ can be found in Chapter 4.

3.3.1 Erlang loss model

Mathematical models that are frequently used in the environment of hospitals are based on the principle of the Erlang loss model[5] [12] [13] [14]. This model assumes that a patient is lost when no bed is available and is based on an exponential inter-arrival time, also called a Poisson arrival process, and the average length of stay in the hospital. Moreover, Karsten et al.[4] described an Erlang delay model, which assumes that a patient is delayed when no bed is available. In the Erlang delay model there is an infinite number of places in the queue available for the delayed patients.

Capacity planning in a perinatal network is the subject described by Asaduzzaman et al.[12]. They observe that in neonatal intensive care, and in intensive care in general, the distribution of both the inter arrival times and length of hospital stay (LOS) are often non-exponential. Generally, the mean value of both the inter arrival times and the LOS are lower than the standard deviations of these parameters [15][16]. These characteristics are in contrast to the exponential distribution and the Markovian assumption as stated by Asaduzzaman et al. Therefore, they analysed each unit of the perinatal network with a overflow loss network where the inter arrival times and services times were generalized, starting from an Erlang loss network. Such a system is called a GI/G/c/0 queueing network. The main advantage of this network is that the arrival and discharge pattern do not have to meet the Markovian property. This is an advantage, since they also concluded that the Markovian approximation for arrival and discharges patterns were the reason for overestimating and underestimating the required capacity.

De Bruin et al. stated that the clinical wards have a certain number of beds based on historical obtained rights. However, this distribution of beds may not be optimal [13]. The Erlang loss model is a good estimation for determining the required number of beds, according to the results of this research.

De Bruin et al. first used another definition for the bed occupancy. Normally, in hospitals this is defined by the number of hospital days (in Dutch: ligdagen). Though, in this article they use a common method used in operations research. With this method, the occupancy is equal to the average number of occupied beds divided by the number of operational beds, in which the number of occupied bed is equal to the number of admissions per time unit multiplied by the average LOS. A disadvantage of this formula, conceived by John Little, is that it is based on the average LOS and that the number of operational beds is not a time-dependent variable [17]. However, in contrast to what was stated by Asaduzzaman et al., De Bruin et al. state that the unscheduled arrivals are according to a Poisson distribution. Despite sawing a difference between the arrival pattern of weekdays and weekend, De Bruin et al. still chose not to model time-dependency due to model complexity. This resulted in a underestimation of the average number of required beds.

Litvak et al.[14] researched an system of intensive care unit, where the number of open beds depend on the amount of available staff. Similarly to De Bruin et al., they state that the arrival process of unscheduled or emergency patients follows a Poisson distribution. However, they also state that this property does not hold for scheduled patients that arrive from the operating rooms. Litvak et al. came up with solutions for preventing that emergency patients should be treated somewhere outside the region. Calculating the blocking probabilities based on the Erlang loss model is not sufficient in case of managing overflow at ICUs. Therefore, they model an equivalent ICU based on generalization of the Equivalent Random Method (ERM). The ER unit is used to mimic a multi-server intensive care unit, which has the same expectation and variance as the original system. This ER unit is only used for managing overflow and therefore the estimated blocking probabilities only hold for patients in the overflow. Therefore, another calculation is needed to calculate the blocking probability of the regular patients. Litvak et al. concluded that the calculated blocking probabilities were too high compared to the observed rejected patients. This can be explained by an overestimation of the LOS, in which the day of admission and the day of discharge are included in the LOS as two whole days.

Bekker et al.[5] analysed the effects of pooling hospital beds, as also mentioned in the section about pooling hospital beds. They use the Erlang loss model, since they want to support management decision making at the two top levels of the hierarchical framework: strategic and tactical level. They assume that the arrival of patient is according to a Poisson process. Furthermore, they assume that the LOS of patients is the same for all patient types and is independent, for which they use an exponential distribution. This distribution results in a smaller variation compared to practice.

The Erlang loss model or loss models in general are frequently used and the articles reviewed above show that they are a good estimation for number of required beds or rejection probabilities. One of the characteristics of these models are that they have a stable workload, since there are limited number of servers. The number of servers at the neonatology department is restricted by the number of open beds. Therefore, another way of modelling a stable workload is explained in the next section: workload control systems.

3.3.2 Workload control systems

Workload control systems are often used in manufacturing and these systems are modelled as closed queueing networks (CQN)[18]. In this type of CQN the number of jobs in the network is somehow restricted. One example of such a restriction is the use of production authorization cards (PACs). These systems are therefore called PAC systems. When no card is available for a new job, then the job has to wait in the queue. Once a job is fully processed, its card becomes available and the first job in the queue can now enter the production line. A schematic overview of a PAC model is given in Figure 3.1.

In modelling such PAC systems the arrival pattern of orders is assumed to follow an exponential distribution, with rate λ. Furthermore, the servers are modelled as a network with M stations. Each station has an expected service time which is indicated by: $\mathbb{E}S_i$. The service times are generalizations of the exponentially distributed service rates. Not all jobs need to visit each station, therefore visit ratios of a job to station i need to be determined. Another

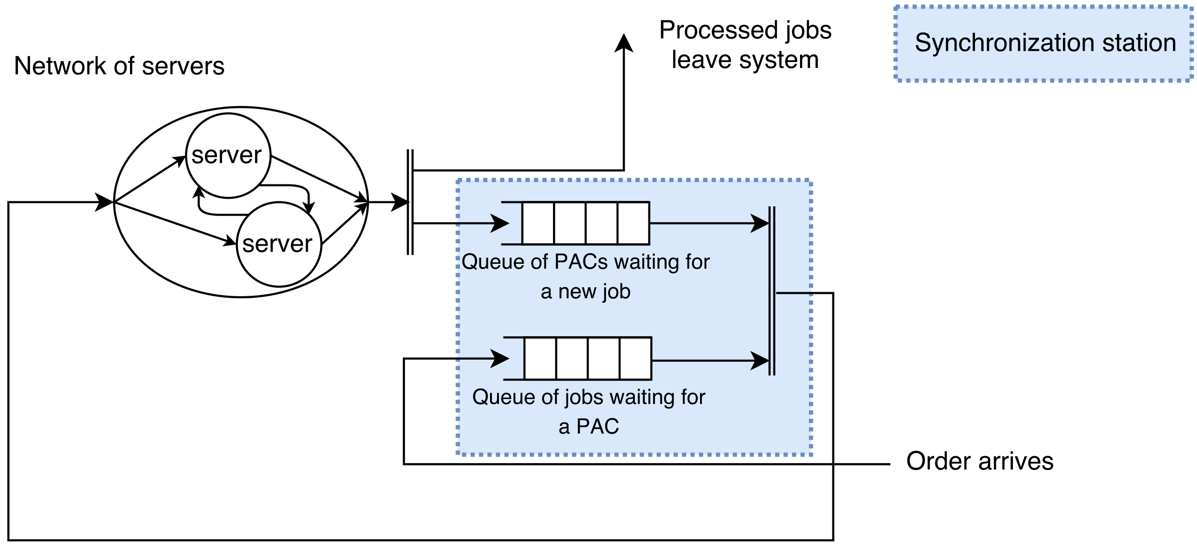

Figure 3.1: a schematic overview of a PAC system

important assumption is that the system is stable, that means that enough resources are available and that there are enough cards for processing all orders. If this assumption is not met, the queues of a PAC system will 'blow up' due to too many jobs coming in and too few leaving the queue. Finally, what is beneficial in PAC systems is that in case of a multi-class network, where multiple types of products are produced, you can have either universal cards or dedicated cards.

In manufacturing, PAC systems are often used to cope with variability in demand by keeping the workload stable. They are used as an extension of the Kanban principle. This type of production systems are often successful in manufacturing industries, such as described by Slomp et al. [19].

The explanation about PAC systems seems only to be applicable to manufacturing and processing job orders. However, this system can easily be translated to the neonatology department. Patients (jobs in case of a PAC system) can only be admitted to the neonatology department when a bed (card) is available. When no bed is available, the patient will be rejected or be put in the queue. In case of the neonatology department, patients will preferably not be placed in the queue, since they require acute care.

In Figure 3.2 the schematic overview given in Figure 3.1 was adjusted for the neonatology department. The network of servers is replaced by 'Treatment', which will consists of two types of servers: a server giving IC treatment and a serving giving HC treatment. This will be discussed more extensively in Chapter 4. Moreover, the opportunity of modelling universal cards or dedicated cards, will be of added value. The beds can now be either dedicated to a certain patient type, or be universal and all patients can be assigned to it.

3.4 Conclusion

The patient flows are a well studied subject in literature. Both the internal and external transfer showed consequences for patients. However, in this study we assume that personnel is

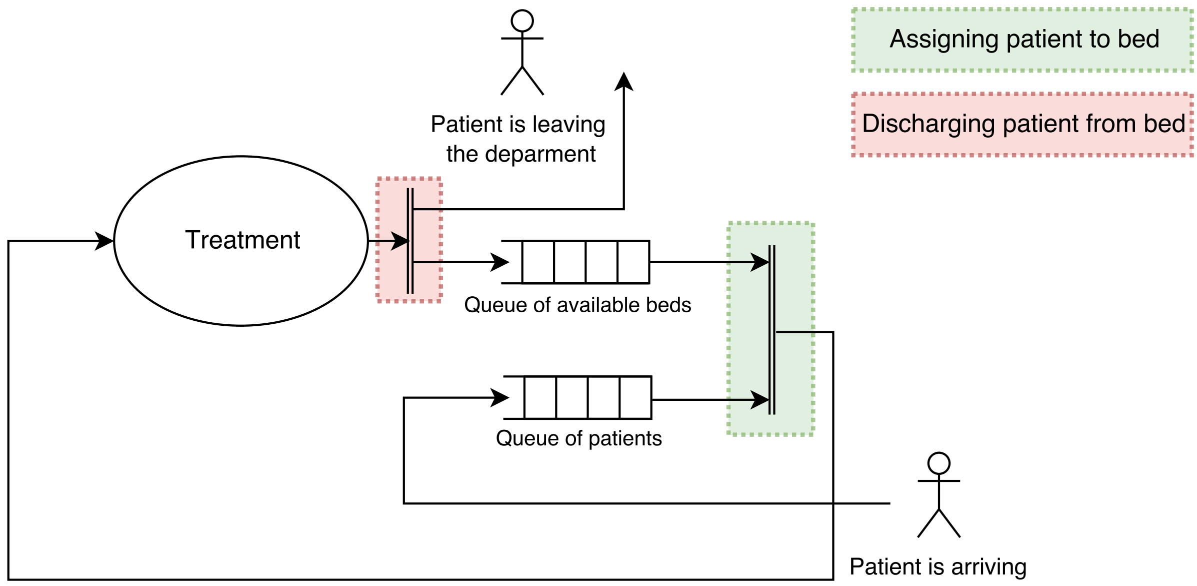

Figure 3.2: a schematic overview of the PAC system at the neonatology department

well educated and that the patients are exposed to minimal amount of risks, which were both factors that caused complications during transport.

Pooling hospital beds is a subject that is of growing interest within the past four years. By pooling multiple patient group the variation in LOS is minimized, and in this way the bed utilization is more constant.

The flow of patients is studied by means of mathematical models as well, in which the Erlang loss model was used most often. We asked ourselves the question what could be the reason of the Erlang loss model being used that often and if similar models are used in manufacturing systems. PAC systems are CQN, in which the workload is kept at a constant level with the use of production authorization cards. Since a description of both models is given in this chapter, in Chapter 4 both models are compared and also the outcomes of these models based on the department of neonatology are compared.

Since the Erlang loss model and PAC system are both based on estimations for among other things the service times, we choose to make a simulation model of the department as well. Simulation models are often used to simulate a complex system, when mathematical methods are not sufficient enough. Simulations model enable using probability distributions as an input and mutual relationship can be defined. This model is still a simplification of reality, however it is more realistic than modelling the department using the Erlang loss or PAC model. In Chapter 5, we describe how we simulate the neonatology department of WKZ.

Chapter 4

Comparison of models

After reviewing the Erlang loss model and the PAC system in Chapter 3, Section 4.1 compares the the characteristics of these two models. This comparison is based on several factors: open or closed queuing network, loss or delay model, assumptions for inter-arrival times and assumption for service times. Afterwards, we perform calculations for both models based on data of the neonatology department. Section 4.2 provides the results based on the Erlang loss model and Section 4.3 those based on the PAC system. Section 4.4 makes a comparison between the results of the two models and then we draw conclusions in Section 4.5.

4.1 Comparison of model characteristics

The Erlang loss model is an open queuing network (OQN), in contradiction to the PAC system, which is a closed queuing network (CQN). In an OQN the arrival pattern is independent from the departure pattern. In a CQN however, the departure pattern determines the arrival pattern of new jobs in the network of servers. This can be explained by the fact that a PAC first should become available, by departure of a job, before a new job can enter the network.

As the name implies, the Erlang loss model is a loss network and the PAC system is a delay network. This means that in case of the Erlang Loss model, patients are lost when there are no servers available. In case of the PAC system, when no bed is available, the patient is placed in a queue where the patients waits for a bed to become available. The patient enters the network with a certain delay. However, in case of the neonatology department a high delay is not preferred, so the number of used beds should be that high that the expected waiting time at the queue is below a certain value.

Regarding the arrival process of patients, both the arrival pattern in the Erlang loss models and the external arrival pattern in a PAC system are assumed to follow a Poisson process, which means that the inter-arrival times are exponentially distributed. The service times in the Erlang loss model are generalized. With PAC systems the service times need to be exponentially distributed as well. Both the arrival rates and the service times are used as input parameters for the Erlang loss model and the PAC system. In Appendix **??** the distributions of data of the neonatology department are explained and we show that they meet the assumptions of both models.

4.2 Results based on Erlang loss model

At the neonatology department, the maximum number of beds and the patients arrival rate and LOS are known, so the number of patients you can treat with these beds can be calculated, even as the rejection probability. Moreover, the number of required beds can be calculated when there is a predetermined rejection rate. Both calculations can be performed with formulas based on the Erlang loss queueing model. All notations of these formulas are given in Table 4.1. In this section we evaluate three patient groups: IC patients, HC patients and the aggregated patient population. Since the arrival rate and LOS are known, the expected number of patients in the system, $\mathbb{E}L$, can be calculated with Equation 4.1.

Variable	Definition
$\mathbb{E}L$	Expected number of patients present
λ	Arrival rate of patients
μ	Service rate for patients
P_c	Rejection probability
c	Number of operational servers
k	Number of occupied servers
N	Average number of occupied beds

Table 4.1: All notations of the formulas for the Erlang loss calculations

$$\mathbb{E}L = \lambda\mu \tag{4.1}$$

Now the expected number of patients in the system is known, the fraction of blocked patients can be calculated. For this we use the equation as used in the article by De Bruin et al.[13], as shown in Equation 4.2. The average number of occupied beds (N) depends on both the expected number of patients in the system, as well as on the fraction of blocked patients, as Equation 4.3 shows.

$$P_c = \frac{\frac{\mathbb{E}L^c}{c!}}{\sum\limits_{k=0}^{c}\left(\frac{\mathbb{E}L^k}{k!}\right)} \tag{4.2}$$

$$N = \mathbb{E}L(1 - P_c) \tag{4.3}$$

First, we determine the rejection probability based on the situation that the maximum capacity is used. The results for all patients groups can be seen in Table 4.2, in which the total resource pooling group represents the performance of the department in care of resource pooling. The arrival rate and LOS are determined based on the average inter-arrival time and LOS of the whole patient population.

The rejection probability for both IC and HC patients is higher than the rejection probability of an arbitrary patient in a system that uses maximum capacity. Since HC patients will never be rejected such as done in an Erlang loss model, we used the formulas of De Bruin et al. [13] to calculate the required number of beds given a certain rejection probability. Results of these calculations are displayed in Table 4.3. The rejection probabilities are based on data from 2016 and 2017, which we elaborate upon in Appendix **??**.

Patient type	Arrival rate (per day)	LOS (in days)	$\mathbb{E}L$	Max. number of beds	Rejection probability
IC patients	2.04	11.87	24.25	24	0.15
HC patients	0.47	13.08	6.12	8	0.13
Total resource pooling	2.30	12.05	27.16	32	0.06

Table 4.2: The rejection probability for maximum capacity, based on the Erlang loss model

Patient type	Arrival rate (per day)	LOS (in days)	$\mathbb{E}L$	Rejection probability	Expected number of occupied beds
IC patients	2.04	11.87	24.25	0.17	21
HC patients	0.47	13.08	6.12	0.00	7
Total resource pooling	2.30	12.05	27.76	0.15	24

Table 4.3: The expected number of occupied beds for a predetermined rejection probability, based on the Erlang loss model

Based on the predetermined rejection probabilities, our results indicate that the department could operate with 24 beds on average with total bed pooling. However, without resource pooling, the department needs at $21 + 7 = 28$ beds on average. However, when this capacity is used the expected rejection rate is higher, since we are talking about the average number of occupied beds, as Table 4.4 shows as well. These actual rejection rates are too high in our opinion, since more than 23% of arriving IC patient is rejected. Moreover, when we compare these numbers to reality, we see that less beds are used, which results in lower rejection rates.

Patient type	Arrival rate (per day)	LOS (in days)	$\mathbb{E}L$	Number of beds	Actual rejection probability
IC patients	2.04	11.87	24.25	21	0.233
HC patients	0.47	13.08	6.12	7	0.193
Total resource pooling	2.30	12.05	27.76	28	0.132

Table 4.4: The actual rejection rate with number of beds as calculated in Table 4.2

4.3 Results based on PAC system

Now the results of the Erlang loss model are given in Section 4.2, we will now continue with the calculations for the PAC model. In PAC system calculations, a distinction is made between systems with universal and dedicated cards, and between single class and multi class systems. Moreover, a PAC system can be a Production-To-Order system or a Production-To-Stock system. At last, there are models for simulating single or multi server stations.

Since at the neonatology department the treatment of a patient depends on the patient type, we model this system as a multi-server station system with universal cards. The motivation for this decision is that performing calculations for dedicated cards are complex and that the same average performance measures can be calculated by multi-server stations. In our case there are two stations: IC and HC treatment. Both stations have a specific number of servers: 24 IC servers and 8 HC servers, the maximum capacity of the department. Furthermore, treating patients at the NICU can be seen as a Production-To-Order system, since they only treat a patient once a patient arrives at the NICU.

All these characteristics caused that we use the Marginal Distribution Analysis (MDA), as described by Zijm [18]. This type of workload controlled manufacturing system analysis is specifically meant for analysing multi-server systems. Algorithm 1 presents the calculations for the MDA. The notation used in this algorithm are defined in Table 4.5 and the notation is translated to the situation at the neonatology department.

Algorithm 1: Marginal Distribution Analysis

1. Initialization. Set $V_0 = 1$. Determine the other visit ratios V_j, $j = 0, ..., M$. Set $n = 0$ and $p_j(0|0) = 1$, $j = 0, ..., M$.

2. $n := n + 1$

3. Compute $\mathbb{E}W_j(n)$ for $j = 0, ..., M$ from:

$$\mathbb{E}W_j(n) = \sum_{k=c_j}^{n-1} \frac{k - c_j + 1}{c_j \mu_j} p_j(k|n-1) + \frac{1}{\mu_j} \tag{4.4}$$

4. Compute $TH_0(n)$ from:

$$TH_0(n) = \frac{n}{\sum_{j=0}^{M} V_j \mathbb{E}W_j(n)} \tag{4.5}$$

   and then compute $TH_j(n)$ for $j = 0, ..., M$ from:

$$TH_j(n) = V_j TH_0(n) \tag{4.6}$$

5. Compute the marginal probabilities $p_j(k|n)$ for $k = 1, ..., n$ and $j = 0, ..., M$ from:

$$\mu_j min(c_j, k) p_j(k|n) = TH_j(n) p_j(k-1|n-1) \tag{4.7}$$

   and compute $p_j(0|n)$ for $j = 0, ..., M$ from:

$$p_j(0|n) = 1 - \sum_{k=1}^{n} p_j(k|n) \tag{4.8}$$

6. If n=N then stop; else go to step 2.

In the first step of this algorithm, the starting position is determined. V_0 is the visit ratio of the synchronization station as was seen in Figure 3.1 and V_j is the visit ratio of station $j = 1, ..., M$, with M is the number of stations, which is 2 in case of the neonatology department. The initial number of beds, n, is set to zero and probability $p_j(0|0) = 1$, in other words the probability of zero patients at the department when there are zero beds. Then in step 2 one bed is added.

Variable	Definition
V_j	Visit ratio at bedtype j
n	Number of operational beds
N	Maximum number of beds
M	Number of bedtypes
$\mathbb{E}W_j(n)$	The expected time a patient of type j spends at the neonatology department, given n operational beds
k	Number of occupied servers
c_j	Number of servers of bedtype j
$p_j(k\|n-1)$	Probability of k patients present of type j, given (n-1) operational beds
μ_j	Service rate of bedtype j
$TH_0(n)$	Throughput of neonatology department, given n operational beds
$TH_j(n)$	Throughput of bedtype j, given n operational beds

Table 4.5: All notations of the formulas for the Mean Distribution Analysis algorithm

In step 3, the expected time in the system is calculated, which can be divided into the expected waiting time and the expected service time, $\frac{1}{\mu_j}$. The expected waiting time is depending on the number of patients in the system, the number of servers of station j and the chance that a patient arrives at the system when all beds are occupied, $p_j(k|n-1)$.

At step 4 the throughput of the whole system, $TH_0(n)$, and the throughput per station, $TH_j(n)$, are calculated. The station specific throughput is the result of a multiplication of the visit ratio of that station with the throughput of the whole system.

Then, in step 5, the marginal probabilities, $p_j(k|n)$, are calculated. All input for this is known or can be found in the previous iteration. When all these probabilities are calculated, also $p_j(0|n)$ can be calculated. Last, when the number of beds (n) is still not equal to 32, continue the algorithm at step 2.

n	$TH_0(n)$ (per hour)	$\mathbb{E}L_{IC}(n)$	$\mathbb{E}L_{HC}(n)$	$\mathbb{E}W_{q,IC}(n)$ (in hours)	$\mathbb{E}W_{q,HC}(n)$ (in hours)
24	0.08287	19.7	4.3	0.00	0.00
25	0.08629	20.5	4.5	0.11	0.00
26	0.08960	21.3	4.7	0.68	0.00
27	0.09262	22.2	4.8	2.26	0.00
28	0.09520	23.0	5.0	5.38	0.00
29	0.09721	23.9	5.1	10.39	0.00
30	0.09865	24.8	5.2	17.31	0.00
31	0.09958	25.7	5.3	25.92	0.00
32	0.10013	26.6	5.4	35.83	0.00

Table 4.6: Summary of the results of the Mean Distribution Analysis

After n reaches $N = 32$, the results of all iterations are analysed: what is the throughput of the system and what is the expected number of patients present and what is their patient type? The reason why we analyse the throughput of the whole system, is to make sure that the system is stable, in other words: that $TH_0(n) > \lambda$. Table 4.6 gives a summary of the results of the MDA calculations. We conclude that the system is stable when it operates with

28 or more beds, then $TH_0(28) = 0.097$ per hour, which is larger than the external arrival rate of $\lambda = 0.094$ per hour. It is important to mention that the number of beds is related to the number of servers per station, which are 24 IC servers and 8 HC servers. When using 28 beds, the expected number of IC patients in the system is 23 and the expected number of HC patients is 5. This number can be calculated by Equation 4.9.

$$\mathbb{E}L_j(n) = \sum_{k=0}^{n} p_j(k|n)k \tag{4.9}$$

We can conclude that on average not all capacity is used for treating IC and HC patients and this also explains why the expected time in the queue, EW_q, is zero for HC patients. However, for IC patients there is a chance that a patient has to wait for an IC server to become available. The more PACs are used, the higher the expected waiting time for IC patients will be, since the number of PACs exceeds the number of IC servers.

Now we know what the results are of using patient specific servers and maximum capacity, in this paragraph we will continue with a situation of simple resource pooling. Such as done in Section 4.2, we will use an arrival rate of $\lambda = 0.0938$ per hour, and an expected service time $\mathbb{E}S = 289.2$ hours. We use algorithm 1 for performing the MDA calculations, but now the number of servers is unrestricted. Therefore, the number of servers is set to 32 for both patient types. Table 4.7 gives a summary of the result of the MDA for simple pooling.

n	$TH_0(n)$	$\mathbb{E}L_{IC}(n)$	$\mathbb{E}L_{HC}(n)$	$\mathbb{E}W_{q,IC}(n)$	$\mathbb{E}W_{q,HC}(n)$
24	0.08287	19.8	4.2	0.00	0.00
25	0.08632	20.6	4.4	0.00	0.00
26	0.08977	21.4	4.6	0.00	0.00
27	0.09323	22.2	4.8	0.00	0.00
28	0.09668	23.1	4.9	0.00	0.00
29	0.10013	23.9	5.1	0.00	0.00
30	0.10359	24.7	5.3	0.00	0.00
31	0.10704	25.5	5.5	0.00	0.00
32	0.11049	26.3	5.7	0.00	0.00

Table 4.7: Summary of the results of the Mean Distribution Analysis for simple resource pooling

The results do not differ much compared to the situation of no pooling, as shown in Table 4.6. Again, we can conclude that the system is stable when it is operating with 28 or more beds, then $TH_0(28) = 0.09668$ per hour, which is larger than the external arrival rate of $\lambda = 0.09375$ per hour. In this case 23 IC and 5 HC patients are present at the department. However, as shown in Table 4.7, the waiting times for IC patient was completely eliminated.

4.4 Comparison of results

With the Erlang loss model we analysed two scenarios: no pooling and simple resource pooling. Furthermore, we determined the rejection probability for maximum capacity and the number of required beds given the rejection probability based on historical data. The rejection probability for maximum capacity is 0.15 for IC patients. If 700 patients need treatment per year, this leads to 105 rejections and 595 patients being assigned to a bed. The rejection probability for

HC patients is not realistic, since this patient type will never be rejected in practice. Therefore, we chose to also calculate the rejection rate based on historical data and set this as a target. For a rejection rate of 0.17 or lower, at least 21 beds are required. For treating all HC patient 7 beds are required and then there will be no rejections. In total, for no resource pooling, 28 beds are required and then the rejection rate is lower compare to the rejection rate of IC patients for 21 beds and the rejection rate of HC patient with using 7 beds. However, if we compare the results with the actual performance of the department, the number of beds that are required for a similar rejection rate are higher.

With the PAC model we also analysed two scenarios: no pooling and simple resource pooling. For both situations the number of beds required for a stable system, when the throughput is larger than the arrival rate, is calculated. For both situations the total number of beds is 28 and in both situations the number of IC patients present is 23 and there are 5 HC patients. The difference between the two is the expected waiting time of IC patients, which is more than 5 hours when there are 28 beds in the situation of no pooling and in case of total resource pooling, We can conclude the waiting time is eliminated.

Both mathematical models give results which are in the same range. However, we see differences between the two models with respect to their capabilities and drawbacks. For example, in case of a CQN, such as a PAC system, the arrival rate per patient type was not taken into account in the algorithm. This can be explained by that PAC system is based on the principle of a steady state and a CQN: a new patient enter the system out of the synchronization station once a discharged patient leaves the system. Secondly, the calculations of the Erlang loss model are less time consuming in comparisons to the PAC model, in which multiple iterations have to be performed. At last, the PAC model, has an advantage compared to the Erlang loss model. In loss models patients are immediately rejected when there is no bed available, while in the PAC models, patient are placed in an external queue. Then the number of beds used can be chose such that the expected waiting is within an acceptable range. In this way a patient can wait for a short period, and can be assigned to a bed becoming available shortly after entering the queue. This is also the case in practice. When the department is called for a new patient, at that moment all beds could be occupied. However, the coordinating staff can forecast whether a patient is discharged within a few hours, so that the bed becomes available for the patient to arrive.

4.5 Conclusion

Resource pooling seems to be beneficial for the neonatology department, based on both models. On one hand, it reduces the number of required beds in the Erlang loss model. On the other hand, it eliminates waiting time for patients in a PAC system. Furthermore, when we compare the two models, we see similar results for the expected number of occupied beds. However, the results found with the two models, are not even close to the actual performance of the neonatology department, which was 20 beds on average in 2016.

The Erlang loss model has the advantages that the calculations are simple and that the results can be used for strategic decision making. However, the calculations are based on average values, which means that seasonal trends are ignored.

The PAC model has the advantage, in our opinion, that a patient is not immediately rejected when no resource are available. In this way, we can adjust the number of beds in such a way that the expected waiting time will not cause medical threats for patients that arrive in an fully occupied system, as explained in the last few sentences of Section 4.4.

Both mathematical models are based on average values for the arrival rate as the service rate. In practice, we see seasonal trends throughout the year, and therefore we choose to simulate the neonatology department to check whether the variety in arrival patterns and LOS will have influence the number of required beds and the rejection rate.

Chapter 5

Simulation model

In Chapter 4, we analysed the neonatology department based on two mathematical models: an Erlang loss model and a workload control model: a PAC system. Since these models are based on average values, we want to see what the influence of the arrival patterns and the varying LOS is on the number of rejections and the required number of beds. By comparing the results of the models of Chapter 4 with the outcomes of a simulation model, we can verify whether the results of the Erlang Loss model and the PAC systems are an accurate estimation of reality. Moreover, with a simulation model we can explore what will happen when the department is rebuilt as well and using the resource pooling strategy in that situation. We use the simulation software called Tecnomatix Plant Simulation by Siemens to simulate the day by day situation at the neonatology department. The steps of a simulation study as designed by Law (2015) are followed.

The first step, according to Law (2015), of the simulation study is to define the problem. Our problem is already stated in Section 1.2 and concerns the influence of pooling hospital beds in case of the rebuilt situation. The next step is to gather necessary data to construct the model. In Chapter 2, we gave information about the arrival pattern, the LOS of patients and the number of rejections in the current situation. The remaining steps of the simulation study are not yet described in this report. These steps can be read in this chapter, which is divided into the following sections: goal of simulation, assumptions, explanation of components of the simulation model, performance indicators, verification, validation, and simulation settings.

5.1 Goal of the simulation study

With the simulation models we want to make a comparison between the current situation and the rebuilt situation. We would like to gain insight in the influence of merging all or a part of the IC and HC beds, as could be done in the rebuilt situation.

We make a live comparison between the no-pooling (NP) strategy and the total pooling (TP) strategy. This is done by duplicating an arriving patient and assigning it both to a bed in the no-pooling department and in the total pooling department. Both situations are visible in the same NICU frame of the model, as can be seen in Appendix **??**.

The performance of the TP strategy is based on the number of rejections, and the number of IC admissions. Since these number add up to the number of arrival, we choose the number of rejections to be the key performance indicator (KPI).

5.2 Assumptions

Processes such as assigning patients to beds at the NICU, can not be modelled with simulation software without assumptions. In our study, assumptions are made for the patient types at the department, the arrival pattern of patients, the presence of multiple births, the maximum waiting time of a patient, the number of open beds and the number of IC beds. All these assumption and their motivation can be found in the following subsections. The numerical and statistical background of these motivations can be read in Appendix **??**.

5.2.1 Patient types

We let IC patients arrive at our simulation department. Of these IC patient 19.49% also need to receive an HC treatment after being treated as an IC patient. Using this percentage results in the same ratio of IC and HC patients as being treated in real life.

5.2.2 Presence of multiple births

In the mean inter-arrival time, as given in Chapter 2, also the inter-arrival times of zero were included. These values mostly occur with patients that are part of a multiple birth. For the simulation model, we chose to exclude these values, and duplicate or triplicate arriving patients based on discrete probabilities. Excluding all zeros from the IAT data, gives an average IAT of 12.82, which is used as IAT for the simulation model. Furthermore, we assume that the occurrence of twins is 16.45% and the occurrence of triplets is 1.63%. We also assume that patients who are part of multiple birth have the same LOS, since the neonatology department aims to discharge the all patients part of that multiple birth at the same time, when they are transferred to a peripheral hospital. In case of a multiple birth arriving at the department, they should all be assigned to a bed or they should all be rejected when not enough beds are available. In practice, the department sometimes decides to assign a patient to an additional bed. We did not include the possibility of temporary expanding capacity to assign more patients.

5.2.3 Arrival pattern of patients

The arrival process of IC patients at the NICU is according to a Poisson process with a mean inter-arrival time of 12.82 hours. The motivation for the exponential distribution is given in Appendix **??**. However, the input parameters for these distributions as they are used in this simulation are explained in Appendix **??**. In Tecnomatix Plant Simulation a Poisson process is simulated by giving a entity a negative exponential inter-arrival time, in which also a minimum and maximum value should be given. For the minimum value we chose zero, since negative inter-arrival times do not occur. For the maximum value we chose the maximum inter-arrival time that was found in the analysed data.

5.2.4 Maximum waiting time

We assume that there is a small time that covers both the discharge moment and the time of assigning a new patient to that bed and therefore, a maximum waiting time was included. When the patient is waiting longer than the maximum waiting time it should be rejected, regardless of a bed becoming available. However, when the waiting time of a patient is less than the maximum waiting time he can still be assigned to the bed that becomes available. The value of the maximum waiting time is verified with professionals of the neonatology department.

5.2.5 Number of open beds

Since the number of open bed depends on the number of available nurses, the number of open beds varies during a year. This seasonal trend is not included in the simulation models. Therefore, an assumption is made for the average number of open beds. For this simulation model, the number of open beds is used as an variable.

5.2.6 Number of IC beds

Just as the number of open beds, the number of IC beds depends on the number of available nurses. However, a part of the open beds are dedicated to the treatment of IC patients, IC beds, and the maximum number of IC patients present at the NICUs is depending on the quality of personnel. Similar to the number of open beds, the number of IC beds is a variable in our simulation model.

5.2.7 Length of hospital stay

By analysing data, as done in Chapter 2 and Appendix **??**, we conclude that the LOS has an exponential distribution. Therefore, we simulate the LOS with a negative exponential distribution. This distribution consists of three parameters: mean value, the lower bound, and the upper bound. The parameter used in the simulation are given in Section 5.6.

5.3 Components of simulation model

Appendix **??** gives the detailed description of components of the simulation model. Furthermore, visualizations of the frames of the simulation models are given in this appendix.

5.4 Performance indicators

To determine the performance of the simulation model, we use several performance indicators. These performance indicators are: number of patients treated and the number of rejections. These performance indicators are related to the input parameters, and therefore expected to differ over the various experiments, as given in Section 5.7.5.

5.5 Verification

Since we made multiple assumptions, these decisions are discussed with professionals of the neonatology department. With verifying the assumptions made, some assumptions had to be adjusted. As an example, we first also let HC patients be rejected in our simulation model. However, the professionals mentioned that this would not occur in practice. Whenever a patient also needs HC treatment but no HC bed are available, this patient will stay at an IC bed, until an HC bed is available. This can eventually lead to a new IC patient being rejected, since no IC bed is available.

5.6 Validation

The simulation model is validated with historical data, based on the number and the type of admissions, the number of rejections and the average length of stay for both patient types. with 32 open beds, 24 IC beds and a maximum waiting time of one hour, the number of patients admitted to a bed in the NP strategy, or current strategy, is 791 and the number of rejected patients is 130. All admissions are not unique patients, since when an HC patient is moved from an IC bed to an HC bed, it is registered as a new patient. These results are reached in practice by using 22 beds on average, which could imply that the simulation generates values that are too high in comparison to reality. This can also be explained by the fact that data about admission and discharge, such as used for these calculations, do not represent the actual time of the patient present at a bed. Therefore, we validated the model by adjusting the LOS in such a way that the same number of admitted patients, can be served with using less beds as well. In other words, we validate the models in respect of the KPI. Appendix **??** provides the details about these validation calculations. Furthermore, in the same appendix the distribution of both the inter-arrival times as the LOS is validated with historical data. It seems contradictory to validate the LOS distribution with historical data, since it was said before that we will adjust the LOS. However, the hypothesis about the data not representing the time a patient is present at a bed, should be confirmed.

Based on the LOS validation performed in Appendix **??**, we chose an negative exponential distribution for the inter-arrival time, with a mean value of 10.75 hours. Secondly, the service times also are negative exponentially distributed and the IC LOS has a mean of 8.87 and a maximum value of 121.00 days. The HC LOS has a mean value of 10.08 and a maximum value of 98.10 days.

5.7 Simulation settings

In order to generate reliable data and being able to reach the goal of the simulation, the simulation should have specific settings. These settings are explained in this section.

5.7.1 Warm-up period

A warm-up period is required for the deletion of the initial output data. In this period the results depend on initial conditions and therefore, these results are not representative for a steady state. This is also the case in the situation of the neonatology department. The behaviour of the neonatology department is depends on the number of patients present the days before. Now the question is: How long should this period be in order to delete the right amount of data?

For determining the warm-up period we considered the distribution of rejections over time, which is the graphical method by Welch. In the resulting graph, we see that the number of rejections are not evenly distributed over the first 365 days. To make sure, that the system is completely stable, we chose the warm-up period to be 365 days, in other words one year. When this warm-up period is finished, the simulation will delete all information in the tables

PatientInfo and *Rejections* and the number of patients and the number of rejections will be reset.

5.7.2 Run length

We are interested in the performance of the system on a yearly basis and therefore, we chose a run length of 365 days. Since, the system is cleared of all patients once it is reset, we should add the warm-up period per run. This results in a total run length of 730 days.

5.7.3 Number of replications

Law [20] mentions that the minimum number of replications is five, but he also gives the sequential method to calculate the number of replications. This method is used and explained in Appendix **??** and from this we conclude that the minimum number of replications per experiment is 20.

5.7.4 Random numbers

Each replication of an experiment has a different random number as seed value. This is achieved by turning on the function *Increment variant on reset* in the *EventController* of Tecnomatix Plant Simulation. The varying random numbers can result in different outcomes per run, which results in the values obtained by the experiments to be average values of all these replications.

5.7.5 Experiments

Now all simulation settings are determined, we need to establish the settings for the experiments. For answering the research questions multiple experiments are needed. In the no pooling strategy, or the current strategy, beds are dedicated to a certain patient type: IC or HC. An HC patients can be assigned to an IC bed and an IC patient cannot be assigned to an HC bed, due to quality constraints. In the pooling strategy all patients can be assigned to all beds, which is called total or simple resource pooling.

Furthermore, there are some parameters that we can change and their effect can be analysed. Since the department is coping with a shortage of personnel, the question of what would be the performance of the department when more beds are open seems to be of additional value for the management team of the department. Furthermore, the number of IC and HC beds can be changed to check what the influence of the number of IC beds is in the current situation.

Table 5.1 gives the configuration of all experiments. In this table, settings for the no-pooling strategy, or current strategy, are indicated with NP and setting for the total pooling strategy is indicated with TP. Since we assess the influence of total resource pooling, the number of IC beds is not set for the total pooling strategy.

Two additional experiments are added: the outcomes of the Erlang loss model, in experiment 13, and those of the PAC system, in experiment 14, as calculated in Chapter 4. With the simulation we can check whether the rejection rate as calculated with the Erlang loss model is as expected. Or whether the expected waiting time of a patient entering the simulation models is as calculated by the PAC model.

Experiment	Number of open beds (NP)	Number of IC beds (NP)	Number of open beds (TP)
1	32	24	32
2	32	26	32
3	32	28	32
4	30	22	30
5	30	24	30
6	30	26	30
7	28	20	28
8	28	22	28
9	28	24	28
10	26	19	26
11	26	20	26
12	26	22	26
13	24	16	24
14	24	18	24
15	24	20	24
16	22	14	22
17	22	16	22
18	22	18	22
19	20	12	20
20	20	14	20
21	20	16	20
22	28	21	28
23	28	23	23

Table 5.1: Configurations for experiments

We perform these experiments by using the *ExperimentManager*, which is an application within the software Tecnomatix Plant Simulation. In Chapter 6, we discuss the results of these experiments.

Chapter 6

Results of simulation experiments

This chapter discusses our analyses of the results of the experiments given in Section 5.7.5 of Chapter 5. The detailed results can be found in Appendix **??**. Since the results are mainly about the influence of resource pooling, we dedicated a section of this chapter to this subject: Section 6.1, which is divided into two subsections: the influence of the number of open beds and the influence of the number of IC beds. Section 6.2 discusses the results of the Erlang loss and PAC experiments. Moreover, we show the financial aspects of pooling in Section 6.3. At last, an overall conclusion is made in Section 6.4.

6.1 Influence of resource pooling

First, we analyse the differences between the total pooling and no pooling strategy. In Section 6.1.1 the influence of the number of open beds is explained and in Section 6.1.2 the influence of the number of IC beds. Figure 6.1 shows the number of rejections for experiments 1 to 21. Experiments 22 and 23 were excluded from this analysis, since we only use these experiments for the comparison to the Erlang loss and PAC model. In Appendix **??**, we perform a paired T-tests with an α of 0.001 to analyse whether the differences between the current and rebuilt situation are significant. The differences in the number of rejections are significant in all experiments.

The results given in Figure 6.1 show that the number of rejections is lower with the pooling strategy and that this does hold for all experiments. In other words, the number of rejections is lower in case of total resource pooling. This can be explained by HC beds being able to only treat HC patients, due to quality constraints and with that, a part of the available capacity is restricted. Since the number of rejections is directly related to the number of admitted IC patients, the number of admitted IC patients are obviously higher in case of total resource pooling.

Figure 6.1 shows a reference line of the number of rejection in 2017, as well. From this we conclude that the performance of the simulation model is not close to the performance of the actual department.

6.1.1 Influence of the number of open beds

First, we conclude that the number of open beds is strongly correlating to the number of rejections. This is obvious, since the more open beds, the more capacity is available to treat patients. Moreover, figure 6.1 shows that the effect of resource pooling is larger in case of less

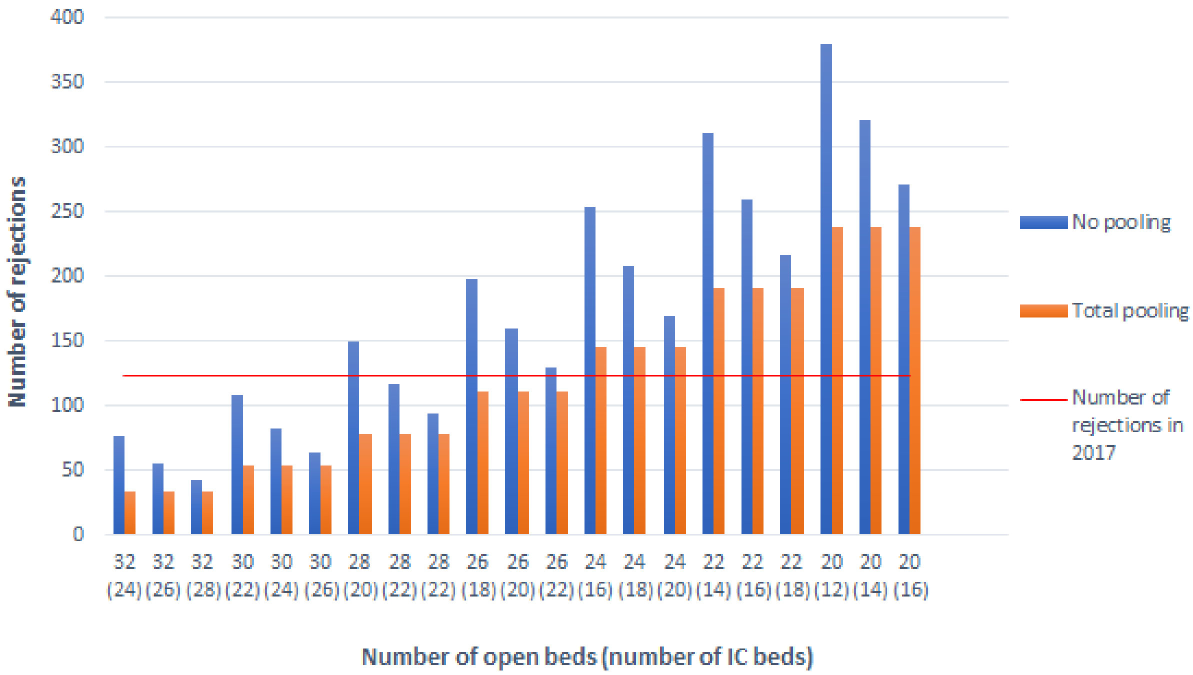

Figure 6.1: Bar chart of the number of rejections for experiments 1 to 21, including a reference line for the number of actual rejections in 2017

capacity.In the experiments with 32 open bed, we see that the benefit of resource pooling is small in comparison to no pooling. However, in experiments 19 to 21, we open only 20 beds, which results in the largest benefit of total resource pooling in comparison to the no resource pooling strategy.

6.1.2 Influence of the number of IC beds

In theory, the number of HC beds is often equal to 8, when there are 32 open beds. However, by adjusting the number of HC beds to 6 or even to 4, the number of rejections is reduced compared to the situation with 8 HC beds. We make the number of IC beds variable for all experiments and with that the number of HC beds also varies. Figure 6.1 shows that by increasing the number of IC beds, the number of rejections decreases. In other words, the less beds are dedicated to HC patients, the more patients can be treated. So, even with such a small adjustment, a reduction of the number of rejections can be achieved. From these results, we conclude that opening 8 HC beds is not efficient for treating most patients.

6.2 Results of the Erlang loss and PAC experiments

Two additional experiments were performed with the settings resulting from the Erlang loss and PAC calculations in Chapter 4. In experiment 22, with the Erlang loss settings, the average number of admissions is 694 and the number of rejections is 137 in the current situation, per year. This results in 831 patient arriving in the system and when 137 of them are rejected, the rejection ratio is 0.165. In case of total resource pooling, the rebuilt situation, the number of admissions is 745 and the number of rejections is 86. This results in 831 patients arriving and then the rejection rate is 0.103. We compare these values to the rejection probabilities as calculated in Chapter 4 and we can conclude that the rejection probabilities in case of the simulation model are higher than as calculated by the Erlang loss model. When we assume that the simulation models is a better representation of reality, and therefore, we conclude the Erlang loss model underestimates the number of rejections. Table 6.1 presents the values used in this comparison.

Type of model	Rejection rate (NP)	Rejection rate (TP)
Erlang loss results	0.098	0.046
Simulation results	0.165	0.103

Table 6.1: The rejection rate as assessed by the Erlang loss model and the simulation model

For determining the similarities or differences between the PAC system and the results of simulation experiment 23, an additional 20 runs were performed. We did not know the waiting time of a patient when the patient is assigned to a bed. Furthermore, when we want to compare experiments 23 with the results of the simulation model, we need to set the maximum waiting time to infinite. In this way the simulation is no longer rejecting patients, as is the case in the PAC calculations in Chapter 4. The results of these adjustments can be found in Table 6.2. We can conclude that the expected waiting as calculated with the PAC model is an underestimation compared to the results of the simulation model. However, it is important to mention that in case of the current situation 237 out of 828 IC patients experienced a waiting time and in the rebuilt situation 166 out of 828 patients. This implies that the expected waiting time of a waiting patient in the queue is even larger.

Type of model	Expected waiting time (C)	Expected waiting time (R)
PAC results	5.38 hours	0.00 hours
Simulation results	20.54 hours	6.47 hours

Table 6.2: The rejection rate as assessed by the Erlang loss model and the simulation model

6.3 Financial aspects of resource pooling

The financial aspects of resource pooling can be divides into costs and benefits. The costs will be generated by invest in the education of HC personnel to be able to care for IC patients as well. Furthermore, the department should invest in medical equipment, for making all beds able to care for an IC patient.

Resource pooling has financial benefits as well. Patients will no longer be transferred between IC and HC beds. This saves a lot of time: cleaning of new and old bed, transferring patient, transferring supplies (catheters, diaper, etcetera), and administrative work. The biggest financial benefit of resource pooling is treating more patients. The neonatology department is paid per hospital day per patient per day, and of this payment the department should pay their bills. One IC hospital day generates an income of €2150, and when we assume that an IC patient stays at the department for 11.87 days on average, we can calculate the financial benefits for all experiments.

Exp. Exp.	Open beds	IC beds	Admissions (NP)	Admissions (TP)	Difference in admissions	Difference in hospital days	Financial benefit (€)
1	32	24	754.1	796.7	42.6	505.7	1,087,173
2	32	26	775.8	796.7	20.9	248.1	533,378
3	32	28	787.6	796.7	9.1	108.0	232,237
4	30	22	722.1	776.7	54.6	648.1	1,393,419
5	30	24	748.4	776.7	28.3	335.3	720,954
6	30	26	766.2	776.7	10.5	124.6	267,965
7	28	20	681.0	752.6	71.6	849.3	1,825,992
8	28	22	713.7	752.6	38.9	461.7	992,747
9	28	24	737.0	752.6	15.6	184.6	396,844
10	26	18	632.9	719.8	86.9	1031.5	2,217,731
11	26	20	670.7	719.8	49.2	583.4	1,254,333
12	26	22	701.3	719.8	18.6	220.2	473,405
13	24	16	577.4	684.8	107.4	1274.8	2,740,902
14	24	18	622.6	684.8	62.3	738.9	1,588,651
15	24	20	660.2	684.8	24.7	292.6	629,080
16	22	14	519.4	640.0	120.6	1430.9	3,076,496
17	22	16	570.1	640.0	69.9	829.1	1,782,607
18	22	18	614.0	640.0	26.0	308.6	663,533
19	20	12	451.1	593.0	141.9	1684.4	3,621,359
20	20	14	509.9	593.0	83.1	986.4	2,120,754
21	20	16	559.9	593.0	33.1	392.9	844,729
22	28	21	693.7	744.9	51.3	608.3	1,307,926
23	28	23	729.2	752.6	23.3	277.2	595,904

Table 6.3: The financial benefits of resource pooling per year

6.4 Conclusion

In conclusion, when assuming that the simulation results are closest to the actual performance, the Erlang loss model and the PAC model underestimate the number of rejections and the expected waiting time respectively. This can be explained by that the Erlang loss model and the PAC model simplify the system at the neonatology department of WKZ even more than is done in the simulation model. The simulation model uses an exponential distributions for the IAT and the LOS, which cause variation in the load of the system. When patients are arriving at a full system, they are rejected after waiting for one hour. This is not taken into account in both the Erlang loss and PAC model, where the arrival of patient is assumed to be with arrival rate λ.

By analysing the results of all experiments, it becomes clear that pooling the IC and HC beds causes a reduction in the number of rejections in the simulation model as well. Unfortunately, even with the adjusted LOS, the number of beds required for a performance close to reality are higher than operational at the neonatology department. We conclude that the simulation model overestimates the number of rejections with a given capacity, when comparing it to the actual performance of the department. One of the reasons that the number of rejections is higher in the simulation model, is the occurrence of enable an additional bed.

Chapter 7

Conclusion and recommendations

This chapter provides the answers to the research questions and the conclusions drawn in this thesis. We give these answers and conclusions in Section 7.1 and this is then again divided into four subsections: Section 7.1.1 about the current performance, Section 7.1.2 about the mathematical models, section 7.1.3 about the simulation model and in Section 7.1.4 an overall conclusion is drawn. Then, in Section 7.2, we give our recommendations, which is done for both the neonatology department in Section 7.2.1 and for research in section 7.2.2.

7.1 Conclusion

The conclusions are divided into three subjects: current performance, mathematical models and the simulation model. In each subsection we answer the corresponding research questions and we draw a conclusion.

7.1.1 Current performance

In general, only IC patients have an initial arrival at the neonatology department of WKZ. HC patients are first treated as IC patients. Once a patient arrives, he can be admitted to an IC bed based on his medical condition. However, arriving patients can only be assigned, when there is an appropriate bed available. When there is no IC bed available for an arriving patient, this patient is rejected. Once an IC patient at the NICU does no longer meet all IC criteria, he can be transferred to an HC bed. This type of transfer is seen as non-medical, since these are meant for making IC beds available for patients to arrive. Only 16% of all IC patients assigned to the NICU, is assigned to an HC bed afterwards. The remaining number of patients is transferred elsewhere. Once a patient does no longer need an IC or HC bed, the patient is discharged from the NICU. In this process many stakeholders are involved, and this process often causes dissatisfaction with both the parents of the patient and personnel.

Moreover, we concluded that the department has a challenging time coping with all arriving patients given their limited capacity, due to shortage of personnel. The number of beds open for treating patients was on average 20 in 2016, which is only 62.5 percent of their maximum capacity. This resulted in 651 IC admissions and 93 patients were rejected in this year, which is 12.5% of all arriving IC patients.

7.1.2 Erlang loss model and PAC model

The flow of patients through hospitals is a well-studied subject in literature. Both the internal and external transfer showed medical consequences for patients. Furthermore, pooling hospital beds is a subject that is of growing interest within the past four years. For assessing the opportunities of resource pooling, mathematical models are used. In this project the Erlang loss model, which is already considered to be a good estimator by literature, and the PAC model, not yet used in healthcare environment, are used. PAC systems are CQN, in which the workload is kept at a constant level with the use of PACs and we conclude that such a system can be applicable to healthcare environments. Furthermore, we concluded that with both models reliable results were found, and total resource pooling seems to be beneficial for the neonatology department. Resource pooling reduces the average number of occupied bed in the Erlang loss model and it eliminates waiting time in a PAC system.

7.1.3 Simulation model

Since the Erlang loss and PAC model are based on average values for the inter-arrival time and the LOS, we simulate the department in Tecnomatix Plant Simulation as well. We conducted experiments with varying settings for both the number of open beds and the number of IC beds. Indubitably, the performance of the department is better when we open more beds. However, in practice, the number of open beds is restricted by available personnel. Furthermore, we concluded that a small number of IC beds limits the ability of the department to treat more patients. With a given number of open beds, a small number of IC beds means that there are more HC beds. The performance is best when all beds are pooled, as evaluated by the rebuilt situation. Then the reduction in the number of rejections is 30%, in average.

In conclusion, in comparison with the results of the simulation, both the Erlang loss model and the PAC model underestimate the number of rejections and the expected waiting time respectively. This can be explained by the fact that the Erlang loss model and the PAC model simplify the system at the neonatology department of WKZ even more than is done in the simulation model.

7.1.4 Contribution to practice

With this research we gained insights in the performance of the neonatology department of WKZ and the processes at a neonatology department in general. We conclude that the neonatology department is a unique environment, where acute patients are admitted and life-threatening situations occur at a daily basis. We see this report as a contribution to the knowledge present at this department. At the neonatology department the main focus is on providing the best possible care, and not on analysing data for logistical purposes. However, we assume that insights in these processes can eventually improve the care provided at the department. By pooling the IC and HC units, less patients are rejected and admitted patients do not have to be transferred to an HC unit after IC treatment, since this is done in the same family room.

7.1.5 Contribution to operations research

We used three models to assess the influence of merging the intensive and high care units at the neonatology department of Wilhelmina Kinderziekenhuis. All three models provide results that show us that with pooling the bed resources of IC and HC units, the number of rejected patients reduces. However, this is already repetitively seen in literature and therefore, we explain what makes this research different. In this research, we translated a workload control method to healthcare, and as far as we know, this is the first time that this is done.

7.2 Recommendations

After drawing conclusions, in this section we give several recommendations. The recommendations are divided in two types: those specifically for the neonatology department of WKZ and those for further research.

7.2.1 Neonatology department

Since total resource pooling is beneficial for the neonatology department, we recommend that the department should build 32 identical rooms that are able to allow both IC and HC patients. However, at the current situation the department can already test the future lay-out. The units are in the front connected to a corridor and the sides of a unit are connected to adjacent units. The units are separated by doors which can easily be opened. By doing so there is one large space with 32 individual incubators. By practising the future lay-out, personnel can experience drawbacks and advantages, which then can result in valuable feedback for the team that is responsible for rebuilding the department in 2021.

Moreover, the department is wondering if and how the patients flow to peripheral hospitals can be improved. We already concluded that 84% of all IC patients is transferred to a peripheral hospital after their IC treatment. By increasing this percentage or by fastening this process, and thus reducing the length of stay, the care intensity (in Dutch: zorgzwaarte) at the department will increase. Then the patients present are no longer some stable IC patient or HC patient, but they all require intensive and extensive care. Moreover, the pressure of transferring the patients to peripheral hospitals and performing these transfers earlier in their treatment, will increase the workforce of medical staff and nurses. Since the current workload at the department is already considered to be high, we would recommend not to aim for more and faster transfers.

7.2.2 Further research

As far as we are aware, this is the first time that a workload control manufacturing system model is used to evaluated patient behaviour and assess the performance of a system in healthcare. In healthcare, the Erlang loss model is used as a golden standard for estimating the rejection rate, the average number of patients present and the occupation level of beds. We think that workload control systems, such as the PAC system, has the advantage of not immediately rejecting a patient when all beds are occupied. Therefore, we recommend that this models should be used for larger scale projects as well. For example, estimating the number of beds necessary for an entire hospital and modelling the different care units as multi server stations.

We did not focus on the flow to peripheral hospitals. Therefore, we suggest that in further research, the performance of an entire region should be assessed, instead of one academic hospital. This is important, in neonatal care as well, since more neonatal departments are coping with capacity problems. We think that it is interesting to compare the resource use and the performance of all neonatal departments of the Netherlands.

7.2.3 Implementation plan

As already mentioned, the strategy of total resource pooling can be tested without rebuilding the department. Moreover, in March 2018, due to capacity problem, the HC unit was closed and HC patient had to be admitted at IC units. By operating in this way, they are already practising the total pooling strategy.

However, not all personnel is educated to care for IC patient and not all beds are equipped in such a way that IC patient can be assigned to them. Therefore, for implementing the total pooling strategy it is necessary to invest in the education of personnel or to come up with a clever way to divide the IC and HC patients over nurses present per day. Moreover, the department should invest in medical equipment for making all beds compatible for IC patients.

Chapter 8

Discussion

This chapter discusses the assumptions made and explains the limitations of this research. For a clear overview, this chapter is divided into the following subjects: HC unit in Section 8.1, time of admission and discharge in Section 8.2, feasibility in Section 8.3, the additional bed in Section 8.4, and rejection of HC patients in Section 8.5.

8.1 HC unit

All input parameters are based on available data and based on these input parameters, results were generated. We consider the data about HC patients to be insufficient. According to data used in this thesis, there were no HC admissions from week 47 of 2016 to week 17 of 2017. Though, we expect that there were HC patients present at the neonatology department during this 23-week period. For calculating the inter-arrival time of patients, we excluded outliers. However, in determining the patient flow, we could only use the admissions that were known. This lack in available data has probably caused a lower IC to HC flow than experienced in practice.

8.2 Time of admission and discharge

Another remark about the data used, as we already mentioned in this thesis, is that we doubt the reliability of registration of the time of admission and discharge. In the simulation models we found a value for LOS that was too high, since using 32 beds was not even enough to achieve the same performance as seen in historical data. This was tackled by adjusting the LOS is such a way, that the output of the simulation was comparable to reality. However, a reduction of three days cannot be explained by a wrong time for the registration of patients.

8.3 Feasibility

In this thesis, we concluded that total resource pooling leads to less rejections, regardless of the number of open beds. However, we did not discuss the feasibility of total resource pooling in practice. For instance, IC patients need additional medical devices for instance for respiratory support and the availability of these devices is not taken into account in any of the calculations of this thesis. Thus, the capacity of other resources than the beds can also restrict the opportunities of bed pooling.

In contrast to the medical resources, we think that with respect to the nursing resources, improvements will be made by pooling all hospital beds. With total pooling, there will be one large group of nurses working in a certain shift. All these nurses can individually be dedicated to a certain patient, instead of assigning a group of nurses to a group of patients. Another point of discussion considering personnel is the quality and education of personnel. In the mathematical and simulation models, we did not include the number and the quality of available nurses. We concluded that the more open beds, the less patients are rejected, obviously. However, this is currently not possible due to a shortage in the number of available and qualified personnel. This is a point of attention in case of total resource pooling, just as it already is in the current situation.

The financial aspect of total resource pooling was not in the main focus of this thesis. However, the department is paid for an occupied bed per hospital day. This amount differs between patient type that is assigned to this bed, since they receive other types of treatment. When pooling all hospital beds, the beds should be equipped with the same medical devices and this will result in all beds being over-equipped for treating HC patients. The IC equipment is not used during the treatment of HC patients, although all equipment and devices should still be maintained and cleaned. This can result in excessive operational costs and these are not completely covered, considering the lower payment for HC patients.

8.4 Additional bed

At last, we did not include the possibility of accepting a patient in an additional bed (in Dutch: overbed). This makes an one-to-one comparison of the number of rejections obtained by the model and the number of rejections obtained by historical data more complex. We assume that the modelled number of rejections is too high compared to reality, since additional beds could enable otherwise rejected patients to be admitted to the unit.

8.5 Rejection of HC patients

In the Erlang loss model, HC patients are treated the same as IC patients. There HC patients can be rejected when there is no available server, which in practice will never be the case, as explained in Chapter 5. At the neonatology department of WKZ, an HC patient will stay at his IC beds to wait for an HC bed to become available instead of being rejected as an HC patient.

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