# ACUITY MEASUREMENT AT THE NEONATAL INTENSIVE CARE UNIT

IE&M Graduation Thesis

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S1014544

1-10-2015

UNIVERSITY OF TWENTE.

# Acuity Measurement at the Neonatal Intensive Care Unit

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*Master thesis Industrial Engineering & Management*

UNIVERSITY OF TWENTE.

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# Management Summary


## Context

Due to an increase in neonatal intensive care demand every year many babies are denied an admission place on the Neonatal Intensive Care Unit (NICU). At the Wilhelmina's Child Hospital (WKZ), part of the University Medical Center Utrecht, this has raised attention to research possible applications of healthcare logistics to grant more babies the care they need.

At the NICU, premature born babies and babies in need of neonatal care are treated by highly specialized neonatologists and nurses. The organization of this care is starting to gain importance because nowadays babies born after 24 weeks of pregnancy can be admitted, and the length of stay reduces due to improvements in healthcare technology. This leads to a more complex logistical process, which more and more can benefit from operations research.

## Problem Statement

The current decision-making process regarding patient logistics, such as admissions and transfers, is done by medical experts and based on subjective information. When the NICU receives a request for admission, the question "can we handle another patient?" is asked among nurses. When too many nurses say no, the request is denied. This is based on the feeling of the nurses, which is hard to measure objectively. This research introduces a way for the NICU to assess the current nurses' workload more objectively in order to make a better informed decision. Simply counting patients is an unreliable source, since the severity of the patients is a large contributing factor.

Better informed decisions lead to fewer false decisions. There are two types of false decisions, which are false admissions and false rejections. When a patient is admitted falsely, the nurses' workload is too high, leading to a lower quality of care and quality of work. When a patient is falsely rejected, the quality of care for that single patient deteriorates unnecessarily and the WKZ misses the income.

Another benefit of measuring the nurses' workload is that it enables quantitative analysis, benchmarking, and optimization. This is a long-term benefit, of which this research the possible applications illustrates via a simulation model to assess policy decisions regarding patient placement and admission levels. This research introduces an own acuity measurement model, combining two existing models to fulfill the WKZ's requirements. Acuity is defined as "the categorization of patients according to an assessment of their nursing care requirements" (Harper and McCulley, 2007).

## The WKZ Neonatal Acuity Measurement Model

Our measurement model is based on the question "*How many of these patients can I handle today at the same time?"* This results in a classification based on the nurse-to-patient ratio, varying from 1-on-1 to 1-on-5. It is important to notice the word *today* in the question. Not only patient criteria are taken into account when classifying. The five criteria to keep in mind when rating are the amount of medication, complicated medical procedures, logistics, education, and psychosocial. Together, these factors contribute to the entire perception of the nurses' workload during a shift. We named our model NAPSS: the Neonatal Acuity-based Patient Scoring System.

## Empirical Test Results

We test the model on alignment, reliability, and validity. The test on alignment proves that the results from the model actually align with the real performance of the department. We test alignment by calculating the average length of stay as generated by a Markov chain analysis of the test results. This resulted in an average

length of stay of 9.4 days, where the hospital estimates this to be 12.5. The discrepancy can is explained by the test period and compensated.

The reliability of the model is measured by comparing the individual nurses' ratings to each other, meaning that the model is an objective measurement. The percentage of absolute agreement is sufficient to assume the model to be reliable. The validity of the model is tested through correlating the perception of workload by the nurses to the results of the model. This is correlated with a significance of <1%, meaning that the model actually measures the nurses' workload. These tests together confirm the model's practical applicability.

## Simulation Experiment Results

After the practical applicability is confirmed, we test for the practical value and implications it can introduce. This is done via a discrete event simulation model. The simulation study executes two experiments. The first experiment is a comparison between the current situation, where the patients are admitted based on the acuity levels, and a policy where only the number of free beds is taken into account. The goal of this experiment is to underline the value of reliably basing the decision on acuity levels. Neglecting acuity leads to a decline of refusals of 24%, raise the average amount of patients with 5,5%, but increase acuity overloaded shifts for nurses over 40%.

The second experiment compares the basic policy, where patients are evenly distributed over the three units of eight beds, to a policy where the units are filled optimally, leaving an as large as possible admission space on the other units. This is called the best-fill policy. Using the best-fill policy leads to a decrease of refusals of 25%, an increase of acuity overloaded shifts of 67%, and an increase in average amount of patients of 5.5%.

## Recommendations

The three main recommendations that follow from this research are:

- Introduce the acuity measurement system. Using the measurement system introduces more objectivity and reliability to base decisions on, as well as enables quantitative analysis, optimization, and benchmarking.
- Start benchmarking. This research identifies three performance indicators that acuity measurement can affect: the number of patient rejections, average utilizations, and the number of overloaded shifts. We also show a way of measuring the performance for all three indicators.
- Use a best-fill policy, despite the fact that this will increase the number of acuity overloaded shifts. The amount in which the average overload is, is less than the bed-filled policy, and when using acuity measurement the threshold, or fill-level, can simply be lowered to decrease these acuity overloads. Especially when combined with benchmarking and raising the bar on acceptable levels of acuity can this policy lead to an decrease of rejections of 25%, and an increase of, on average, 1 patient per day. This can lead to a maximum increase in revenue of €1,000,000 per year.

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# Abbreviations and Glossary

*Acuity* The categorization of patients according to an assessment of their nursing care requirements.
*Alignment* The measure for agreement between the calculations with the test results and real-life measurements or observations.
*Cohen's kappa* A statistic that measures inter-rater agreement.
*CRIB* Clinical Risk Index for Babies.
*Discrete event simulation* A quantitative method of analyzing a process through programming the process in a software package that compares several process compositions based on random numbers. The time series follows an order of well-defined events.
*HC* High Care.
*IC* Intensive Care.
*ICC* Intra-Class Correlation.
*IV* Intravenous.
*NAPSS* Neonatal Acuity-based Patient Scoring System.
*Neonatology* The area within medicine concerned with the care of newborn infants.
*NICU* Neonatal Intensive Care Unit.
*NTISS* Neonatal Therapeutic Intervention Scoring System.
*Markov Chain* Representation of a process as a chain of possible states.
*MC* Medium Care.
*OR* Operating Room.
*PA* Physician Assistant.
*Pairwise comparison* A method of comparing test results by comparing each pair of individual results with the same test subject.
*PCS* Patient Classification System.
*Pearson's r* A statistic that measures the correlation between two variables.
*Reliability* The measure for consistency and repeatability of the tests and models.
*Significance* Term to value the test results. We use 5% significance, meaning that test results that promise 95% certainty or more are accepted.
*SNAP* Score for Neonatal Acute Physiology.
*UMC* University Medical Center.
*Validity* The measure for the representation of the real-life for the tests and models.
*WANNNT* Winnipeg Assessment of Neonatal Nursing Needs Tool.
*WKZ* Wilhelmina's Child Hospital.

# Preface

Before you lies the report of my master thesis project at the Wilhelmina's Child Hospital of the University Medical Center Utrecht. This project was conducted from September 2014 until September 2015. The main result is a way of measuring the nurses' workload, which is a newly developed method we have called NAPSS (Neonatal Acuity-based Patient Scoring System.

Finishing this project means that I receive my master's degree in Industrial Engineering and Management at the University of Twente. I thank Willem de Vries for the opportunity to do this project at the WKZ, and together with Mayko Louer for their involvement and enthusiasm. Especially the fact that the system will be used in the future is something that I am proud of, which entirely compensates the slow progress we made at some times.

When I started my master program, I did not think that I would do my master thesis project in healthcare. I thank Erwin Hans for this opportunity , his immense enthusiasm, and his valuable comments. For his involvement and comments do I also thank Marco Schutten. A lot of nurses contributed to this project during the test period and pilot project, of which I want to thank Marion Bouman in particular for her involvement and input.

And of course do I want to thank my family for their support throughout my study and having to listen to me endlessly chattering about the project and related topics, and Jet specially for her correction of the thesis.

Willem Hoek

Enschede, October 2015

# 1.Research Outline

The Wilhelmina Children´s Hospital has a neonatal intensive care unit where newborns in need of intensive care are treated. Although the hospital tries to deliver appropriate care for all patients, it regularly has to refuse admission to newborns because of capacity constraints. This report explores the possible applications of healthcare logistics to the perinatal division, discusses a method to inform decisions regarding patient logistics, and recommends the application of a placement heuristic.

Section 1.1 introduces the context and motivation of this research. Section 1.2 describes the challenges faced by the WKZ's neonatal intensive care unit. Section 1.3 states the research goal and scope. Section 1.4 discusses the research questions and methodology that is used in this research.

## 1.1 Context and Motivation

Due to a lot of novelties and researches, the chance of survival for premature newborns has significantly increased over the years. The knowledge and resources to provide this type of care is rare, which is why there are only ten Neonatal Intensive Care Units (NICUs) in the Netherlands. The Wilhelmina Children's Hospital (WKZ) in Utrecht, part of the University Medical Centre Utrecht (UMC Utrecht), specializes in children's care and is one of the ten NICUs in the Netherlands.

**Figure 1: The WKZ**

The WKZ is part of the UMC Utrecht since 1999, when the Academic Hospital Utrecht, Medical faculty of Utrecht University, and the WKZ merged. With a total of 11,210 employees and 3,537 medical students (UMC, 2014), the UMC Utrecht is among the largest hospitals in the Netherlands. The WKZ owns over 220 beds, hospitalizes around 5,000 children each year, and about 3,000 children are being born yearly at the maternity ward.

The neonatal department is part of the WKZ birth center and consists of an Intensive Care (IC) unit, High Care (HC) unit, and a Medium Care (MC) unit. These units provide 24-hour treatment to newborns in need of neonatal care, some born after as little as 24 weeks of pregnancy. This research has been executed within the neonatal division, with a focus on the NICU.

Two trends are seen in neonatal care, which are that more newborns can be treated, and that the number of days spent in the hospital decreases. This makes patient logistics an increasingly relevant topic, since admissions and transferrals, both within and between hospitals, are rising in number. This increases the importance of the patient flow throughout the department. The WKZ wants to be able to treat all newborns that need neonatal care within its own target region. This theoretically impossible endeavor is the main reason why this research focuses on reducing the number of newborns that have to be rejected by the WKZ.

## 1.2 Problem description

As described above, the motivation behind the current research is the number of times the NICU is unable to accept a patient. The management team states that this number is too high, and that they want an exploration of the applications of patient logistics within the department. This section briefly elaborates on the origin of the problem and include a problem tangle with the selection of the main problem that is addressed in this research.

When a patient is admitted to the NICU, a few checks are made to assess whether or not there is a spot available. First, there must be a bed available. If there is no place to put the patient, the patient is refused. Then, all units are asked if they can handle another patient. This is an estimation made mainly by the nursing staff. When both these prerequisites are matched the patient gets admitted to the ward. Patients are generally refused because of a lack of physical space, or a shortage of nursing capacity. Included in these considerations is the question whether there are any patients that are ready for transfer. Figure 2 illustrates this decision process.

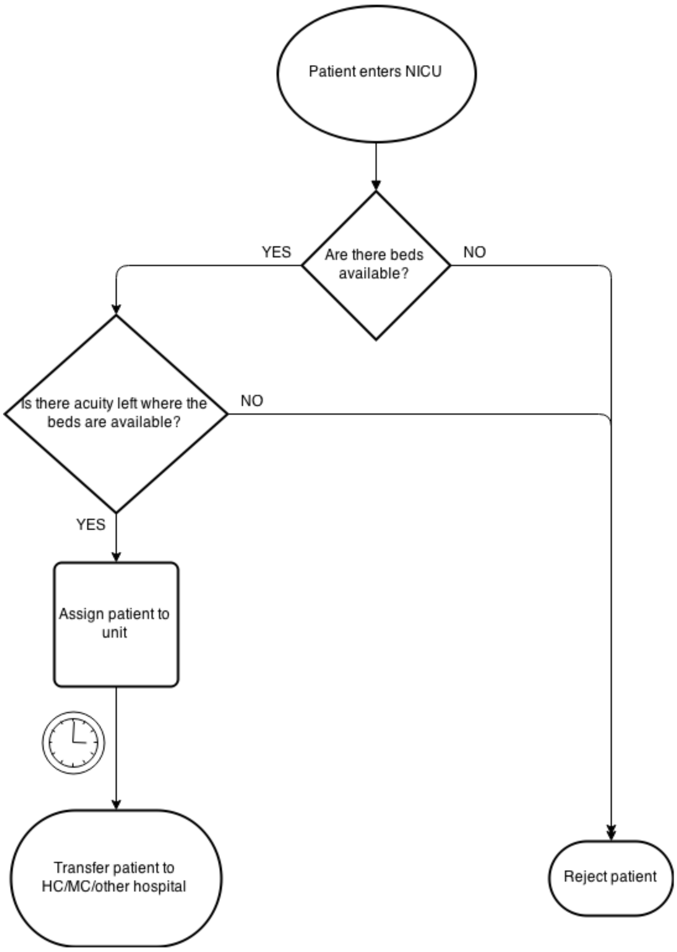


**Figure 2: Current Decision Process**

When lacking physical space, the NICU can also use a little capacity of the adjacent high care unit. According to the management team, physical space is not the main bottleneck of the logistical process of patient placement. However, there is no data available to base this statement on. Looking at the shortage of nursing capacity, we found that it is hard to define the nurses' workload. Before we can assess the performance or even improve it, we need to have a way of measuring the nurses' workload.

Because there is currently no way of measuring the workload on the NICU, the decisions regarding patient logistics are based on assumptions: the nurses' subjective perception of their own workload. Apart from the fact that this excludes the use of quantitative analysis, optimization, and benchmarking, it can lead to unjustified decisions. Due to faulty estimations, two types of unjustified decisions can be made, 1) acceptations when the unit cannot handle the workload, and 2) refusals when the unit could have handled the workload.

The first unjustified decision leads to two things, which are a lower quality of care and a lower quality of work. When the nurses cannot handle the workload, the quality of care they can deliver deteriorates. When faced with a high workload for a longer period of time, nurses can have a burn-out, which can circle into an even larger staffing problem. The second unjustified decision leads to missed income and a lower quality of care, since acuteness is often an important factor for the NICU's patients.

For the department's three stakeholders, patients, management, and staff, we see that there is a tradeoff between their stakes. The management team wants a high productivity, the patient wants a high quality of care, and the staff wants a high quality of work. The department wants to have grip on this tradeoff, and perform steadily among the chosen path in this tradeoff, their strategy. This means that they wants to be able to cope with events such as peak periods, quiet periods, and personnel absence, but first these stakes need to be translated into performance indicators. Once these indicators are identified, the hospital can define a benchmark, measure their performance, and decide whether improvements are necessary.

Hans, Van Houdenhoven and Hulshof (2011) use four levels of planning, which are on- and off-line operational, tactical, and strategical. Strategical decisions address long-term decisions, such as personnel and the number of beds. Operational decisions are short-term decisions, for example which patient is treated by which nurse. Off-line operational decisions are operational decisions that are made in advance of operations and are fixed, while on-line operational decisions react on unforeseen situations and can change during operations. Tactical decisions regard the usage of resources between the operational and strategical level. Policies on how to assign operational decisions within the strategically determined setting are tactical decisions.

As stated above, before improvement projects regarding these healthcare logistics topics on the NICU can be done, we need to be able to measure the workload on the units. We have also seen that being able to base decisions on a more objective basis may in itself be beneficial to the performance of the division. Objectifying the decision-making processes can thus result in an immediate improvement on the operational level, and enable improvements regarding the tactical planning level, which is currently practically ignored at the NICU. As can be seen in the problem tangle, the lack of information and objectivity in the decision-making process is a root problem. It has therefore been selected as the main problem to be addressed in this study.

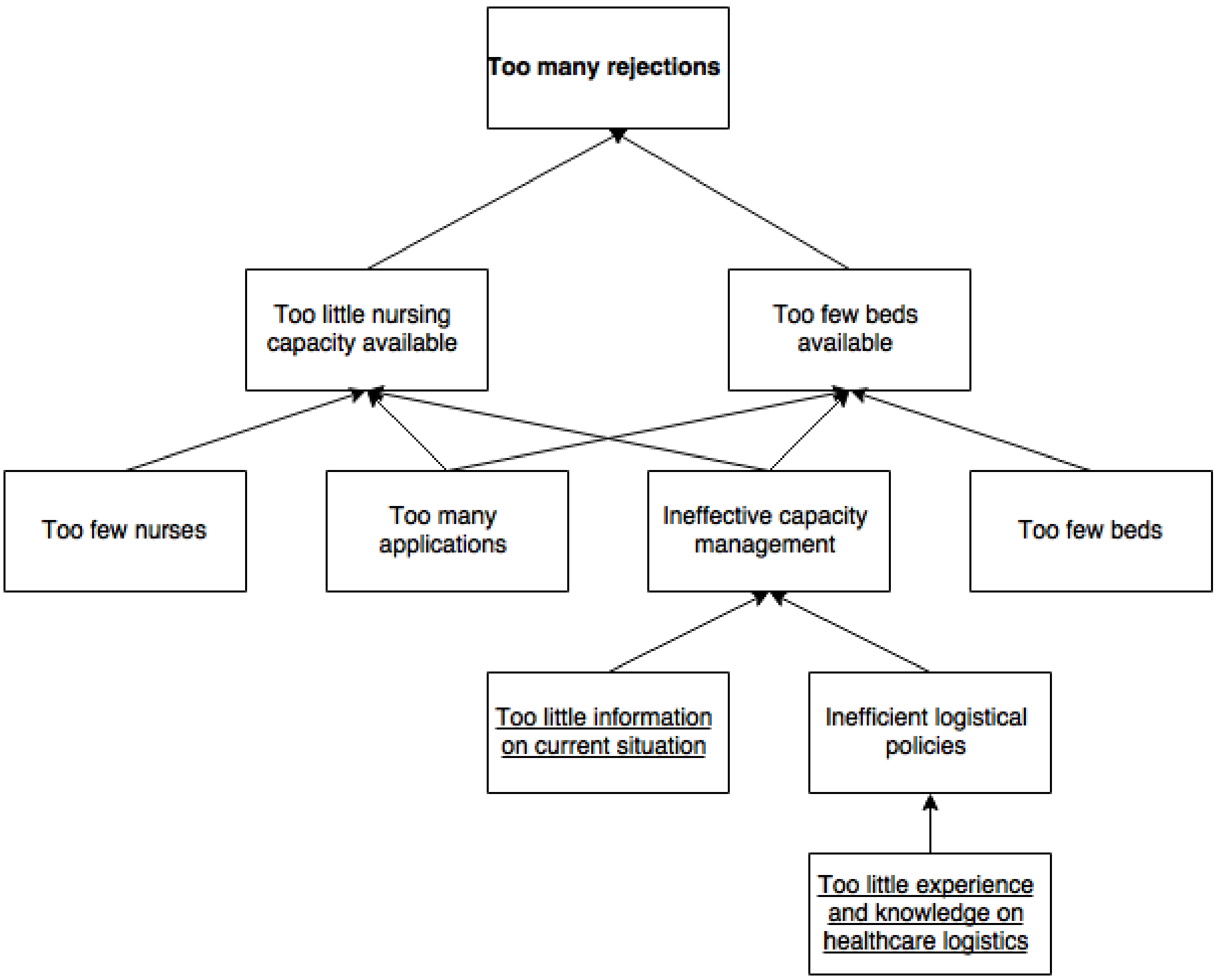


**Figure 3: The Problem Tangle**

The problem tangle (Figure 3) starts with the main motivation for this research, which is the amount of rejections. A patient is either rejected because there is no nursing capacity, or no bed available. Purchasing more beds or hiring more nurses is not an option, and the number of requests for admissions cannot be altered. This leaves the root problems that the capacity management is ineffective due to a lack of information on the current situation on the units regarding the nurses workload, and the fact that little planning methodology or strategies are used. This research focuses on these two root problems.

## 1.3 Research Goal and Scope

The main motivator of the management team to start this research is to decrease the amount of rejections. However, we have seen that this cannot be accomplished easily. Because the operational decisions regarding patient logistics, for instance admissions and transfers should be more informed, which would also allow for better performance measurement and improvements, this is chosen as main goal of this research:

*To be able to measure the current nurses' workload to improve performance measurement, operational decision-making processes, and tactical resource capacity planning.*

The scope for the entire research will be the IC unit of neonatology at the WKZ, with a little attention on the HC and MC units. The main reason for this is that the IC refuses the most patients, and most issues regarding workload complaints are on the IC. We focus at workload measurement methods because currently the department lacks a method to measure this performance indicator. In addition, measuring the workload would help making better informed decisions regarding patient logistics, since there is more certainty on the current utilization of the department.

## 1.4 Research Questions and Methodology

In the previous section we have seen the goal that this research aims to reach. This section discusses the methodology on how to reach this goal and translates that into research questions. For all these research questions is elaborated on how they are answered.

The research goal can be described as two action problems, which are the main problems in the problem tangle (Figure 3):

1. There is no reliable method on the current situation on the NICU to base operational decisions regarding patient logistics, and
2. There is too little information available to measure the department's performance.

Both these observations are a discrepancy from the norm, and need to be addressed. These action problems are solvable by addressing several knowledge problems, which are the research questions of this research. For each of these research questions is given which section addresses this question.

First, we need information on the current situation on the NICU.

1. "What kind of process does the NICU work with and how is the NICU organized?" (Sections 2.1 and 2.2)
2. "How is the current performance of the NICU measured?" (Section 2.3)

Because we focus on the measurement of the nurses' workload, the following questions need to be answered next:

3. "What kind of nurses' workload measurement methods exist?" (Section 3.2)
4. "What are the WKZ's requirements for a measurement method?" (Section 3.2)
5. "What does the method we will use look like? (Section 3.3)

Because we introduce our own model in Chapter 3, we test this model for several of its properties and the effects of introducing the model on the NICU:

6. “How practically applicable is our own model?” (Chapter 4)
7. “What are the prospected effects of implementing the model?” (Chapter 5)

The first two questions are answered by interviews and discussions with NICU staff, observation days, and formal documents. Question 3 is answered through a literature review. Question 4 and 5 are answered on the basis of discussions with experts. Question 6 is answered through empirical tests, and question 7 is answered using an analytical test done via a computer simulation.

# 2. The NICU

This chapter introduces the neonatal department of the WKZ, with its focus on the NICU. From these insights the problem analysis is drawn and the research focus is determined. Section 2.1 describes the main processes on the NICU. Section 2.2 explains how these processes are organized. Section 2.3 assesses the current performance, and Section 2.4 analyzes the situation and identifies the main problem of this research.

Several methods were used to collect information regarding the neonatal department. Discussions with staff members and formal documentation of the organization were used, as well as several observation days.

## 2.1 Process Description

In order to understand the research problems as given in the previous chapter, we first need to understand the NICU environment. This section introduces the three units within the unit, the patient flow, and the types of staff members that work on the units daily, along with their tasks and responsibilities.

### 2.1.1 The Units

The neonatal department of the WKZ consists of three divisions: the IC, HC, and MC. The IC has a capacity of 24 beds, divided over three units. The HC is one unit of 8 beds, and the MC has a capacity of 15 beds divided over three units. At the IC, premature newborns, starting at babies born after 24 weeks of pregnancy, as well as newborns with a need for intensive care are being treated. The IC is the only division of the three with respiratory equipment. The IC spaces are equipped with incubators, IV equipment, monitors and sensors for blood pressure, heartbeat, and much more (see Figure 4). The HC is a relatively small ward adjacent to the IC, and is primarily used as a stopover between the IC and MC. At the MC, most patients lie in a crib which may be heated to help the patient stay warm. Here, parents are often encouraged to participate as much as possible in the care of the child and help with activities such as feeding, changing diapers, and bathing.

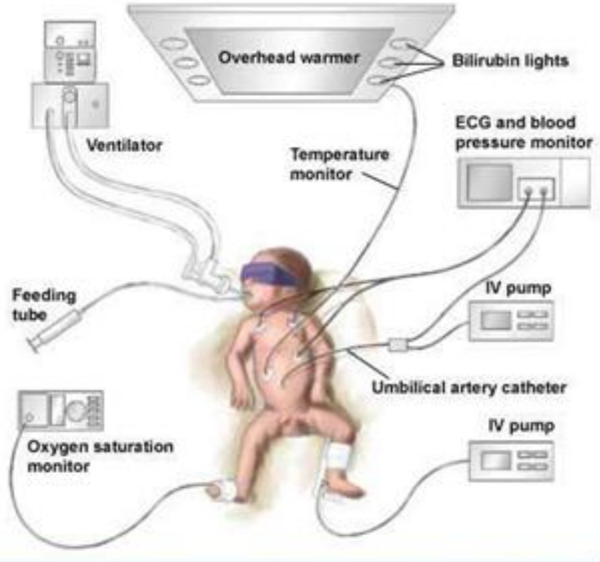


Figure 4: The IC equipment (Mayo Foundation for Medical Education and Research)

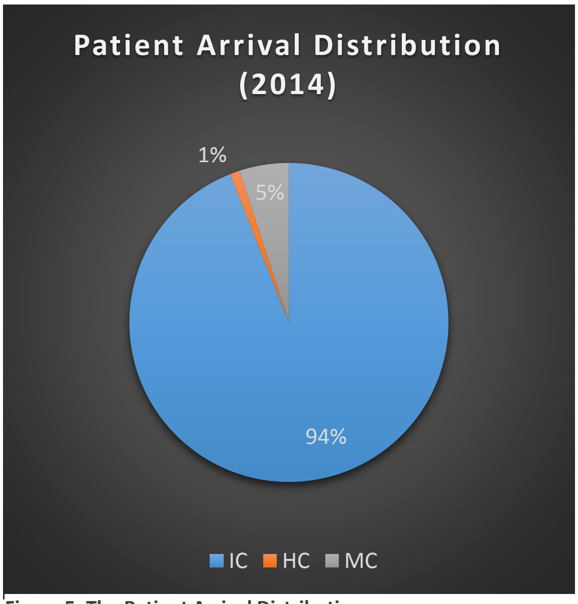


Figure 5: The Patient Arrival Distribution (589 patients, hospital database, 2014)

### 2.1.2 Patient Flow

In 2014, 589 patients were admitted to the IC, 5 patients directly to the HC, and 30 patients directly to the MC (Figure 5). 67% of the transfers from the neonatal division go to other hospitals, and 24% of the transfers go directly home. 8% of the patients deceases, and 1% is transferred otherwise (Figure 6).

47% of these transfers comes from the IC, 14% from the HC, 26% from the MC, and the rest (13%) from other wards within the WKZ (Figure 7). According to the WKZ's own estimation based on earlier research,

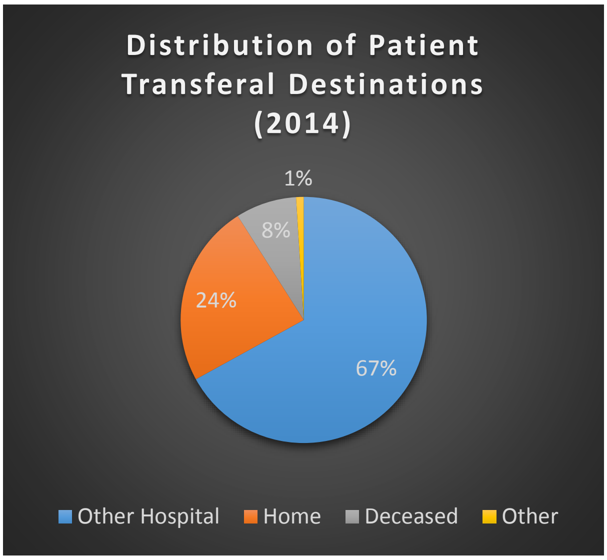


**Figure 6: The Distribution of Destinations for Patients after Transfer from WKZ**
**(589 patients, hospital database, 2014)**

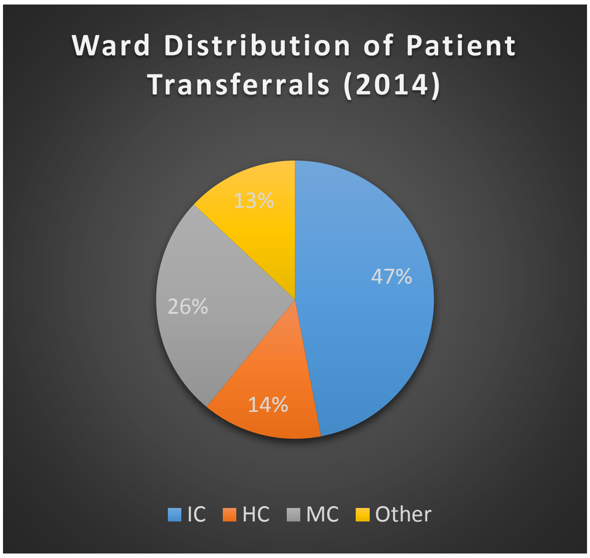


**Figure 7: The Distribution of Departments from which Patients Are Transferred Outside the WKZ.**
**(589 patients, hospital database, 2014)**

the average length of stay on the NICU is 12.5 days.

All NICUs in the Netherlands have their own target region. This means that when a baby with IC requirement is born within that region, the NICU within that region is responsible for taking care of that patient. These patients can come from within the WKZ, but also from regional hospitals, private practices, and homes. When the WKZ receives such a request, it is obliged to find the patient a place on a NICU. This means that when it has no admission space itself, the WKZ needs to look among other NICUs for an admission space, and manage the transportation of the patient. The WKZ focuses on the patients from their own target region and have set the goal to never deny those patients admission.

### 2.1.3 Staff

Two important types of staff members that are constantly present on the neonatal units are the nurses and physician-assistants. The nurses are taking care of the constant needs of the patients, including diaper changes, washing, feeding, and medication. Every shift a number of patients is assigned to each nurse, depending on the care requirements of the patients. Each unit has a coordinating nurse, who is involved in decisions regarding patient placement, nursing care requirements, and work evaluations. One nurse coordinates the entire IC.

Four nurses are working on a unit during dayshifts in the NICU, and three during evening- and nightshifts. A lot of nurses prefer working evenings and nights to working day shifts. During the day, a lot of activities occur that do not occur during the other shifts, such as tests and treatment updates. In addition, almost all transfers happen during the day, as do almost all internal admissions. During dayshifts, nurses have to constantly adapt their planning to accommodate any changes, which is why most nurses prefer working evening- or nightshifts. In the current situation almost all tests and examinations are done in the morning because these departments close during the night. This causes  long queues during the morning, and long waiting times for the results. The hospital considers studying the effects of opening these departments 24 hours per day to work more efficiently on all departments of the hospital.

This idea can also work on the NICU. When nurses prefer night shifts above day shifts, it can be worth researching whether the nurses´ workload is higher during the day or whether it is the nature of the extra activities during the day that causes this. Either cause can be an interesting reason to shift some activities from the day shifts to the other two shifts.

In addition to the patient care there are other necessary activities to be done by the nurses, for example administration and operational improvement projects. If the workload on a unit is low, nurses should be able to spend some time on these activities. However, it appears to be hard to identify when the workload allows one nurse to leave the unit for a while. The department is introducing some lean projects, clearing time for nurses to do the complementary things. It is hard, however, to efficiently use the extra time because of the lack of insight in the amount of patient care required. Especially at the end of a shift when the workload is not that high, the nurses have finished the necessities and can spare some time.

**Figure 8: The NICU**

Each unit has one or two physician-assistants (PAs) during dayshifts. During the other shifts one PA is responsible for the entire IC. These PAs monitor the patients' care paths and update treatments when necessary. They make rounds to check on the patients and monitor respiratory and circulatory trends. There are daily meetings with all PAs and several specialists from other departments. For instance, there is a radiology meeting where the newest scans and photos are discussed, and a neurology meeting where the patients in need of neurological care are discussed. These meetings can directly influence a patient's treatment, which means that the nurses will have to adapt their planning. These meetings only happen during day shift, and contributes to an emphasis of working evenings and nights by the nursing staff.

On all three divisions, the nurses and PAs work in three shifts, day-, evening- and nightshifts. There are more nurses present during the dayshift because of tests, treatment discussion, parent involvement and educational purposes. During dayshifts there are usually four nurses working on each IC unit. During the other shifts, three nurses are available on each IC unit. In the MC, five nurses work the dayshift, the other two shifts are worked by three nurses. Medication is prepared by each nurse for their own shift, receives a sticker with a barcode, and is double checked by a colleague. When administering the medication, the barcode is scanned and matched to the patient ensuring no patient receives the medication of another patient.

In the IC, one nurse per unit is assigned so-called transport duty. This means that when an emergency request for admission arrives, this nurse will go on the ambulance to escort the patient to the WKZ. When this happens, the unit is temporarily one nurse short. If a transport request comes at a time when no nurse can be spared, a difficult decision has to be made whether or not the patient can be admitted.

When a new patient is admitted, several steps need to be undertaken. Naturally, the patient has to be set up with all monitors and machines first. Once this is done, the nurse has to enter the patient in the information system. The short term treatment has to be discussed and documented, as well as the long term treatment. Medication and nutrition has to be prepared and checked, and some other administrative tasks such as printing the barcodes for scanning have to be done. All of this makes admittances a significant amount of work for a nurse. This is in contrast to a transfer to the HC or MC, which does not entail much more than physically transferring the patient and asking the administrative staff to transfer the system entry to the new spot.

## 2.2 Process Organization

Section 2.1 described the daily pursuits of the IC, HC, and MC. Organizing these processes takes a lot of effort and is a complex process in itself. In order to assess the current situation on the NICU, this section discusses the ways in which several important processes are organized. Section 2.2.1 discusses the staff, Section 2.2.2 the logistics, and Section 2.2.3 the information systems. The latter are important processes of which the organization is relevant for answering our research questions.

### 2.2.1 Staff

We divide the organization of the staff into two groups, which are the medical staff and nursing staff. The medical staff consists of 17 neonatologists, of which at all time at least one needs to be present. This responsibility is part of their job, which means that they can be called when needed. When no neonatologist is available, they need to close the NICU. This has never happened and is not likely to happen. The neonatologists, together with the physician assistants, plan the individual treatment of patients continuously. The work schedule is made by one of the neonatologists.

**Figure 9: A Prematurely Born Patient**

The nursing staff is managed differently. The head of the care unit is responsible for the nursing staff, and enforces the dimensioning in terms of total number of nurses employed by the hospital, and the number of nurses during each shift. The work schedule is made and managed by the schedule office. When too few nurses are available during a shift can the head of the care unit decide to close several beds for new admissions. This does not happen often, and is a very undesirable situation. During the shifts can the nurses themselves schedule their work, except for the rounds with the neonatologists.

### 2.2.2 Logistics

One major logistical process managed by the department itself is patient placement. Once there is a request for admission, the division coordinator decides after consulting the units if and where there is a spot available. At the start of a shift, the coordinating physician assistant consults the maternity ward about expectations regarding new NICU patients for the upcoming hours, so the units can prepare a bed if needed. During this meeting the capacity of the entire department is expressed strictly in number of beds still available.

When an admission request is filed form outside the WKZ, the coordinating neonatologist consults the units to see if and where the patient can be admitted. This decision-making process is a major factor in the utilization of the department and the workload on the units. As explained above, this influences the financial position of the department, the quality of work, and the quality of care delivered by the NICU. This decision is based on subjective measurements, discussion, and experience. The decision-maker is a medical expert, who is not equipped with logistical insights and methods. This raises questions on the quality of the decisions that are being made. The unit with the lowest perceived workload receives the new patient.


**Figure 10: A NICU Transport per Ambulance**

### 2.2.3 Information Technology

The neonatal department uses an information system that is specifically designed for NICUs. Every bed has a computer on which patient data can be accessed and added. This system is used in addition to the hospital information system that, save a few exceptions, the rest of the hospital also uses. The hospital information system does not meet all the NICU's requirements, and is not easily adjustable to meet NICU demands. This generates lots of redundant work, which is all done by expensive doctors. The NICU system also cannot interact with the radiology department's system. Because the x-rays that are made of the patient cannot

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| | Naam | Gegevens | Probleem | Resp | Circ | Infect | Gastro | Milieu interne | Neuro | Dienst | Score | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | | 25+5<br>795 gr. | prematuur | NCPAP | NAL+NVL | AB | 6x | | CFM+NIRS | | | wis |
| 2. | | 28+4<br>1185 gr. | Prematuur | NCPAP | NAL+NVL<br>Slotje | | 12x | | CFM+NIRS | | | wis |
| 3. | | 27<br>1045 gr. | Prematuur | NCPAP<br>weanen | ... | | 12x | | | | | wis |
| 4. | | 25+3<br>960 gr. | prematuur | NCPAP<br>weanen | | | 8x | | | contactisolatie | | wis |
| 5. | | 25+3<br>650 gr. | Prematuur | NCPAP<br>weanen | | | 12x | | | Contactisolatie | | wis |
| 6. | | 26+2<br>550 gr. | Prematuur, infectie<br>20-4 laseren ogen bdz | BiPAP | Per. Inf | | 12x | | | | | wis |
| 7. | | a terme<br>3365 gr. | Dysmorfe kenmerken | | Per. Inf | | 8x | | | net binnen | | wis |
| 8. | | gr. | | | | | | | | | | wis |

Opmerkingen:

Situatie op unit:

Verpleegkunige die gescoord heeft:

Print scoreformulier

**Figure 11: The Excel Sheet With the Patients' summary**

be uploaded to the NICU's system are they printed, passed around and physically stored. Every unit also keeps an Excel document up-to-date which provides the nurses with a quick overview of the unit, and is mainly used for the transition of shifts (Figure 11) .

The patients' medication is taken care of by the pharmaceutical department, ensuring that all necessities are in stock and all inquiries delivered on time. The facilities department cleans the beds after transfers, and refills the cabinets. However, the WKZ still uses fax as a communication method between departments. This means that a digital receipt has to be printed and scanned instead of uploaded into a system. Not only does this cost lots of paper and ink, but also includes multiple possible errors. It happens that printers are broken or empty, or that the faxed messages are is not received correctly due to interferences. This is why the nurses developed the habit of calling the pharmaceutical department after faxing the receipt to confirm its arrival.

## 2.3 Current Performance

In order to make improvements the current performance has to be assessed. This raises several questions, which are answered in this section. First we need to know how to define the performance of the NICU. What are the performance indicators and which ones are most important to the WKZ? It then has to be established how these indicators are measured, and what acceptable scores are. When this is known the current situation at the NICU can be measured and assessed.

### 2.3.1 Stakeholders

The performance indicators from the NICU are not predetermined by the WKZ. The joint NICUs in the Netherlands are working on identifying performance indicators, but this is not an easy endeavor. Section 2.3.2 discusses the challenges on identifying performance indicators for NICUs. The WKZ does, however, have a strategy and mission statement, from which focus areas can be determined. The official mission from the division Woman and Baby, from which the Neonatal department is a sub department, states:

*"We deliver top care and subsequently academic research to both woman and baby"*

This states that quality of care is an important performance indicator. Quality of care is one of the three outputs that result from the healthcare stakeholder triangle, which is patient, staff, and management (Figure 12). Quality of care is important to the patient, management wants to see productivity, and staff needs quality of work. There is a certain tradeoff between these outputs, since a high productivity can lead to low quality of care and quality of work when nurses and doctors are overworking themselves. This said, it is not impossible to improve the performance on one criterion without other outputs deteriorating. If this can be achieved. it means that the total performance has been raised.

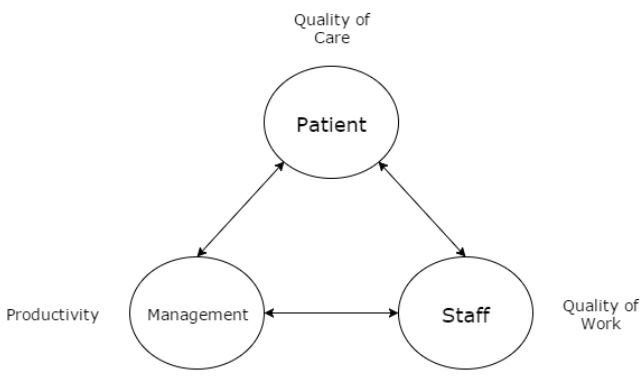



**Figure 12: The Stakeholder Triangle**

### 2.3.2 Performance Indicators

Performance indicators need to be measurable, to be able to benchmark performance and assess the current situation. For all three stakeholders are possible performance indicators identified, but not all of these indicators work in practice.

## Patients

The patients want an as high quality of care as possible. This raises the question: What determines quality of care? The joint NICUs in the Netherlands have not yet identified indicators that objectively compare NICUs. Profit et al. (2013) work with eight indicators of quality of care, which are:

1. Survival rate
2. Any antenatal corticosteroid use
3. Number of hypothermia <36$^{o}$C at 1 hour of life
4. Number of pneumothorax
5. Number of health care-associated infections
6. High velocity growth over 12,4 g/kg/d
7. Number of chronic lung disease at 36 weeks gestational age
8. Discharge on any human breast milk

Especially using the survival rate looks like an easy, unambiguous indicator. However, all of these indicators are not usable when comparing different NICUs, since the patient mix varies too much. For instance, the WKZ specializes in neurology, which means that they treat patients in need of complex neurological care from other hospitals when possible. The WKZ is also one of the few hospitals that is able to treat all NICU patients, which means that the patient mix at the WKZ consists of more patients in need of very high care compared to smaller NICUs that transfer those patients to, for instance, the WKZ. Comparing the survival rate would rate the smaller hospitals better, since their patient mix simply has a higher chance of survival. This reasoning holds for all of the above-mentioned eight indicators.

The WKZ currently uses a measure of pain, consisting of several physical tests that indicate how comfortable and relaxed the patient is, but this is not used in all NICUs. This measure indicates the level of involvement and understanding the department has of all patients, but is still based on patient-mix. Another measure that currently is used is the follow-up results. A certain protocol is followed, where former NICU patients are checked for their development. The results of these follow-ups can also be used as performance indicator, but is also dependable on the patient mix.

Because each NICU is responsible for the patients within their own target region, we can also measure the degree in which the NICU takes care of this responsibility. This can be very objective for all NICUs, since the size of the NICU will be matched to the target region's demand of care or the other way around. We will use a version of this measure as performance indicator in this research, since one of the main motivators of this research is the amount of rejections from within the target region. Since the information whether a patient comes from within the target region is not tracked for the data set, we will generalize this performance indicator and use the percentage of patient rejections for all requests for admission [Table 1].

## Staff

The staff is as stakeholder looking for quality of work. The WKZ currently uses work experience researches, which are periodically held. This is, however, a rather subjective measure, although it is well comparable between NICUs. They also use a Kaizen-method, where errors should be documented and analyzed. These errors can be situations someone cannot do their work due to certain events, or when tasks go wrong due to personal mistakes. The nature of these errors can be a qualitative measure for the quality of work, but the number of documented errors highly depends on corporate culture and expectations. This means that the number of errors  cannot be used as performance indicator.

One measure of quality of work is the percentage of time that the nurses are having a busy shift. This either means that they have to endure more stress than desirable, or that they have too little time to finish their tasks and have to work overtime. Both of these results are perceived as not desirable and deteriorate the quality of work. This research uses the percentage of busy shifts for nurses as performance indicator for quality of work, since it is quantifiable and important for the actual work perception. [Table 1]

#### Management

As seen in Figure 12 the productivity of the department is the main focus of the management. In the hospital the budgets are fixed with a so-called '0-line'. This means that, regardless of the predicted and realized cash flow, the budget of the NICU is almost entirely independent of the actual performance of the department. This makes the management's main focus not the financial performance, but the productivity itself. The management wants to manage the processes as efficiently as possible in order to fulfill their role as provider of care as good as possible.

Of course will the financial performance on the long run be kept in eye, but when the department makes profit will their budget likely be cut since they apparently do not need that much money. This is the problem when working with budgets, and is a reason why efficiently is often not important for the management. This research will use the average utilization of the department in terms of percentage of occupied beds as performance indicator, but will also translate the results of this to the impact on the financial performance.

We can conclude on using three performance indicators, one for each stakeholder. Table 1 shows these indicators.

| Stakeholder | Wishes | WKZ | Performance Indicator |
|---|---|---|---|
| Staff | Quality of Work | Few Busy Shifts | %Shifts overloaded |
| Patient | Quality of Care | Few Rejections | %Rejections |
| Management | Productivity | High Utilization | %Beds Occupied |

**Table 1: The Stakeholder Overview**

### 2.3.3 The Current Situation

In order to assess the current situation, we need to know how the NICU scores on the three performance indicators. The amount of rejections, both within and outside the target region, over the past years were not available. The average utilization can be determined by the data on admissions to the NICU, which was 589 over 2014, and the average length of stay as given by the WKZ of 12,5 days. This results in an average utilization of 20,17 beds. With 24 beds available, this makes the average percentage of beds occupied 84%. The performance indicator for the quality of work, which is the percentage of shifts that are overloaded, is not yet measurable because there is not yet a method to measure the nurses' workload.

## 2.4 Problem Analysis

Section 2.3 introduces the lack of knowledge on the current situation. The amount of rejections within the target region was too high according to the WKZ, although it was unable to present specific numbers. The fact that a performance indicator is missing for quality of work is a more drastic problem, and can be seen as a main problem in our problem tangle. The problems that are noticed on the NICU have been collected, and the problem tangle shows their relationships. This section discusses the problem tangle and explains how the main problem of this research was identified.

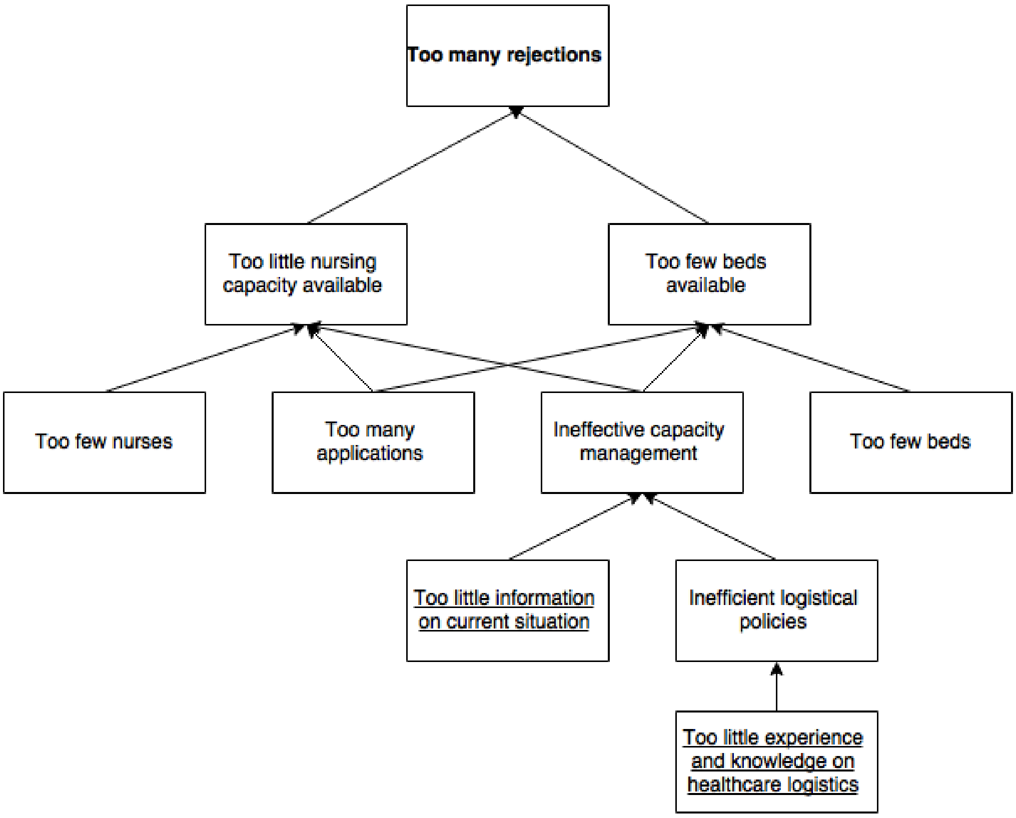



**Figure 13: The Problem Tangle (copy of Figure 3)**

In the problem tangle, we identify five root problems, which are the problems in the tangle without further cause. These are:

1) Too few nurses
2) Too many applications
3) Too little information on current situation
4) Too little experience and knowledge on healthcare logistics
5) Too few beds

Sub 1. Raising the physical capacity by recruiting more nurses or purchasing more beds is only a temporary solution, since it only raises costs without increasing efficiency. This way the department will quickly get used to the new capacity and only work more inefficiently. This holds for root problem 1 and 5.

Sub 2. The amount of applications cannot be changed. The only way this can be changed is if the target region changes, which is not up to the hospital to do.

Sub 3. There is little information at the real-time utilization of the department. This is chosen as focus of this research, since the department thinks that this should be possible and would have a direct positive impact on the performance of the department.

Sub 4. This research is a start to explore the possible applications of this field of research to the department. One of the motivators behind the research is the curiosity of the department to the effects of these endeavors.

Sub 5. See sub 1.

Root problems 3 and 4 both lead to ineffective capacity management, which leads to either too few beds or too little nursing capacity available. This leads to rejections. In other words, targeting the main problems will lead to fewer rejections. The shortness of information on the current situation is described above as shortcoming of performance indicators. These performance indicators can both on long and short term improve operations. When the indicators are known, measurable and are benchmarked, the department will be able to better inform their decisions regarding patient placement, nursing care capacity distribution. Besides this will the information enable optimization and quantitative analysis.

This chapter introduced the neonatal department of the WKZ, and focused on the NICU in particular. Organizing this specialized care is a complex process. Patient care is delivered by doctors and nurses, and they have a large influence on the way in which that care is organized. Because the amount of rejections was perceived as too high are we looking at the current performance of the department. Since the current situation lacks a method to measure the nursing workload, which is required to benchmark the quality of work, this research focuses on finding a method to do so and proving its value. This also highlights the value of introducing knowledge on healthcare logistics on the NICU.

# 3. The Neonatal Acuity-based Patient Scoring System

In order to be able to measure the current workload on the NICU we need a measurement tool. This chapter discusses how and why we created our own measurement system. Section 3.1 emphasizes the need to measure workload and introduces possible types of measurement systems. Section 3.2 explains why there are no existing models directly applicable to the WKZ's NICU. Section 3.3 discusses our acuity system, the factors we included, and the use of the system. We named our new system the Neonatal Acuity-based Patient Scoring System (NAPSS).

## 3.1 Introduction and Literature on Acuity Systems

To understand why we created our own measurement model, we need to explain three things: 1) Why do we want to measure workload?, 2) Why are current systems not applicable?, and 3) How does our model look like? The first question is answered in Chapter 2, but will be elaborated on some more throughout this section. This section introduces Patient Classification Systems (PCSs) and Acuity Systems and emphasizes the need to measure the nurses' workload.

Chapter 2 concluded that being able to measure nursing care requirements could not only improve the units' performance on the short-term, but also enable tactical planning improvements. But how can this requirement be measured? The amount of beds occupied is not a realistic measurement of the amount of work during a certain shift, since the composition of the patients can differ a lot. This means that we need to find a measure that classifies patients according to the intensity of the care they need.

This kind of system is called a Patient Classification System. A PCS is generally used for monitoring the use of overtime, gathering data for utilization review, and providing necessary information for patient program planning and monitoring quality improvement activities (Martorella, 1996). PCSs are generally divided into two categories: prototype evaluation systems and factor evaluation systems (Van Slyck & Bermas, 1984).

Prototype evaluation systems are systems that use a characterization of the patient where the user can choose between mutually exclusive and collectively exhaustive categories to categorize a patient. This may, for example, be done by establishing the severity of the patient's condition, or by measuring the hours of care needed by nurses per day. Factor evaluation systems evaluate a set of patent indicators that determine the intensity his condition and rate those indicators accordingly. A combination of these ratings, often numeric, constitute a patient's classification (Bigbee, Collins & Deeds, 1992).

Prototype evaluation systems benefit from the ease of use, and quickness of determining the patient classification. A disadvantage is that they do not allow for a great level of detail, which results in a measurement that is not very accurate. Factor evaluation systems perform just the other way around. Their benefit is that they can include a lot of details, but can take a long time to use (Bigbee, Collins & Deeds, 1992). The choice of system depends on its intended purpose. Prototype evaluation systems carry sufficient amount of detail for our cause, because we only need a reliable estimation of the nursing care requirements per patient, not the details of these requirements. Because we do not want the use of the model to be too much of a burden in itself, we only consider prototype evaluation systems.

Since we want to measure the workload on the work units, we can limit the scope of searching a PCS to acuity systems. Patient acuity is defined by Harper and McCully (2007) as "the categorization of patients according to an assessment of their nursing care requirements". A system that uses these requirements to classify patients can predict the total workload on the division, and thus help support patient placement decisions.

## 3.2 Must-have Features for Acuity Models by Garcia (2013)

In order to qualify for the selection for the WKZ, models need to meet certain prerequisites. Garcia (2013), identifies 10 must-have features for acuity models. A model can be implemented if it possesses all these features. Which one of the models is most suited for the WKZ is based on selection criteria. Section 3.3 discusses this.

1. Reliable & Objective. When determining the nursing care requirements, it should be noted that not all nurses have the same productivity or the same interpretation of whether a shift is busy or not. Acuity models should provide objective scores, resulting in a reliable measurement of the nursing care requirements.
2. Valid. The results of an acuity model should accurately represent the nurses' workload. If the model indicates a busy shift, the observed situation should be busy too. This can be tested by correlating the scores with the nurses' perception of workload that shift.
3. Patient-centered. The acuity model should include all nursing time required to address all care needed by a patient.
4. Efficient. Using the system should not take too much time.
5. Inclusive and Collaborative. Information from other departments should be present and used to help the scoring.
6. Aligned. The results from the scores should be aligned with the actual length of stay and in the long run be a reliable forecast of remaining length of stay.
7. Predictive. Knowing the total acuity on the unit can help predict nursing care requirements.
8. Outcomes driven. The model should be able to alarm irregular patient behavior
9. Actionable. The acuity model should be updated when necessary and provide up to date information.
10. Informative. Long-term trends and data should be derived from the model to improve the value of the model. Examples of these trends are nursing care requirements throughout the year to help plan vacation days or extra staffing, estimate the financial value of one hour of nursing care, and benchmark nurses' performance.

## 3.3 Evaluation of Existing Models

Now that we have seen that we need to find an acuity system to measure the nursing care requirements, we can explore the requirements of the NICU and match them to known acuity models. This section describes this process. First the system requirements are stated, after which several existing acuity models are presented. When scoring the systems to the WKZ's requirements, no system is found to promise a sufficient performance for the WKZ's NICU.

### 3.3.1 Suitability Criteria

The acuity model we want to use for measuring the current state of the NICU and representing the system in a simulation model needs to fulfill a couple of criteria, which are:

1) Accurately representing the complete neonatal nursing care requirements (inclusive)
2) Easy to use
3) Applicable to the entire perinatal division
4) Quantifiable

These criteria were derived from discussions with the problem owners.

Sub 1. The first criterion, that the system must be inclusive of all relevant factors, is important because the WKZ wants to be able to identify the amount of work required of a nurse to handle a [atient accurately. Acuity is not simply definable by clinical parameters, but all activities and disturbances caused by a patient need to be taken into account, since it all feeds into the nurses' perception of work pressure. For instance, the time a nurse is busy with educational activities, since the WKZ is an academic hospital, and the time spent communicating with the patients' family are hard to include in hard parameters. Harper and McCulley (2007), call these influences educational and psychosocial factors.

Sub 2. The second criterion is that the acuity system needs to be easy to use. In order to gain acceptance on the work floor, as well as not letting the model deteriorate the nurses' productivity by requesting too much time from them, it is important that the model is easy to use. A system that uses hard data and already exists in a computer system works best for this, as it immediately generates results. However, such a system does not fulfill the first criterion, since only clinical data can be generated this way. This means that we need to find a model that uses little time from the nurses, but still represent the entire nurses' workload accurately. The threshold for this usage time is unclear, but we eliminate extensive methods beforehand.

Sub 3. The third criterion is that the model needs to be applicable to the entire perinatal division. Models that rely on clinical parameters need to be specialized for the IC, HC, and MC. We are looking for a model that is either compatible with all divisions, or easily adaptable. The focus of this research is the IC, but having all divisions of the neonatal department use the same measurement system can enhance the holistic view of the department and enable planners to inform their decisions even more.

Sub 4. Because we want to calculate not only the workload of one single patient, but also of units or entire divisions, we want the acuity model to be quantifiable. This is the fourth criterion. if a classification is given by the model, we want to know how it relates to other classifications in terms of ratios. The model being quantifiable is also crucial for the purpose of making a simulation of the NICU.

### 3.3.2 Existing Acuity Models

Now that it is clear the WKZ's requirements are for an acuity model, we can look for applicable systems Papers reporting on potentially useful systems were searched using mostly Google Scholar, but also Scopus and Web of Science were used. Search terms used were "neonatal", "NICU", "patient classification system", and "acuity", in various combinations. This led to a very large amount of papers and researches, of which we did a quick scan on which papers seemed usable based on their title. After this search, forward and backward search from the usable papers led to the final paper selection. This resulted in 14 papers that introduce new methods of measurement, or discuss the applicability of several methods.

Two models will prove to be relevant in the remainder of this research and are therefore elaborated on in this section. The first system is the Winnipeg Assessment of Neonatal Nursing Needs Tool (WANNNT) (Sawatzky-Dickson & Bodnaryk, 2009). This model works with six levels, each with its own criteria. The highest level for which a patient matches one criterion will be the assigned class, and the authors identified the amount of nurses it takes to take care of the patients of all six levels. The criteria are determined by medical experts and the authors claim them to be collectively exhaustive. An example of this model is added in Appendix A.

The second system is the PCS tool of Harper and McCulley (2007). They identify five criteria on which nurses spend time. These five criteria are scored through predetermined identifiers, and the average of these criteria is the category in which the patient is classified. The criteria are medication, complex procedures, education, psychosocial, and intravenous medication. An example of this tool is added in Appendix B.

The first one of the systems that were also considered is the Neonatal Acuity System (NAS) of Mullinax and Lawley (2002). Almeida and Persson, 1998, discuss four models that are used on NICUs in Sweden. These four models are:

- The Neonatal Therapeutic Intervention Scoring System (NTISS) (Gray et al., 1992)
- The NICU risk model (Horbar et al.,1993)
- The Score for Neonatal acute Physiology (SNAP), (Richardson et al., 1993)
- The Clinical Risk Index for Babies (CRIB) (Tarnow-Mordi et al., 1993)

How these models score on applicability will be shown in the next section, but since they prove to be irrelevant for the remainder of this research are they not discussed in more detail.

### 3.3.3 Acuity Models Suitability

The previous sections discussed the model requirements for the WKZ and introduced several models that can be tested for their applicability. The results of this assessment are given in Table 2.

| | Inclusive | Easy to use | Entire division | Quantifiable |
|---|---|---|---|---|
| WANNNT | - | + | - | + |
| PCS | + | 0 | 0 | - |
| NAS | - | + | + | - |
| NTISS | - | - | + | - |
| NICU RISK | - | 0 | - | - |
| SNAP | - | - | - | - |
| CRIB | - | + | - | - |

**Table 2: The Existing Acuity Models' Score**

Because of their relevance, only the scores for the WANNNT and PCS are discussed here.

WANNNT scores low on inclusiveness because it only involves clinical factors. It ignores educational, psychosocial, and logistical factors, and is not easily adaptable to include these factors. It is easy to use, since nurses can simply start at the bottom of the form, work their way up to a criterion they see matching the patient and the classification is done. The model is based on NICU patients, and even has as criterion "has met discharge criteria". This means that all new criteria and levels would have to be developed for HC and MC use. Since WANNNT includes the amount of nurses that are needed for each level it is perfectly quantifiable. The amount of nurses can simply be summed to arrive at a unit's total nursing requirement.

The PCS by Harper and McCulley has almost completely inverted scores from WANNNT. The method is inclusive and easily adaptable to new factors when needed. It is not particularly hard to use, but also not easy. The PCS needs some adjustments for usage on several levels of neonatal care, but can be used on all units when adjusted. It is, however, not quantifiable, since the end score is an average of all factors and it is unclear what a rise of 1 point will do with the nursing requirement of that patient.

## 3.4 NAPSS: A New Model for Measuring Patient Acuity

Because no existing model matched all of the WKZ's criteria, we have combined several factors of existing models to create our own model, called the Neonatal Acuity-based Patient Scoring System, or NAPSS. This section discusses the factors the new model includes, how NAPSS looks like and how it is used.

The two models we are combining are WANNNT and the PCS tool of Harper and McCulley. WANNNT uses levels to classify patients, and matches these levels to an amount of nurses needed. This ensures that the model is quantifiable and easy to use, since we can add the nurses needed, and we only have to score one number. The PCS tool of Harper and McCulley identifies criteria to be taken into account when scoring. These criteria are originally individually scored and added, weighted equally.

We use the levels and the amount of nurses needed per patient as a lead for our scores. The question `*How many of this patient can you work on simultaneously this shift?'* results in a categorization of the patients according to the ratios as given in Table 3. Each individual patient is scored, and by adding all the nurses needed per patient, resulting in the workload at that moment.

| Level | Ratio | Nurses per patient |
|---|---|---|
| 6 | 1 on 1 | 1 |
| 5 | 1 on 1.5 | 0,67 |
| 4 | 1 on 2 | 0,5 |
| 3 | 1 on 3 | 0,33 |
| 2 | 1 on 4 | 0,25 |
| 1 | 1 on 5 | 0,2 |

**Table 3: The Levels and Ratios**

Note the addition of "*this shift*" to the leading question. The workload for nurses during a shift does not only depend on patient characteristics, but also on other factors, such as transfers and admittances. This is why we are using the criteria from Harper and McCulley to identify the factors that contribute to the total workload of that shift. We have slightly adjusted the criteria to meet neonatology-specific criteria, and we test the method to ensure the validity of these criteria.

The resulting five criteria are:

1. **Medication**. The amount of medication the patient receives, both intravenously and non-intravenously.
2. **Complicated medical procedures.** Procedures such as intubating and extubating.
3. **Logistics.** Transferals, acute admissions, MRI's, OR on ward.
4. **Education.** Both coping with unknown situations and working with students.
5. **Psychosocial.** Interaction with family, stress.

These criteria are not individually scored, but are to be kept in mind when classifying a patient, thus resulting in one score per patient. If we now look at the four selection criteria for an acuity measurement tool as given in the previous section, we see that the model scores well on all criteria. The model is inclusive and easy to use, the ratios can easily be adjusted for HC or MC standards without the model losing reliability, and the scores are quantifiable.

## 3.5 Conclusion

Acuity measurement systems measure nursing care requirements, which the WKZ needs to assess the performance of the capacity management of the NICU. There are many acuity measurement systems, but the NICU has a very specific set of requirements. The selection criteria are not met by one single existing system, so we combined two systems to come up with a method that meets all criteria. Each patient is scored by the nurses on how many of these patients the nurses can currently work on, which results in a total amount of nurses required on the unit. This score includes all factors that contribute to the workload. In theory, this method scores well on all criteria, but is has not yet been tested on NICUs. In the next chapter we will determine what tests we need to assess the method, as well as carry out these tests.

# 4. Model Experiments

Chapter 3 introduced our acuity model. Before this model can be used we should assess the feasibility of using the model in practice. This chapter follows a couple of steps to assess the model. Section 4.1 introduces ten must-have features for acuity models, and evaluates NAPSS on basis of these features. Three features are not easily assumed to be features of NAPSS and need to be tested. These features are alignment, reliability, and validity. Section 4.2 elaborates on these features and introduces tests associated with these feature: pairwise comparison, Cohen's kappa, Pearson's r, and a Markov chain analysis. Section 4.3 explains how these tests are executed and how we use the test results to assess the model. All tests score within a range from sufficient to very good, so we conclude the model to be feasible to use.

## 4.1 Model Tests

When assessing the model, we need to test several properties of the model. This section discusses 10 must-have features identified by Garcia (2013) that all acuity systems should have. For seven of these features do we argue why the model scores sufficiently, for the other three features why additional testing is required.

### 4.1.1 Sufficient Features

Seven features are assumed to be sufficiently present in our acuity model. What these features are and how each feature is included in our acuity model is discussed below.

- Patient-centered. NAPSS includes all nursing time required to address all care needed for a patient in the total nursing care required ratios.
- Efficient. The use of NAPSS is simply one score per patient and updating the status will take little time.
- Inclusive and Collaborative. It is very well possible when the HC and MC are included in the system that the information from other departments is implemented in the system to raise the quality of the information.
- Predictive. The total score from NAPSS can indicate the number of nurses that are needed at any time.
- Outcome driven. NAPSS will be able to compare average scores and length of stay from patients to individual patients. When the score of an individual patient is an outlier, the model can recognize this and notify the nurses.
- Actionable. NAPSS can be updated and rescored at any moment.
- Informative. By keeping track of the scores in NAPSS, trends can be discovered and analyzed. Busy periods and quiet periods can be predicted, and the value of extra hours of nursing capacity available can be derived.

### 4.1.2 Features That Have to Be Tested

Three features are not immediatly assumed to be sufficiently represented in our acuity model. What these features are and how they can be tested is discussed below. Section 4.2 will further discuss these tests.

- Aligned. This can be tested by creating a transition diagram in which for all scores the chance of transitioning to another score the next shift is given. A Markov chain analysis can predict the length of stay and thus the alignment of the scores and the predicted situation. Appendix E explains and executes this analysis.

- Reliable & Objective. This can be tested by comparing the individual scores of nurses for the same observed patients to each other. These comparisons are called pairwise comparisons and are further discussed in Section 4.2.2.
- Valid. This can be tested by correlating the scores with the nurses' perception of workload that shift. Section 4.2.3 discusses and tests validity in more detail.

# 4.2 Alignment, Reliability, and Validity tests

Because three necessary features for acuity models are not directly assumed to be present in NAPSS these are to be tested. This section elaborates more on these features (alignment, reliability, and validity) and introduces tests on how to prove the presence of these features.

## 4.2.1 Alignment

As seen in Section 4.1.2, alignment is the extent to which the results of the acuity model agree with the actual performance of the department. The average length of stay of patients is one way to compare these two situations, and will in this report be used to assess the alignment. The method that is used to make this comparison is performing a Markov chain analysis.

A Markov chain is a process that can be represented by states, where each state has a probability of transitioning into the other states. Our Markov chain has the absorbing characteristic, meaning that one of the states has the property that once that state is reached, you will not leave (Winston, 2004). For us, leaving the NICU is the absorbing state. In reality, patients can return to the NICU, which is represented by a new entry in the system.

For an absorbing Markov chain it can be calculated what the average amount of steps is before the absorbing state will be reached. Translated to the NICU we can find the average amount of nurses' shifts it will take on average for patients to leave the NICU. Section 4.3.2 shows these calculations and the Markov representation of our system.

## 4.2.2 Reliability

There is a couple of ways in which reliability can been measured. The reliability of the acuity model is also called inter-rater agreement, which simply means the degree to which two separate raters perceive the subject identically. Graham et al. (2012) identify three ways to measure inter-rater agreement, which are Cohen's Kappa, Intra-class correlation (ICC), and the percentage of absolute agreement.

Cohen's Kappa is a statistical test that compares two forms and assesses the probability that two raters rate the same subject. This is done by looking at the amount of options a rater has, which results in a probability that two raters accidentally agree, and the amount of subjects that are rated. When scoring high above the probability of accidental agreement, the test indicates a significant reliability. For instance, when two people rate the same number when having 100 options to choose from, the probability is lower than when choosing from 10 options, and agreeing once can be chance, but agreeing multiple times is a sign of reliability. Cohen's kappa can only be used to compare individuals, so it is not a good measure to use on a large scale. The number of comparisons will be low, but can be used to identify personal differences and possible outliers, positive or negative. The test works with a level of significance, which we set at 5%.

The ICC depends on the variation of the observations. However, since the mean score of all subjects is different, the variation of the observations cannot easily be generalized. This means that this test is not suitable for our purpose.

The percentage of absolute agreement is simply the comparison of all individual observations of the same subjects. The percentage that these observations agree is the outcome of this measure. An example for

NAPSS: Nurse A and B each score 8 patients. The results are given in Table 4, as well as the results of the comparisons.

Two percentages are valuable to assess, which are the absolute agreement and the 1-off agreement. When the individual scores given to a patient match, we have an agreement. When they differ 1 point or less, we have a 1-off agreement. For instance, patient 1 is no agreement, but is a 1-off agreement because 2 and 3 differ only 1.

| | **Nurse A** | **Nurse B** | **Agreement?** | **1-off?** |
|---|---|---|---|---|
| Patient 1 | 2 | 3 | NO | YES |
| Patient 2 | 2 | 2 | YES | YES |
| Patient 3 | 3 | 3 | YES | YES |
| Patient 4 | 5 | 4 | NO | YES |
| Patient 5 | 2 | 2 | YES | YES |
| Patient 6 | 3 | 3 | YES | YES |
| Patient 7 | 4 | 6 | NO | NO |
| Patient 8 | 4 | 4 | YES | YES |
| Score | | | 5 of 8 | 7 of 8 |
| Percentage | | | 62.50% | 87.50% |

**Table 4: Example of Pairwise Comparisons**

By calculating the amount of pairs that agree, we get our measure for inter-rater agreement, or model reliability. Graham et al. (2012) also name a minimum percentage of agreement a test should generate. If there are few rating levels, for instance 1-4, the minimum percentage should be 90%,. With 5-7 75% should be sufficient. Bigbee et al. (1992) call 70% agreement acceptable, 80% adequate, and 90% good. These thresholds seem to be consistent with each other. It is obvious that when there are more rating levels to choose from, the expected percentage of agreement deteriorates. However, using more rating levels enables the rater to differentiate between subjects, and thus raise the validity.

Because there is a tradeoff between the validity of the test and the reliability of the test, we may choose to use the percentage of total agreement plus or minus one level, which is the 1-off measure (Stemler, 2004). According to Graham et al. (2012), the minimum level of this measurement should be above 90%. It is good to note that these thresholds are based on objective measurements, meaning that all raters perceive the test subject equally. Workload is not an objective measurement, but since there is a lack of thresholds for subjective measurements will we use a relaxation of the threshold for objective measurements.

### 4.2.3 Validity

The validity of the model measures if the model we use actually represents what we want to measure. NAPSS needs to be tested on validity before we can use it. The workload measurement should be correlated with the overall feeling of the nurses on how busy the shift was. We prove the validity of the measurement by correlating the feelings of the nurses to the total nursing care requirements of that shift in relation to the number of nurses that worked that shift. This way, we can test NAPSS's validity by comparing the results of both measurements and calculating a correlation. We can do this by using Pearson's r (Stemler, 2004), which results in a number between -1 and 1, where -1 is a perfect negative correlation, and 1 is a perfect positive correlation. We are looking for a positive correlation which proves to be significant at a significance level of 5%.

## 4.3 Testing the Model

The previous section explained why the model should be tested and which tests should be executed to assess the value of the model. The features that are tested are alignment, reliability, and validity. This section discusses the two phases in which we have tested; pilot phase and the test phase. First the pilot phase and the associated tests will be explained, then the test phase.

### 4.3.1 Pilot testing

Before we are going to test the value of the model and look for the theoretical improvements it can bring to the WKZ, we need to test the model on reliability and validity. This is why we conducted a pilot before we gathered the data for the main research. This pilot project has several goals: 1) Check if the method is clear to the nurses who will use it and gather some feedback. 2) Check for reliability (Are the levels distinctive enough?), and 3) Check for validity. (Are the five criteria from Section 3.4 sufficiently taken into account?).

#### *The pilot*

Because the NICU has proven to be rough on new initiatives, and not all nurses are fond of experiments, we decided to test the model very carefully. We started with a pilot of three days at one unit. For each shift, all nurses rated all patients on their unit independently, as well as the entire shift for its workload. This last rating is a 5-scale rating. Three days of testing with three shifts each day means nine measurement points. With 2,3, or 4 nurses working each shift, 31 forms could be filled in, of which 25 were handed in. 1 form was not usable, leaving 24 usable measurements.

#### *Reliability*

To test the reliability of NAPSS, we used the percentage of absolute agreement, and Cohen's kappa, as explained in Section 4.2.2. Starting with the percentage of absolute agreement, we have seen that this should be at least 70%. The percentage of agreement within one level buffer needs to be at least 90%. 154 comparisons could be made from the received data.

| Pairwise comparisons | Goal | Measurement(n=154) |
|---|---|---|
| Absolute | 70% | 55.8% |
| 1 Off | 90% | 96.1% |

**Table 5: Results Pairwise Comparisons at Pilot**

We see that the absolute percentage is not sufficient for objective measurements, but using the one level buffer, the percentage is very high. These goals are set for objective measurements, while this is a subjective measurement. We can argue that the rate of absolute agreement will be lower when nurses disagree on the requirements of the patient, but we have no way of adjusting the goal or the measurement for this score.

Cohen's kappa allows a comparison between individual ratings. There were 17 comparisons possible, of which 9 were significant, meaning that we can safely assume them to have scored equally. 2 were almost significant (5.3%), and 6 were not significant. Of the 15 nurses that participated in the pilot, all non-significant ratings came from three nurses. This leads to the hypothesis that these nurses have a different individual capacity, either positive or negative. This is checked by the team leader of this unit, and is found to be plausible.

Including the facts that this is a trial period, and the overall frame of reference of the nurses will converge over time, we conclude that the way of measuring is sufficiently reliable to proceed. The difference in absolute and one-off agreement shows that acuity is a subjective term. We also conclude that when using the model, when one person will rate for the entire team, the rater is carefully chosen to be representable for all the team members in terms of individual capacity.

#### *Validity*

The validity is tested in order to know that we actually measure the workload. Because workload is an interpretation by each individual nurse, it is a subjective term. We asked each participant to rate the workload of the shift on a five point scale, ranging from very quiet to very busy. We used this to correlate the acuity score to. The acuity score is measured in the following way. Each nurse scored all patients according to the ratios. We add the amount of nurses required, resulting in a total amount of nurses required. Once we divide that with the amount of nurses that are present that shift, we get a measurement of nurse utilization.

*Nurse utilization = number of nurses required / number of nurses present*

When measuring the acuity, the nurse utilization should be correlated to the nurses' individual rating of the shift. We found this to be significant during the pilot period, with a correlation score of 0.445 and a significance of 2.9%. The correlation score indicates the effect of changing one score on the result of the other, and the significance is the measure for certainty of assuming the correlation to be present. We assume scores <5% to be sufficient. We used Pearson's r for this test, in IBM SPSS Statistics 22.

### 4.3.2 Test period

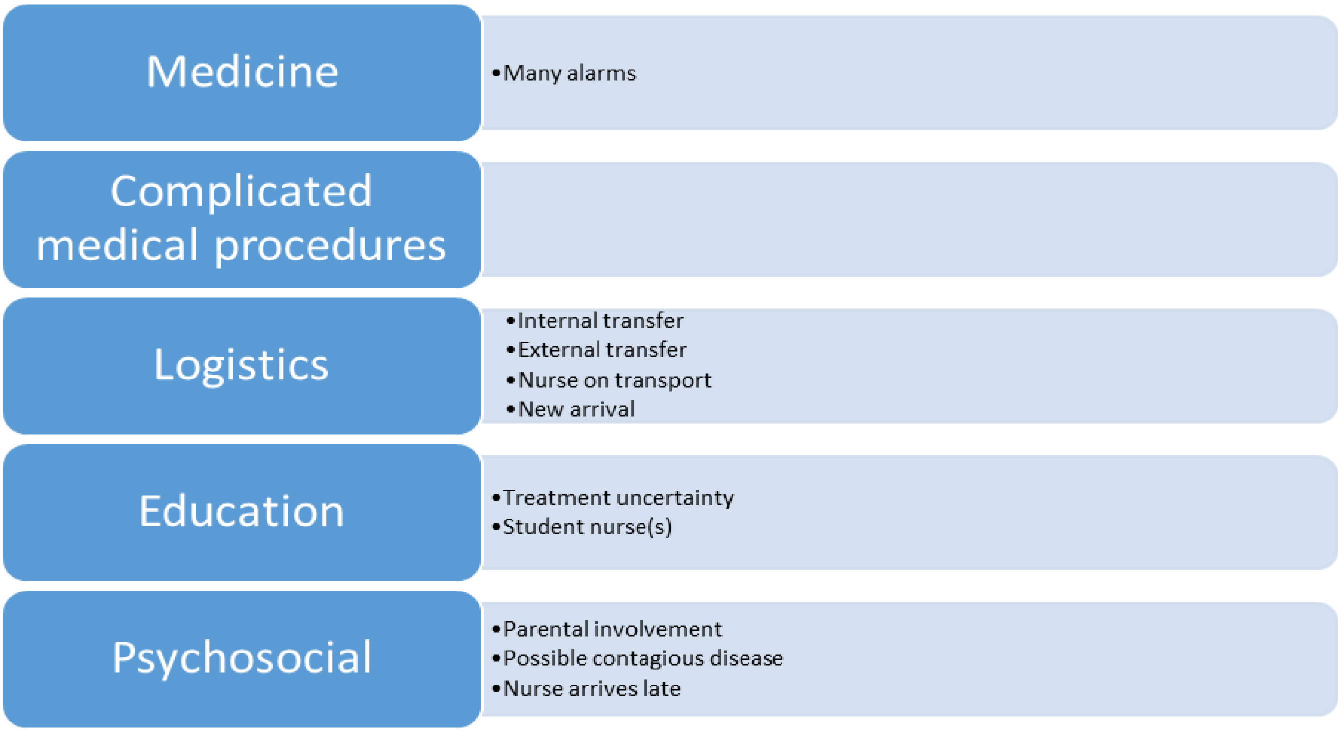
The main goal of the pilot project was to see how the nurses would handle the measurement system, and to test the system for its reliability and validity. The results were evaluated, and some feedback from the nurses was used to change the way the model was introduced and explained. The model itself did not need any adjustments, so we started the two-weeks test period. One of the goals of the test period is to gather data for the simulation of Chapter 5. In addition to serving as input for this, the test period will be used for some empirical analyses. In this section, we will first explain the test in more detail, then discuss the feedback from the nurses when using the model for a longer period of time, and repeat the tests done at the pilot for a larger test group.

#### *The Test Period*

During a two week period, all available nurses on all three units measured their acuity every shift. This results in a maximum number of single patient observations of 3024, where every observation is made on average by four nurses, having 1008 unique patient scores. During these two weeks, all nurses filled in the same form as during the test period. Some shifts forgot to measure, some individual nurses forgot or were otherwise occupied, which resulted in 1248 observations of which 533 were unique patient scores. 68 nurses in total participated in the test.

#### *Feedback*

At the bottom of the form the nurses used to score the patients was an open box for thoughts and suggestions. Remarkable was that a lot of nurses wrote down why that shift was busy or not. This created a list of events that contribute to the acuity of the unit. We see that all factors were listed as causes for a high acuity, except for complicated medical procedures. This is explained by the fact that both medicine and complicated medical procedures are automatically included in the patient categorization by the nurse, while the other factors are not directly patient related.




#### *Alignment*

As stated in Section 4.2.1. is testing for alignment necessary to assess the model's value. This is done through a Markov chain analysis. For an absorbing Markov chain can be calculated what the average amount of steps is before the absorbing state will be reached. Translated to the NICU can we find the average amount of nurses' shifts it will take on average for patients to leave the NICU. This calculation can be used to test the quality of our data. Appendix E shows the calculations for our average amount of time, which is 9.7 days. The hospital's own estimation of length of stay is 12.5 days. We believe that the data gathered in the test period underestimates the length of stay through missing data which leads to earlier discharges than actually occurred. This leads to the assumption that the test data does align sufficiently with the actual performance. This test on alignment is only executed for the test phase because the pilot project lacked a sufficient amount of data entries.

#### *Repeated Pilot Tests*

Because the test phase results in a lot more data entries, we can repeat the tests that are done in the pilot phase, and test the model for a much larger test group. The tests that we repeat are the pairwise comparisons and Pearson's r.

Over the entire test period, a total of 1168 pairwise comparisons could be made. Out of these 1168 comparisons, 778 were identical. This is a score of 67.0%, which is significantly higher than the pilot phase. The k+1 comparisons resulted in a percentage of 95.5%, which is a slightly lower score than the pilot, but still great. We conclude that, as expected, the nurses' frames of reference have converged, which makes the acuity measurement more objective.

| | Pilot(n=154) | Test(n=1168) |
|---|---|---|
| K | 55.8% | 67.0% |
| K+1 | 96.1% | 95.5% |

Table 6: Pairwise Comparison Results

Pearson's r results in a correlation coefficient of 0.60 and a significance level under 1%. The coefficient is a little different from the pilot's but since the significance and test group are very large, we can assume the new coefficient as more reliable than the pilot's.

We conclude that the test phase confirms the conclusions drawn from the pilot phase, and even results in a more aligned, reliable, and valid measurement.

## 4.4 Conclusion

This chapter discussed the tests on alignment, validity, and reliability that were executed on NAPSS. The pilot project of three days proved that the model actually measures the workload by correlating the results of NAPSS to the workload perception of the nurses. We also concluded that the model is sufficiently reliable by looking at the absolute agreement of the pairwise comparisons. This encouraged a two-week test period, which provided a larger test group and resulted in even more conclusive results. The percentage of absolute agreement rose from 55.8% to 67%, and the correlation between the nurse utilization and workload perception was more significant, most likely because of the larger test group. The alignment was tested by means of a Markov chain analysis and was assumed to be sufficient for the model to have practical value.

# 5. Simulation Experiments

Now that NAPSS is tested for feasibility and practical use is it necessary to research the practical value of using the model. This chapter introduces discrete event simulation and describes how experimenting within such a simulation model is used as a quantitative analysis method. Section 5.1 introduces simulation models and explains why discrete event simulation is used in this research. Section 5.2 describes our simulation model and the decisions made to create the model. Section 5.3 describes the experiments done in the simulation. Section 5.4 shows the results of the experiments and analyzes the outcomes. The experiments show a tradeoff between utilization and patient rejections, for which the application of the acuity measurement model helps to align the department's strategy for this tradeoff with the actual performance of the department.

## 5.1 Introduction Simulation

Acuity measurement allows us to gather data over a longer period of time, which was not possible before. In this research, this data is enables a discrete event simulation model in which experiments can be run on several policy decisions regarding patient placement. This includes the choice to base the decision on acuity, not on beds available, but also which unit to place the new patient and the acuity level to fill the units. The factors addressed in the experiments directly affect the amount of refusals and overloaded days, which are the problems this research aims to solve. Chapter 6 discusses several other options that can now be researched and may prove to be valuable to the NICU, but are outside the scope of this research.

In the simulation, the NICU is represented as a system of processing units and buffers, which together form the path a patient follows throughout his stay. This is called the simulation model. This model is based on a set of assumptions that Section 5.2 elaborates on to represent the real world system as accurately as possible within a certain level of detail. The computer evaluates this model numerically, and gathered data is used to estimate the desired true characteristics of the model (Law, 2007). By changing input parameters or policies, we can forecast the effect of possible changes in the represented system. The forecasts will always be at best an estimation of the effects, but simulation has proven to be a reliable method, provided that the model is a reliable representation of the real system.

Within healthcare it is especially hard to experiment with system settings in real life. There is always a risk of failure, and the consequences can be enormous. On the NICU, these risks can mean life or death for the patients. This is why simulation is an appropriate way to experiment for the NICU. With a certain level of significance, simulation can statistically compare two scenarios, and forecast the risks and perks. This research uses the simulation software Technomatix Plant Simulation 11. This is a discrete event simulation tool, which means that the simulation follows a sequence of events based on the input parameters, and the system changes its state event by event.

There are many other ways to do quantitative analysis on these kind of systems, but discrete event simulation proved to be the most convenient method for this research. The experiments that are done, which are explained in Section 5.3, involve changes in work policy. Simulation works excellently with these kinds of experiments, since the system is modelled and programmed through coding, which allows these types of changes in the system to be made. Markov chain analysis, for instance, works well for numerical changes in, for instance, processing time or number of processing units and analyzing the effects on the other parameters. When looking for an optimal number of nurses, beds, hours of overtime, or expected casualties, integer programming seem to be a very suitable method as well. However, this method does hardly allow policy changes and is therefore less applicable for this research.

Law (2007) describes a 10 step plan to create a sound simulation study. These steps are all present in this documentation:

1) *Formulate the problem and plan the study.*
   The goals of the simulation are given in the Section 5.2.1 as part of the conceptual model.
2) *Collect data and define a model.*
   The conceptual model includes the process-flow diagram and flowcharts, as well as the summaries of the input data.
3) *Is the assumptions document valid?*
   The model has a low level of complexity, which strengthens the validity of the assumptions, since there are only few to be made. The process-flow diagram and flowcharts are checked by the problem-owners.
4) *Construct a computer program and verify.*
   See Figure 17 for a screenshot of the program.
5) *Make pilot runs.*
   This is done, and the results of the pilot runs are used in Section 5.4.2 for the purpose of checking the validity and compared to the expected values.
6) *Is the programmed model valid?*
   The pilot runs are shown, including the animation, to the supervisors. Section 5.4.6 also describes the sensitivity analysis that will prove the robustness of the conclusions.
7) *Design experiments.*
   Section 5.3 describes all experiments conducted with the program.
8) *Make production runs.*
   The outputs from one experiment are given in Appendix C as illustration.
9) *Analyze output data.*
   This is done in Section 5.4.
10) *Document, present, and use results.*

## 5.2 Conceptual Model

The basis of the simulation is the conceptual model, also called the assumptions document. The conceptual model contains the documentation of all model concepts, assumptions, algorithms, and data summaries (Law, 2007). Following Law, the following section will elaborate on all of these points.

### 5.2.1 Simulation goals

As mentioned in Section 5.1, the goal of the simulation is to compare several policy decisions regarding patient admission and placement. The first comparison will be that of basing admission decisions on acuity, rather than on beds available. In addition, we want to analyze the effect of changing the threshold on patient admissions on refusals and acuity overload. Finally, we want to compare different methods of distributing for patients over the three units, comparing an even distribution with a largest-gap method. These experiments will be discussed further in the next section.

The output of the simulation will be the number of refusals during the run, the number of shifts during which there is an acuity overload, and the average occupation. Although the amount of refusals is correlated with the average occupation, both outputs are necessary to analyze. The amount of refusals is a measure of quality of care, and the average occupation directly translates into the department's productivity. These three outputs are related to the stakeholder triangle: management, staff, and patient. This enables a conclusive comparison between the policies.

### 5.2.2 Process-flow diagram

The path the patients follow through the model is represented in a process-flow diagram. Since the scope of the simulation is only the NICU, the process-flow diagram is very simple, and given in Figure 14. This picture shows the road a patient follows through the system. When a patient is admitted to the NICU, it is admitted to one of the three units. Over time, the patient either deceases or recovers until it can be transferred. However, there are some rules for the patient flow. In the original situation, two checks are made before a patient is admitted. The first one is whether there are any beds available or not. The second one is whether that unit can handle another patient or not. This is represented in a flowchart, Figure 15.

Each unit has patients that are categorized by their six possible levels of acuity. Every eight hours, representing the measurement moments during each shift, the acuity levels of the patients are updated through a transition matrix. For each level of acuity, this diagram has a distribution to the next possible states of the patient. This diagram is given in Section 5.2.5 as part of the data calculation. In principle, the transition matrix should favor the odds for recovery, allowing the patients to flow through the system in due time.

Because each level of acuity represents a fractional occupation of a nurse, we can introduce a system where each level represents a number of "acuity points". These points are simply the amount of nurses times 5, which will simplify the calculations, since we will not only be working with fractions. Table 7 shows this

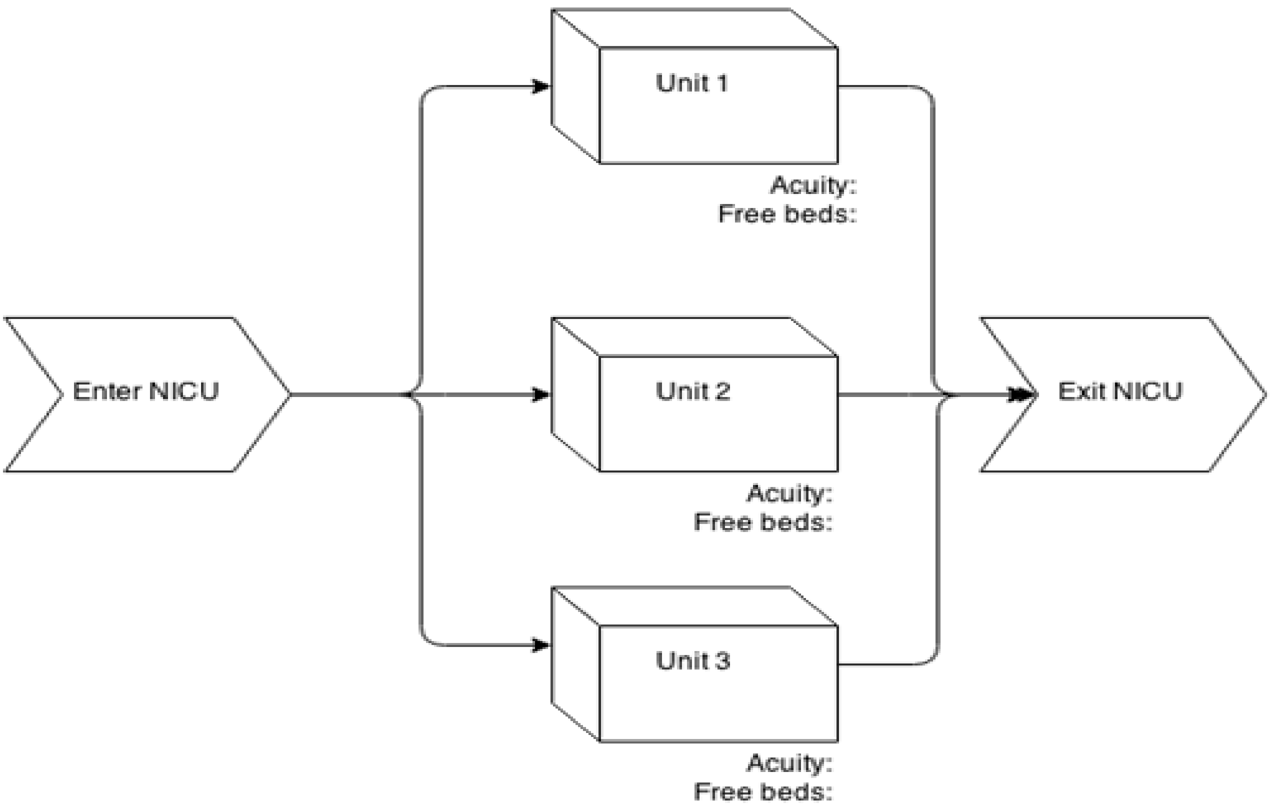



**Figure 14: The process-Flow Diagram**

system. As seen in the pilot, when each nurse is normally busy, the workload is five points per nurse. This agrees with each nurse working a 1-on-1 patient (level 6).

| Level | Ratio | Nurses | Points |
|---|---|---|---|
| 6 | 1 to 1 | 1 | 5.00 |
| 5 | 1 to 1.5 | 0.67 | 3.33 |
| 4 | 1 to 2 | 0.5 | 2.50 |
| 3 | 1 to 3 | 0.33 | 1.67 |
| 2 | 1 to 4 | 0.25 | 1.25 |
| 1 | 1 to 5 | 0.2 | 1.00 |

**Table 7: The Scores Translated to Points**

### 5.2.3 Simplifying assumptions

Models are simplified representations of real-life systems. Simple models are more likely to be programmed correctly, require less data, and are more easily interpreted (Robinson, 2008). The opposite holds for complicated models. Assumptions have to be made in order to simplify the model. When making these assumptions, it is important to keep a level of detail at which the model is still representative and we can

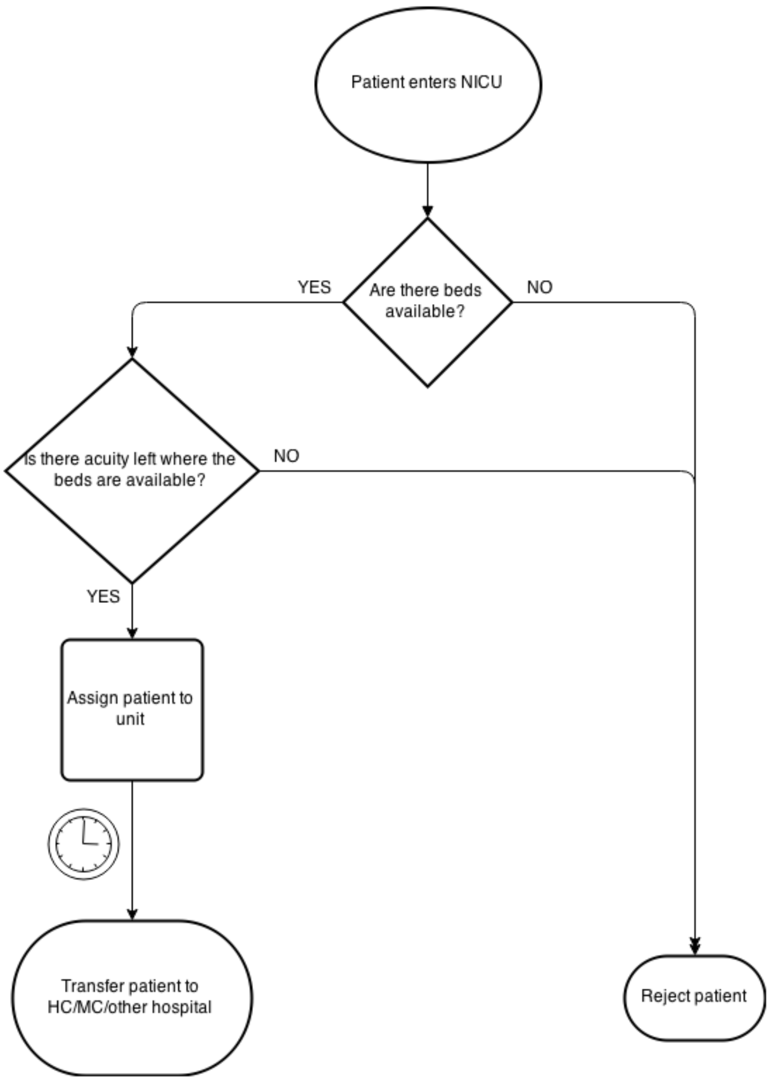



**Figure 15: Acuity-Based Decision Process (copy of Figure 2)**

draw conclusions from the experiments with confidence. We assume for all simplifications that the deviation from reality will not significantly impact our conclusions.

The first assumption is that the data that has been collected in the first two weeks in June reliably represents the yearly patient mix. If this assumption does not hold, the transition matrix can change. The effect of this will be that the outputs change, but we assume that this changes equally throughout our experiments, resulting in no effect on out conclusions.

The second assumption is that the maximum acuity a unit can handle is always equal. This, however, completely depends on the nurses who are working the shift. We assume that the total capacity of the teams of nurses does not fluctuate enough to impact the conclusions of our simulation.

The third assumption is that we treat all patients equally. In reality, the patient mix consists of patients from the WKZ, patients from within the WKZ's target region, patients from outside this region, and internal and external transferals. Especially internal transferals can be foreseen and anticipated, but we assume one homogenous patient mix. The fourth simplification is the fact that we always assume four nurses to be available during all shifts. In reality, three to five nurses will be scheduled, depending on the period and shift.

### 5.2.4 Limitations of the model

Either the simplifications that are applied to the model, or the complexity of the system the model represents leads to limitations of the model. These can be solved with further development of the model, but this is not necessary for our research goal. We do not distinguish between the three different shifts in the model. The input data will provide a mix of busy and quiet shifts, which can be translated into either busy and quiet periods or the different shifts.

The model also does not allow nurses to help each other. In reality, when one unit is quiet, nurses can help other units. The model cannot lower the threshold of acuity on one unit to help other units. The threshold is always four nurses who do not want to be more busy than "reasonably busy", which was four points on the five-point scale we used to inquire about the nurses' perception of workload. This agrees with the limitation that there are always four nurses available to every shift.

### 5.2.5 Summaries of the data

Three entries in the model are based on data. These are: 1) the arrival distribution of the patients, 2) the distribution of acuity level on arrival, and 3) the transition matrix. This section will summarize these inputs and refer to the accompanying appendix for the calculations.

The arrival distribution of the patients is derived from the arrivals during the test period. As stated in Section 5.2.4, we assume the data we use for the transition matrix to be representable for the entire year. This generalization includes the arrival rate. During the 18 days of the test, 34 new patients arrived. This would result in a Poisson arrival process with lambda 18/34 in days, but Plant Simulation does not accept lambda values over 700, which have to be seconds. That is why the approximation of the Poisson distribution through the normal distribution is used, with lambda as mean and variance. These are respectively 12.7 hours and 3.52 hours. In 2014 the NICU admitted 589 patients. This would mean 29 patients in 18 days, which is why in the sensitivity analysis we test the influence of this deviation on the results of the experiments.

The distribution of the acuity level on arrival is directly derived from the test data. During this period, 34 patients were admitted to the NICU. Table 8 shows the distribution of the patients' associated acuity levels upon arrival. For six of the new patients no score on entry was available. The reliability of this distribution is, due to the small number of entries, discussed with the management team of the WKZ, and is found to be sufficiently reliable.

| Level: | Entries: | Probability: |
|---|---|---|
| 1 | 0 | 0 |
| 2 | 1 | 0.04 |
| 3 | 11 | 0.39 |
| 4 | 7 | 0.25 |
| 5 | 7 | 0.25 |
| 6 | 2 | 0.07 |
| Total | 28 | |

Table 8: Acuity Distribution Among Entries

The transition matrix is the main result of the test period. For all patients, for every data entry during the test period, the transition of one acuity level to another is counted. This combined forms for every level of acuity the amount of times that it transitions to all other possible levels or leaves the system. We can transform these numbers into the probability of a patient being at a certain level the next shift on the basis of the current shift. The original transition matrix is given in Table 9. Appendix D shows the calculations for this matrix.

| | 1 | 2 | 3 | 4 | 5 | 6 | Transfer |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0.5 | 0 | 0 | 0.5 |
| 2 | 0.025641 | 0.205128 | 0.512821 | 0.230769 | 0 | 0 | 0.02564103 |
| 3 | 0 | 0.214876 | 0.553719 | 0.206612 | 0.008264 | 0 | 0.01652893 |
| 4 | 0.010309 | 0.123711 | 0.453608 | 0.329897 | 0.041237 | 0.020619 | 0.02061856 |
| 5 | 0 | 0.0625 | 0.375 | 0.375 | 0.1875 | 0 | 0 |
| 6 | 0 | 0 | 0.166667 | 0.833333 | 0 | 0 | 0 |
| Transfer | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

Table 9: Original Transition Matrix

We can see the system as represented by the transition matrix as a Markov chain. A Markov chain, introduced in Section 4.1.2, is a process that can be represented by states, in which each state has a probability of transitioning into the other states. Our Markov chain has the absorbing characteristic, meaning that one of the states has the property that once you reach that state, you will not leave (Winston, 2004). For us, leaving the NICU is the absorbing state. In reality, patients can return to the NICU, which in the model is represented by a new entry in the system.

For an absorbing Markov chain we calculated what the average amount of steps is before the absorbing state will be reached. Translated to the NICU can we find the average amount of nurses' shifts it will take for patients to leave the NICU. This calculation can be used to test the quality of our data. Appendix E shows the calculations for the average length of stay during the test period, which was found to be 9.7 days. In this calculation, the amount of leaving patients is overestimated because for a few leaving patients, we have no transition data, meaning that they may have left the system on a later moment. At the same time, while leaving the system, it is likely that they recovered further over the following shifts before leaving. This means that we overestimate both the amount of patients leaving as well as the average level of acuity. Because of this, we adjust the leaving distribution and numbers as in Table 10. This adjustment is done in agreement with the hospital, who agree that the new amounts are more representative of the yearly patient mix.

| Level: | Old amount | New amount |
|---|---|---|
| 1 | 1 | 1 |
| 2 | 1 | 1 |
| 3 | 5 | 2 |
| 4 | 2 | 2 |
| 5 | 0 | 0 |
| 6 | 0 | 0 |
| Total: | 9 | 6 |

**Table 10: Entry Adjustments**

This results in a new average length of stay of 14.96 days. Table 11 shows the new transition matrix.

| | 1 | 2 | 3 | 4 | 5 | 6 | Transfer |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0.5 | 0 | 0 | 0.5 |
| 2 | 0.025641 | 0.205128 | 0.512821 | 0.230769 | 0 | 0 | 0.02564103 |
| 3 | 0 | 0.214876 | 0.553719 | 0.206612 | 0.008264 | 0 | 0.01652893 |
| 4 | 0.010417 | 0.125 | 0.458333 | 0.333333 | 0.041667 | 0.020833 | 0.01041667 |
| 5 | 0 | 0.0625 | 0.375 | 0.375 | 0.1875 | 0 | 0 |
| 6 | 0 | 0 | 0.166667 | 0.833333 | 0 | 0 | 0 |
| Transfer | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

**Table 11: Adjusted Transition Matrix**

Appendix E calculates the effect of rounding the probabilities, resulting in an expected average length of stay of 13.33 days. This comes close to the hospital's own estimation of the length of stay, which is 12.5 days. We assume the rounded probability matrix to be sufficiently reliable. The average length of stay of the patients influences the occupation (Harper&Shahani, 2002), and we assume that changes in this behavior result in effects comparable to adjusting the arrival rate. This assumption cannot be tested and therefore is a limitation to the model, but seems necessary to be made.

## 5.3 The Experiments

The goal of the simulation is to statistically compare several policies on the chosen performance criteria. This section explains and illustrates all experiments done to reach this goal. The first comparison will be between patients being admitted to the unit with the most beds available and patients being admitted to the unit with the most acuity available. This evaluates the choice to include acuity in the decision , which is not common practice at all wards. Then, we will introduce a second way of acuity-based patient admittance. Patients will not be admitted to the unit with the most acuity left, but to the unit where they fit best, filling the unit most optimally. This method will be discussed more in Section 5.3.2.

After we have tested the three policies, we will change the threshold on acuity on which to reject patients. For several acuity levels, we will look at the effects on the performance indicators. This way we can determine whether overloading the units is worth the effort. Finally, we slightly change the patient arrival rate and acuity mix on arrival to see how they affect the results in a sensitivity analysis. This can prove the importance of the quality of the data we use as input.

### 5.3.1 Bed-based versus acuity-based

The first experiment concerns the policy of patient admittance and placement. In the first policy, the patient is admitted considering both the available beds and the available acuity. This is in agreement with the decision-making process as described in the conceptual model. We call this policy “basic”, since it represents the current way of working. The only difference with the current way of working is the fact that in the simulation the acuity levels are known and reliable, and in reality these are estimations.

In the second policy, the admittance process invilves only the occupancy of the units. We call this policy “bed-based” The decision-making process is represented in Figure 16. The patient is admitted to the unit with the most beds available. Acuity is not taken into account in either admittance or patient placement.

These policies are compared on number of refusals, the number of overloaded shifts, and the average number of patients.

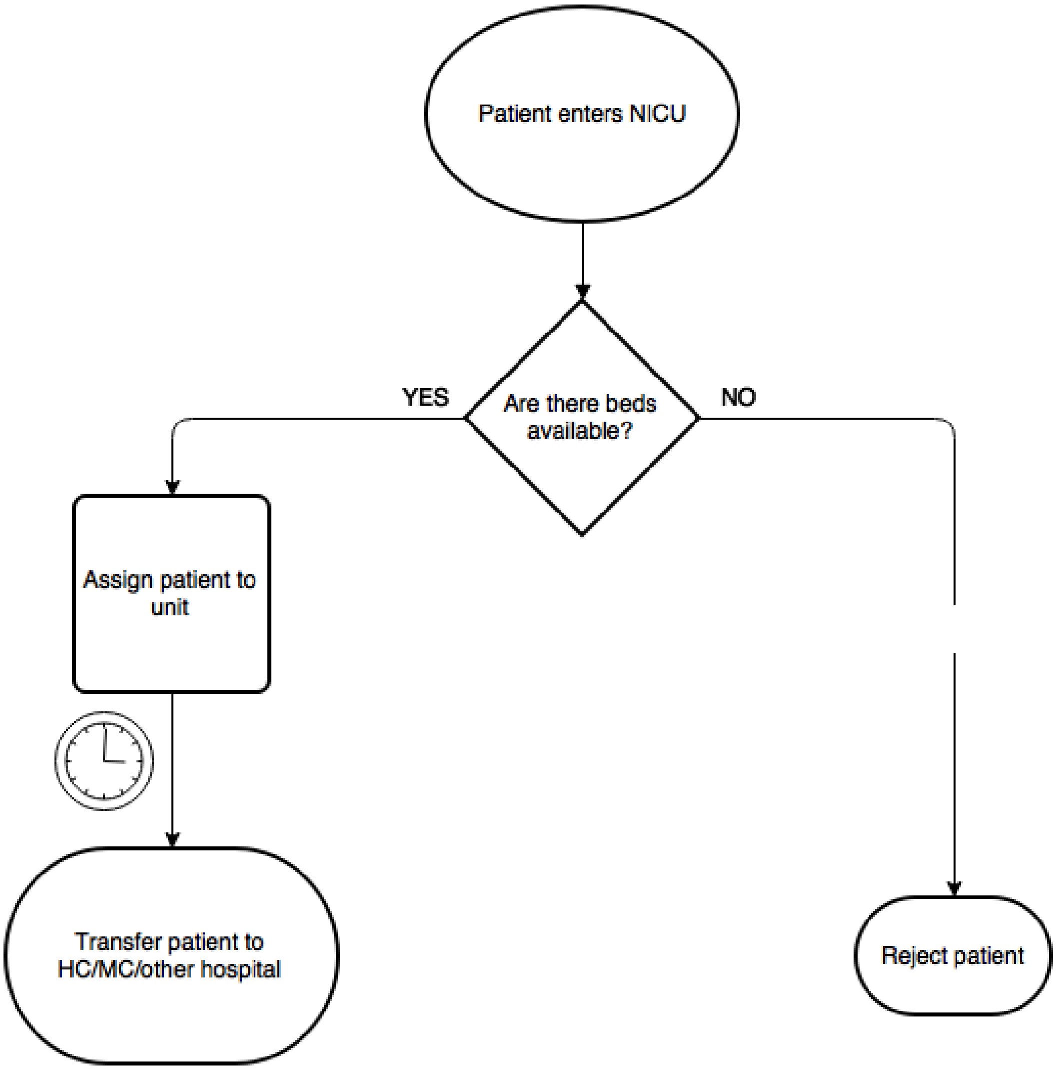



Figure 16: The Bed-based Policy

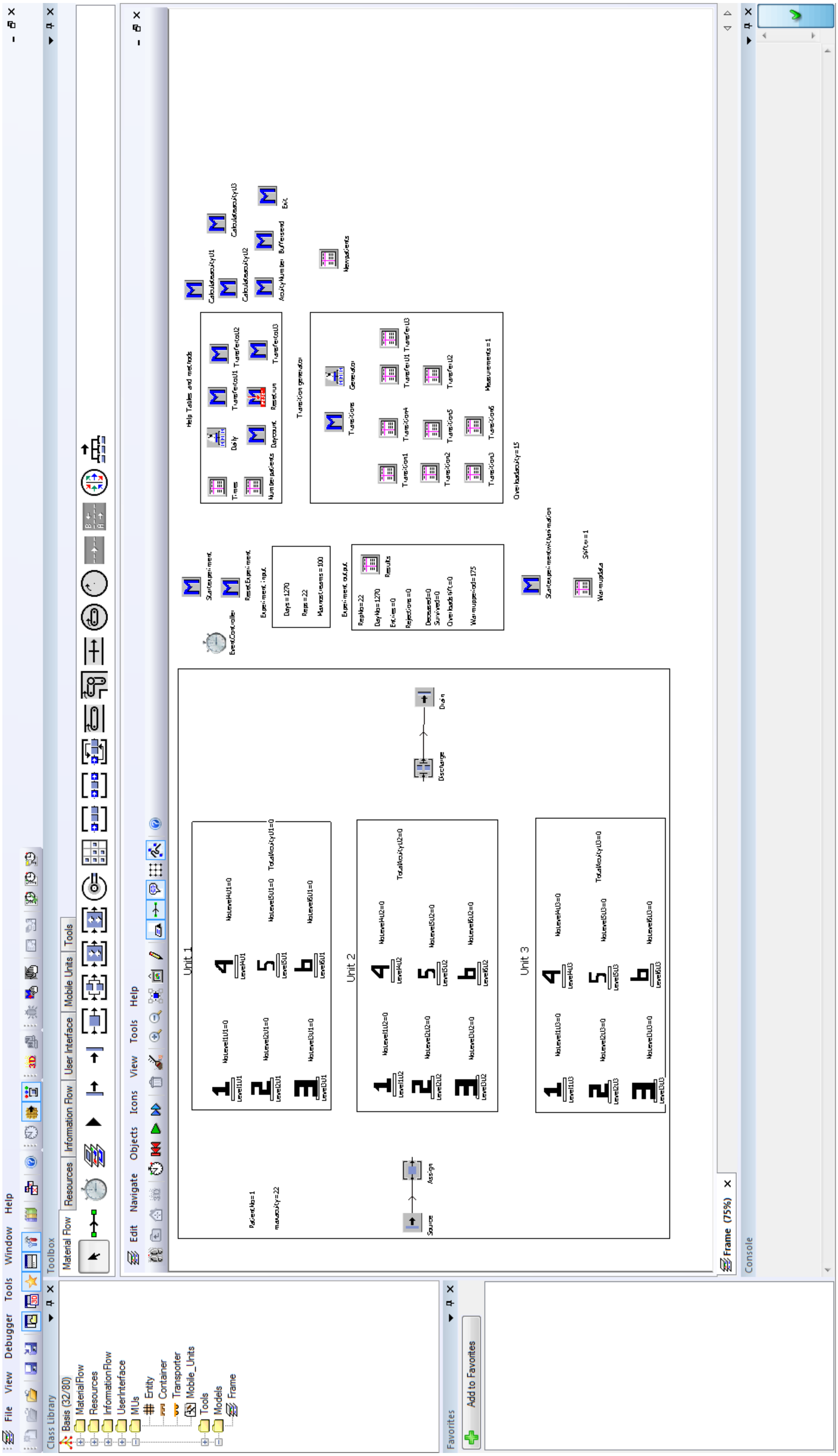



**Figure 17: Screenshot of the Simulation Model**

### 5.3.2 Best Fill

The third policy that is tested is what we will call the "best-fill" option. The admittance criteria are the same as in the basic policy, both acuity and available beds are taken into account. However, the method by which a new patient is assigned to a unit is slightly different. The idea is that when all units are equally filled, they may all have little room left for a new admittance. However, when one or two units are completely filled, the third unit may have a larger admittance space. This is illustrated in Figure 18. Hans, van Houdenhoven and Hulshof (2012) identify these kinds of policy decisions as "admission planning", which regards resource capacity planning on a tactical planning level.

For instance, assume the total load on a certain moment is 66, and the maximum acuity for one unit is 24. When all units are equally filled, a new admittance of acuity 4 has to be rejected. When using best fill, it may be the case that two units are completely filled, leaving enough space for the new patient to be admitted to the third unit. The drawback of this method is that it is more likely for the best fill method to result in an acuity overload at the best filled units when one or more patients are getting worse. The unit that has the most admittance space does not always have to be the same unit. This would lead to an uneven distribution of average acuity over the nurses.

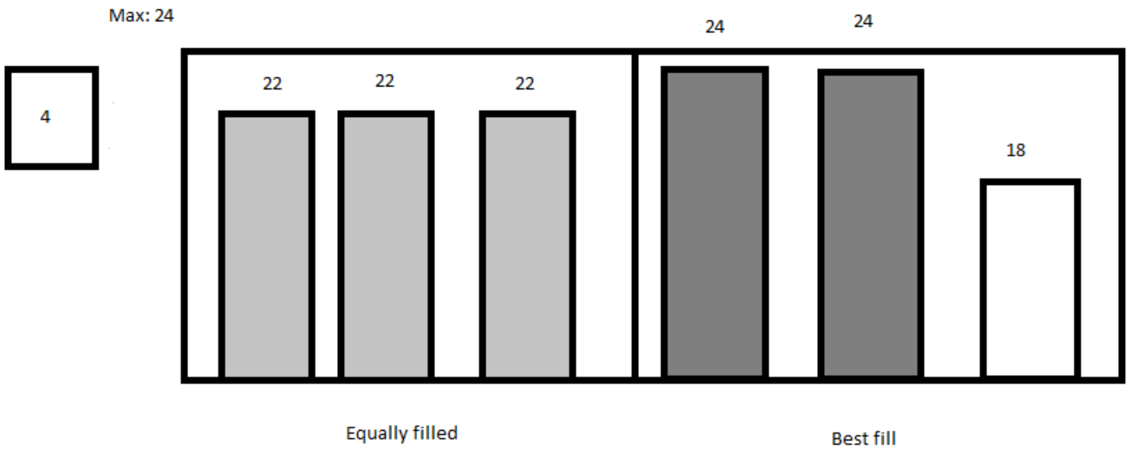



**Figure 18: Equally Filled vs Best Fill**

The acuity overload that results from the best filled policy is likely to be smaller than the amount of overload that will result from bed-based placement. To compare these overloads, the simulation will also give the maximum acuity overload and average acuity overload as output for comparison. The main similarities and differences between the policy are given in Table 12.

| Policy name | Basic | Bed-based | Best-fill |
|---|---|---|---|
| Involves Acuity? | Yes | No | Yes |
| Placement Method | Most Acuity | Most Beds | Least Acuity Left |
| Possible Without Acuity Measurement? | Flawed | Yes | No |

**Table 12: Policy Comparison**

### 5.3.3 The Acuity Threshold

Taking acuity into account when admitting or rejecting a patient, we have to set a threshold: when do we start rejecting? The connection between occupancy ratings and refusals has been researched in simulation studies before (Ridge et al., 1998; Harper&Shahani, 2002). We will verify this connection for our nurses' workload utilization measure.

We have seen in the pilot that the correlation between the occupancy and the workload perception is 0.4453. This means that, calculating with the point-based acuity levels, an increase of 1 on the workload perception will increase the utilization with 0.4453. This means that the utilization for each nurse will be 1.4453 when scoring a "fairly busy", resulting in 7.25 points of acuity per nurse, with a unit total of 7.25*3=21.75 points. Allowing more than 22 points on a unit results in a "too busy" workload, so the threshold will be somewhere around 22 points. The first experiments are executed with the normal workload threshold, being 5*3=15 points per unit.

The bed-based policy does not include acuity, so we do not have to involve this policy in this experiment. The other two policies will be tested for acuity thresholds ranging from 12 to 28, with a 3-point interval.

### 5.3.4 Sensitivity analysis

Because we use two weeks of data for the transition matrix and the arrivals of a previous year, we have to check how important it is that this represents the current situation, or future situations. First, we will check the effect of changes in the arrival rate. For all three policies, the arrival rates will be adjusted both up and down to see the importance of this parameter. The test data show 34 arrivals in 18 days, and we will experiment with values of 34 arrivals in 14 days to 34 arrivals in 22 days, with a 2-day interval.

The second sensitivity analysis is the mix of acuity in which the patients arrive. The distribution in the normal situation is given in Table 13, but it is good to test what happens when this distribution changes. The distribution is derived from a small sample test and checked by the management, so it is not unlikely that the odds are a little off. The values for which we check the distributions are also given in Table 13. The centered distribution is more focused on the middle levels, the high distribution on the high levels, and the low distribution on the lower levels.

| Alternative | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 | Level 6 |
|---|---|---|---|---|---|---|
| Normal | 0% | 3% | 40% | 25% | 25% | 7% |
| Centered | 0% | 0% | 45% | 25% | 30% | 0% |
| High | 0% | 0% | 35% | 25% | 30% | 10% |
| Low | 0% | 10% | 45% | 25% | 20% | 0% |

**Table 13: Acuity Distributions on Arrival**

## 5.4 Experiment Results

The experiments that are discussed in the previous section can now be run through the simulation. Starting with the basic policy, we first have to determine several simulation settings, for instance the number of days, warmup period, and number of runs to simulate. When these settings are determined, we can run all experiments, provide the outputs, and analyze the results.

### 5.4.1 Simulation Settings

For the first experiments, some settings that later will be experimented upon will be used as standard. We assume that on average three nurses are available on each unit, and we will set the acuity overload score as 15, since a higher score will result in busy shifts. The threshold for the maximum acuity will be 22, since it that is the threshold for a "too busy" shift, rounded to the nearest integer.

The system is empty when we start the simulation. Following the arrival distribution, the patients enter the system and the NICU is filled. This means that the first period of time is not representative for the total results of the policy. We need to find the point at which the system behaves as if it has been working for decades, and start measuring at that point. We do this by visually checking when the outputs stop changing a lot. This is called Welch's method (Law, 2009). For the basic policy, we simulated 10000 days for one run, and measured the amount of rejections, acuity overloaded shifts, and the average time spent in a the system by the patients. The graphs are presented in Figures 19, 20, and 21. We can see that for the second and third factor the graphs visually stabilize at a little over 500 shifts. Especially in Figures 20 and 21 can we zoom in and see the beginning of a steady state after a little over 520 shifts. This is why we will use 175 days as warmup period (175 days with 3 shifts per day).

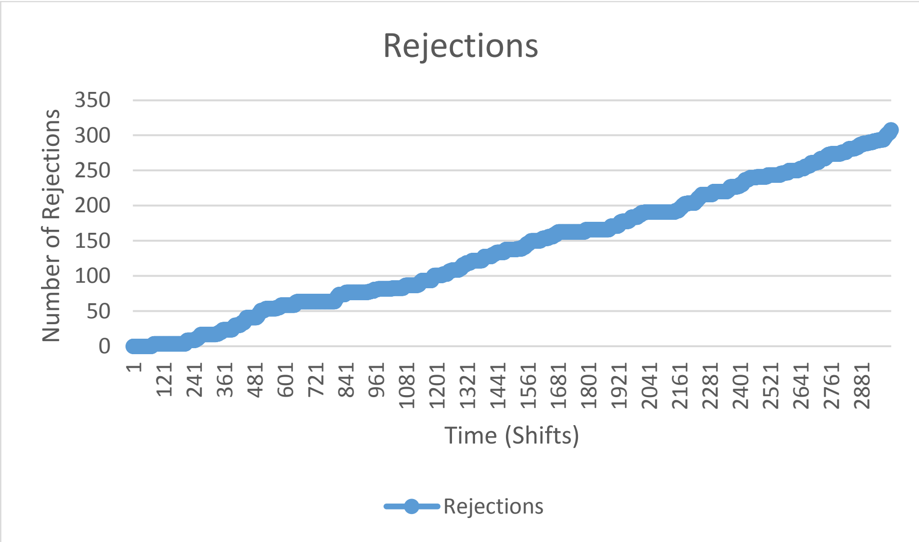



**Figure 19: Rejections During 1000 Days**

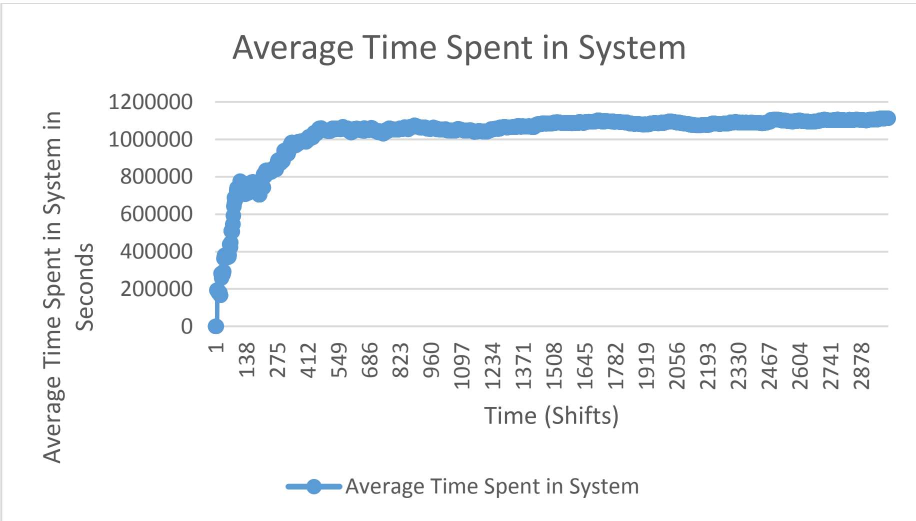



**Figure 20: Average Time Spent in System during 1000 Days**

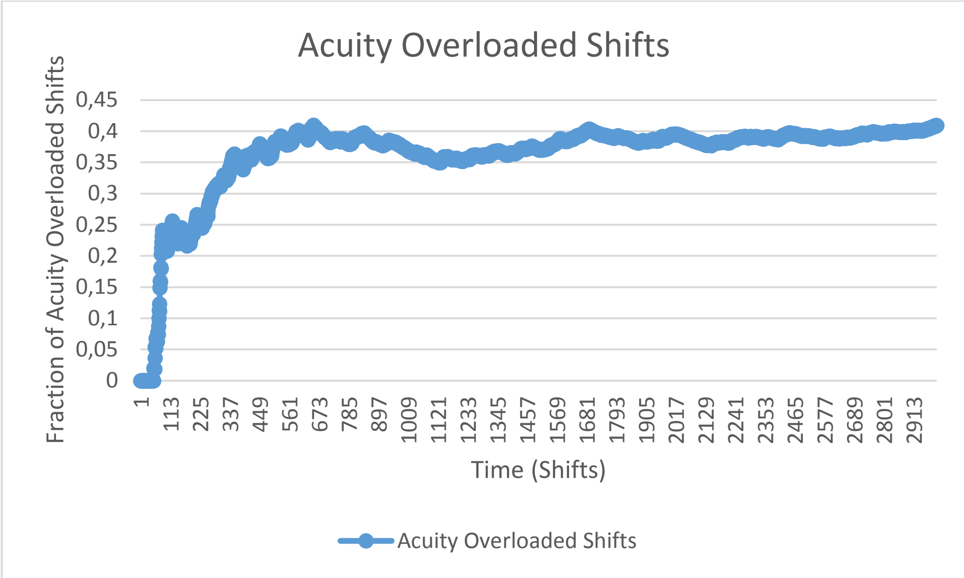



**Figure 21: Percentage of Acuity Overloaded Shifts During 1000 Days**

In the simulation, the patients flow through the model for as long as we make them go. However, we want to stop at one point and go to the next experiment. The simulation runs for a certain number of days, then starts again, simulating the same period of time with different random numbers. The simulation uses common random numbers, which means that each experimental setting uses the same random numbers, which enables a reliable comparison between the policies. However within one experiment, each separate day within and between every run uses random numbers to determine the following state of the system.

The number of days for which each replication runs is chosen by hand and should simply be much larger than the warm-up period. Since the warm-up period is 175 days, and we see in the Figures 19, 20, and 21 a steady state being formed, we choose 1270 days to be our run length, representing three years once warmed up.

The number of runs, or replications, we should do is calculated via the replication/deletion approach for means (Law, 2007). In this method, we calculate for all outputs the average over the chosen amount of days, excluding the warm-up period. For all runs, starting at the first, we calculate the moving average over the runs and compare the mean with the confidence interval half-width of the variance. When the confidence interval half-width is close enough to the moving average, we conclude the number of runs to be sufficient to have come to a steady-state mean.

The confidence interval half-width is calculated by Formula 1, where n is the number of runs and alpha is the level of significance of at least 0.05.

$$\delta(n,\alpha) = t_{n-1,1-\alpha/2}\sqrt{S_n^2/n} \qquad \textit{Formula 1}$$

The allowable error *e* is maximally 0.05. Then, for each run, we divide the confidence interval half-width and choose the number of replications the number of runs it takes to fulfill Formula 2.

$$\delta(n,\alpha)/\bar{X}_n \leq \gamma' \qquad \textit{Formula 2}$$

This is done for the basic policy, with 1270 days and excluding the warmup period, starting with 25 runs. We did this for all three outputs, the number of rejections, the amount of acuity overloaded shifts, and the average number of patients in the system, so we are sure not to have too large an error on any of these.

For all calculations, see appendix F. From the tables we can see that the number of replications should be 22 to get a steady-state mean for the number of rejections, 11 for the number of shifts with an acuity overload, and 2 for the average number of patients. This is why 22 should be the minimum amount of replications to be made. This number of replications is used in all experiments.

### 5.4.2 Verifying the Simulation

Because we want to know how well the simulation represents the actual system, we will do three tests to compare the simulation model to the real system. This is the validation of the simulation model. Two factors will be compared: the average number of patients in the system, and the average number of time spent in the system. The third method of validation is checking the simulation model through animation.

The average amount of patients in the system for the basic policy over 25 runs is 20.42. With a mean arrival time of 12.7 hours, the total amount of patients to enter the system is 2069. Of this 2069, an average number of 357 is rejected. This results in an average interarrival time to the units of 15.35 hours. We can use Little’s law (Little, 1961) to calculate the average amount of patients in the system. Little’s law states that the expected amount of products in a system is the average time spent in the system times the arrival rate. The average time spent in the system is 13.24 days, and the arrival rate is 1.56 per day. This results in an average amount of patients in the system of 20.65. This is close to the 20.42 from the simulation. The difference may be explained by the fact that the interarrival time in the simulation does not use a Poisson distribution, but an approximation via the normal distribution.

The second check is the average amount of time patients spend in the system. The average amount of time spent by patients in the system is 13.24 days in the simulation, whereas we calculated an expected average of 14.96 days in Section 4.2. This difference can be explained by the rounding of the transition matrix. The transition matrix used in the simulation uses integers as percentages, which means all probabilities are rounded to the nearest integer. Using the Markov analysis for the transition matrix with rounded probabilities, we see an expected average stay of 13.33 (See Appendix E). The difference in average length of stay may be explained by the fact that this does not include rejected patients, and that rejected patients will have a high acuity level on average. Patients with a high acuity level have a longer average stay than low-level patients, so the rejections will lead to a higher average length of stay.

The third check is visually checking the way the moving units in the simulation behave through simulation. Starting the simulation very slowly, the main screen as displayed in Figure 17 shows the arrival, placement, and exit of patient. By checking visually whether the acuity levels change and the placement method is followed correctly the validity of the simulation model can be confirmed. The simulation behaved as it was supposed to, which means that the experiments can be executed.

### 5.4.3 Acuity-based Versus Bed-based

The first experiment compares the basic situation to a bed-based strategy. The results of the 22 runs for the three outputs are given in Figures 22, 23, and 24. What can be observed is that the use of common random numbers, as introduced in Section 5.4.1, is represented in the outputs.

None of the graphs cross lines, which means that the results are consistent every run it can be visually determined that the tests for a shared distribution can be executed for a one-sided deviation. Seeing the three graphs next to each other clearly illustrates the tradeoff between busy shifts and overtime, and rejections. Table 14 shows the average results over all runs for the two experiments.

A t-test is done for all outputs to check for likeliness of an agreeing mean. These t-tests are two-sided and assume an unequal variance. These t-tests are done in Excel. For this experiment, all results of the t-tests were under the 1%. We can thus assume that using an acuity-based policy over a bed-based policy raises the number of rejections and average amount of patients, but reduces the amount of overloaded shifts.

| Basic | Mean | St. Deviation |
|---|---|---|
| Rejections | 356.86 | 32.77 |
| Acuity overload | 1395.97 | 81.21 |
| Average amount of patients | 20.42 | 0.14 |

**Table 14: Summary Results Basic**

| Bed-Based | Mean | St. Deviation |
|---|---|---|
| Rejections | 271.68 | 30.00 |
| Acuity overload | 1940.63 | 103.57 |
| Average amount of patients | 21.53 | 0.17 |

**Table 15: Summary Result Bed-Based**

| Experiment | Rejections | Acuity overload | Average amount of patients |
|---|---|---|---|
| Basic | 356.86 | 1395.97 | 20.42 |
| Bed-based | 271.68 | 1940.63 | 21.53 |
| | | | |
| Difference | -85.18 | 544.66 | 1.11 |
| Probability of agreement | <1% | <1% | <1% |

**Table 16: Basic vs Bed-Based**


**Figure 22: Basic vs Bed-Based Rejections**

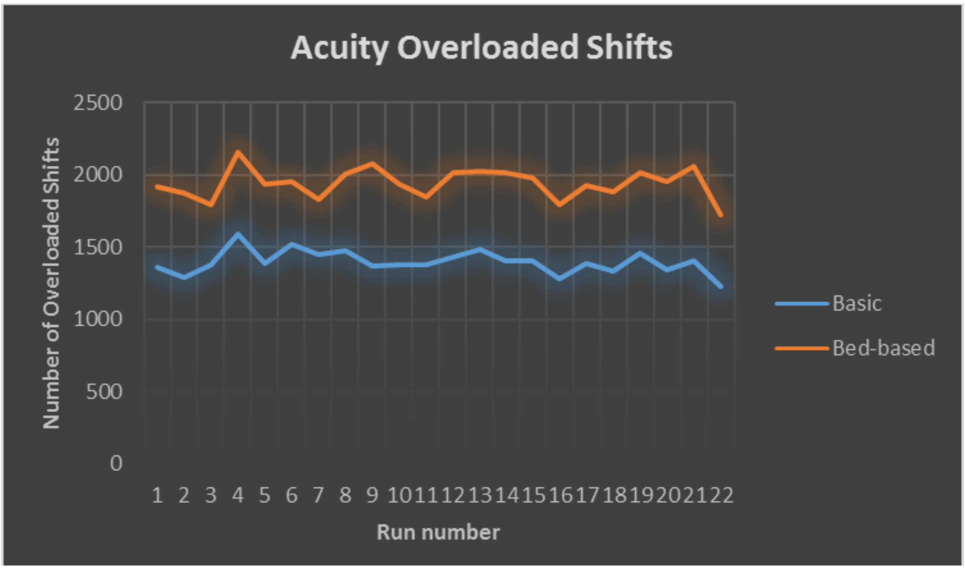



**Figure 23: Basic vs Bed-Based Acuity Overloaded Shifts**

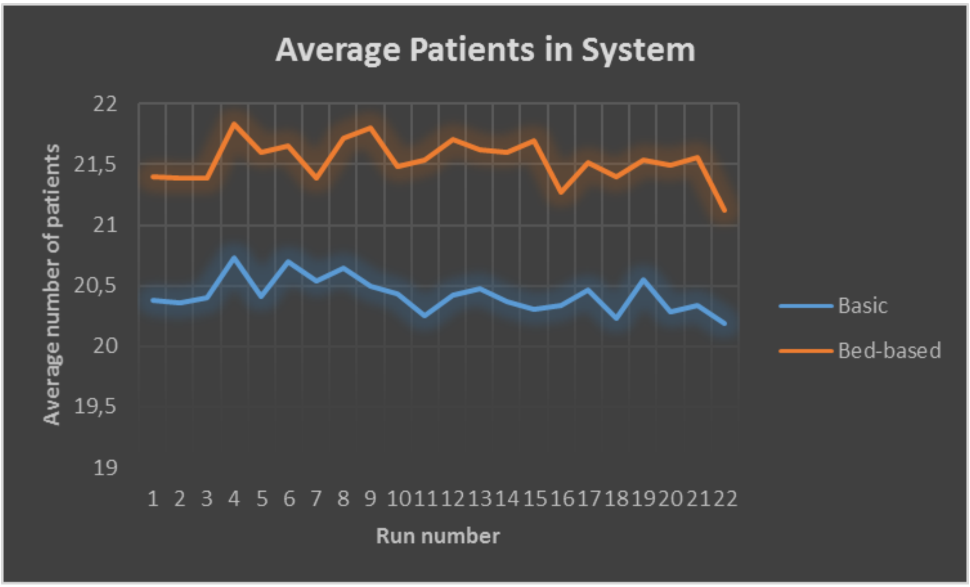



**Figure 24: Basic vs Bed-Based Average Patients in System**

### 5.4.4 Best-fill

The next experiment looks into the effects of using the best-fill policy in acuity-based placement. The comparisons to the basic policy are given in Table 18.

| Best-Fill | Mean | St. Deviation |
|---|---|---|
| Rejections | 271.13 | 31.13 |
| Acuity overload | 2338.14 | 86.29 |
| Average amount of patients | 21.54 | 0.21 |

**Table 17: Summary Results Best-Fill**

| Experiment | Rejections | Acuity overload | Average amount of patients |
|---|---|---|---|
| Basic | 356.9 | 1396.0 | 20.42 |
| Best fill | 271.1 | 2338.1 | 21.54 |
| Difference | -85.8 | 942.1 | 1.12 |
| Probability of agreement | <1% | <1% | <1% |

**Table 18: Basic vs Best-Fill**

We see that the best-fill policy allows for more patients to enter the system, but also more overloaded shifts. When comparing the best-fill option with the bed-based policy (Table 19), we see that the performance is about the same for rejections and average amount of patients, but best-fill has more acuity overload.

| Experiment | Rejections | Acuity overload | Average amount of patients |
|---|---|---|---|
| Bed Based | 271.68 | 1940.64 | 21.53 |
| Best fill | 271.14 | 2338.14 | 21.54 |
| Difference | -0.55 | 397.50 | 0.00 |
| Probability of agreement | 95% | <1% | 94% |

**Table 19: Bed-Based vs Best-Fill**

The fact that best-fill currently has more acuity overloaded days than bed-based is curious. When having no restriction at all for the total amount of acuity in the system, there should be more overloaded shifts than when acuity is taken into account. If the input data underestimates the average acuity, the units are less likely to be overloaded with fewer than eight patients, and acuity-based patient placement will have less advantages. In the current situation, the best fill has the most overload because the best filled unit has the highest probability of being overloaded. If the average level of acuity over the three units raises, it is likely that the best fill policy will outperform the bed-based policy. This will be researched in the sensitivity analysis in Section 5.4.6.

For now, we conclude that using the best fill option will improve the number of patients that are treated, at the cost of some overloaded shifts.

### 5.4.5 Acuity Thresholds

When basing the admittance process on acuity, the question is to which level of acuity the units will be filled. To see how fill levels affect the performance of the units, we can simulate the different fill levels and plot the results. These are Figures 25, 26, and 27. We can see that using a fill level above 18 does not influence the performance of the unit any more. It is up to the management to decide what the acceptable amount of time is the nurses have busy shifts. When using best fill and fill level 18, an average of 2263 overloaded shifts occur over a three year period. This means 68.88% of the shifts will be at least “busy”. Fill level 15 will result in an average of 1636 overloaded shifts, meaning that 50% of the shifts are at least busy.

Using acuity measurement, busy shifts can be supported by nurses from the other units who identify their unit as not very busy. This means that a larger amount of shifts can be “busy”, since the translation into real work can often be “normal”. Since the basic acuity-based policy has fewer options to expand the number of overloaded shifts and improve the average number of patients treated, best fill can be used to enhance the performance of the entire department, assuming nurses support each other and show great teamwork skills. As seen in Table 18, this may lead to 1 extra treated patient per day. For every treated patient receives the WKZ €2,521.70. Treating 1 patient per day extra can result in a yearly extra turnover of around €1,000,000.

### 5.4.6 Sensitivity Analysis

Now we have seen how the model responds to several experiments, we can start drawing conclusions and formulating recommendations. However, these conclusions rely heavily on the input data we have used in the simulation. Because our test period during which oud data was gathered was only 18 days, we have to test the importance of the quality of the data. This is done by means of a sensitivity analysis, in which we will alter two inputs to see how changes in the input data impact the results and conclusions we draw from the experiments. The two inputs that are subject to the sensitivity analysis are the number of patients entering the system per day, and the acuity distribution on arrival.

The number of patients that entered the system during the test period was 34. This results in a mean number of patients that arrive per day of 34/18. The sensitivity analysis is conducted by looking at the outputs for both the basic and best fill experiments when changing the arrival rate. The arrival rates for which we checked this were as if the test period was shorter and longer, ranging from 34 arrivals in 14 days to 22 days, with steps of 2 days. The results of these experiments are presented in Figures 28, 29, and 30.

All three graphs show the same trends for both policies. The average number of patients seems to converge more than the other two graphs, but for all graphs holds that the two lines do not cross each other. This means that while the arrival rate of the patients greatly influences the performance of both policies, the comparison between the two policies holds for adjacent values. We can thus conclude that for the conclusions and recommendations, the arrival rate we used as input is sufficiently reliable.

The second sensitivity analysis compares different values of acuity distribution on arrival. Because this means that we are altering up to six probabilities, three alternatives are compared to the basic situation. The first one is called “centered”, meaning that the probabilities are altered to favor levels 3, 4, and 5, instead of 2 and 6. The second alternative is “high”, which favors the probabilities for the higher levels of acuity. The third alternative is “low”, which favors the lower levels. The probabilities are given in Table 20. The results of these tests are presented in Figures 31, 32, and 33.

| Alternative | Level 1 | Level 2 | Level 3 | Level 4 | Level 5 | Level 6 |
|---|---|---|---|---|---|---|
| Normal | 0% | 3% | 40% | 25% | 25% | 7% |
| Centered | 0% | 0% | 45% | 25% | 30% | 0% |
| High | 0% | 0% | 35% | 25% | 30% | 10% |
| Low | 0% | 10% | 45% | 25% | 20% | 0% |

**Table 20: Experimental Probabilities for Acuity Distribution on Arrival**


**Figure 25: Basic vs Best-Fill Rejections**

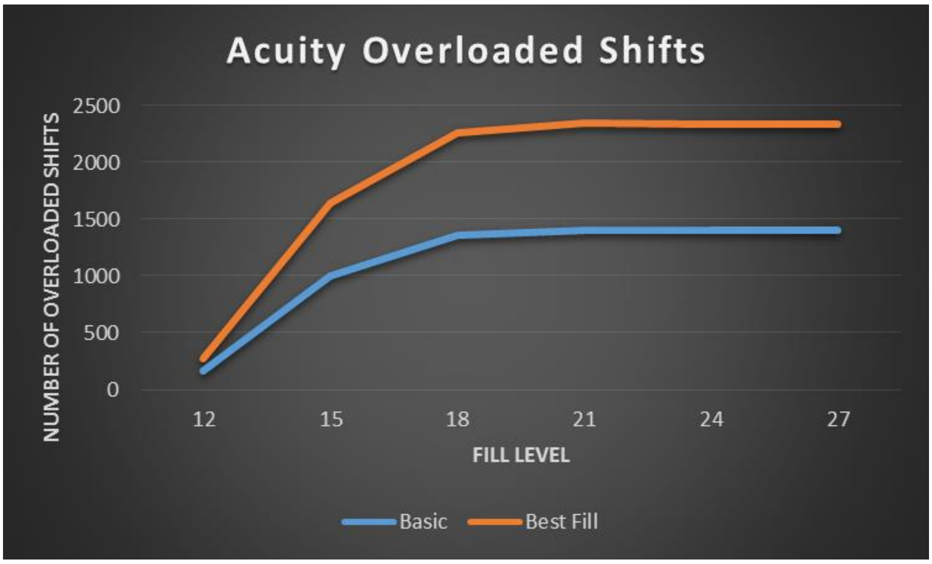



**Figure 26: Basic vs Best-Fill Acuity Overloaded Shifts**

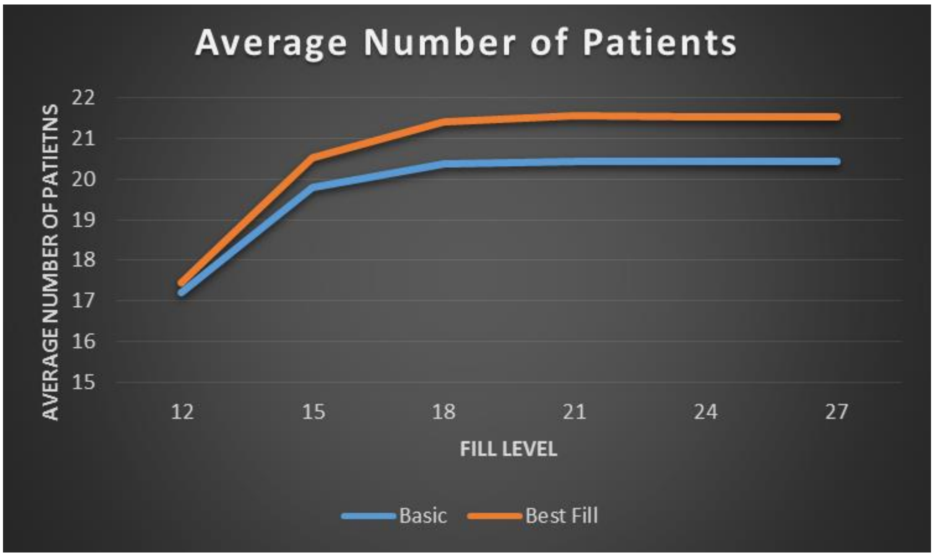



**Figure 27: Basic vs Best-Fill Average Number of Patients**


**Figure 28: Rejections for Changing Arrival Rate**

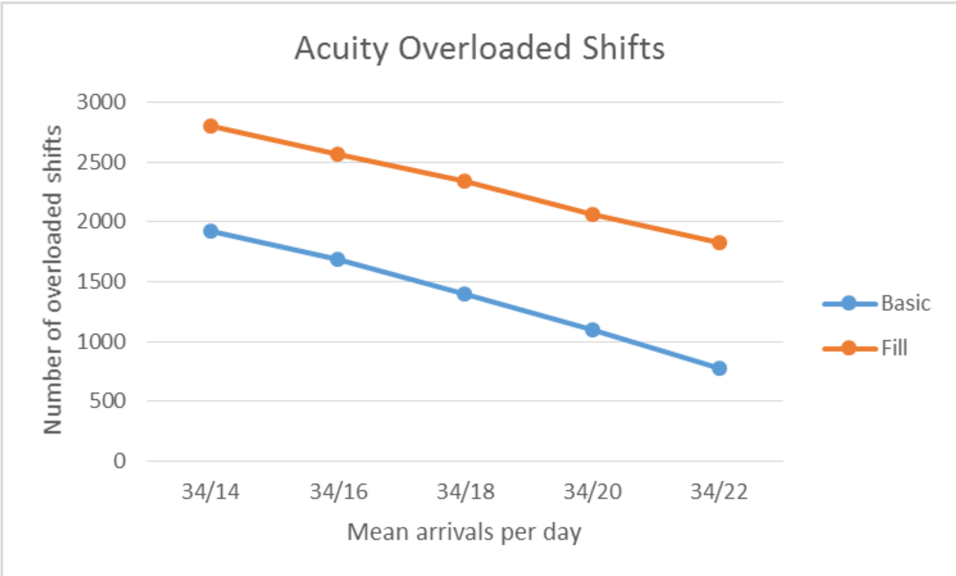



**Figure 29: Acuity Overloaded Shifts for Changing Arrival Rate**

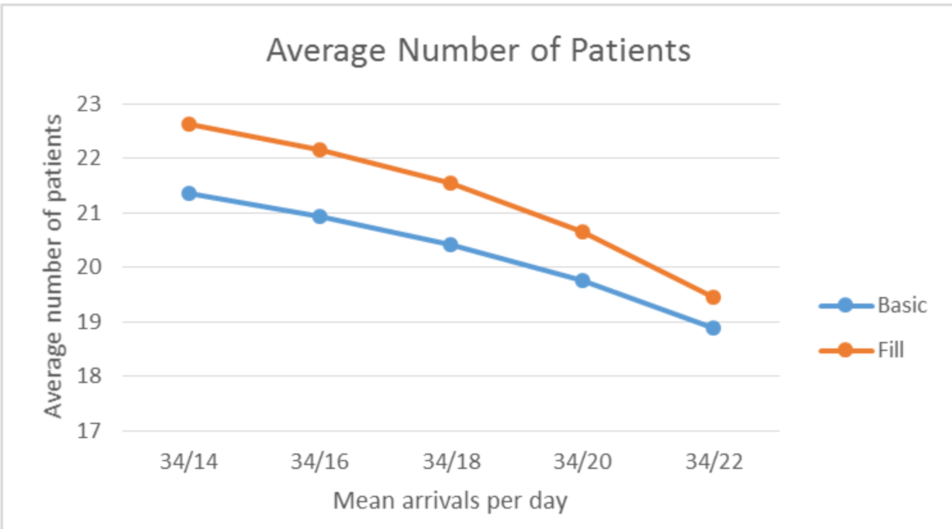



**Figure 30: Average Number of Patients for Changing Arrival Rate**

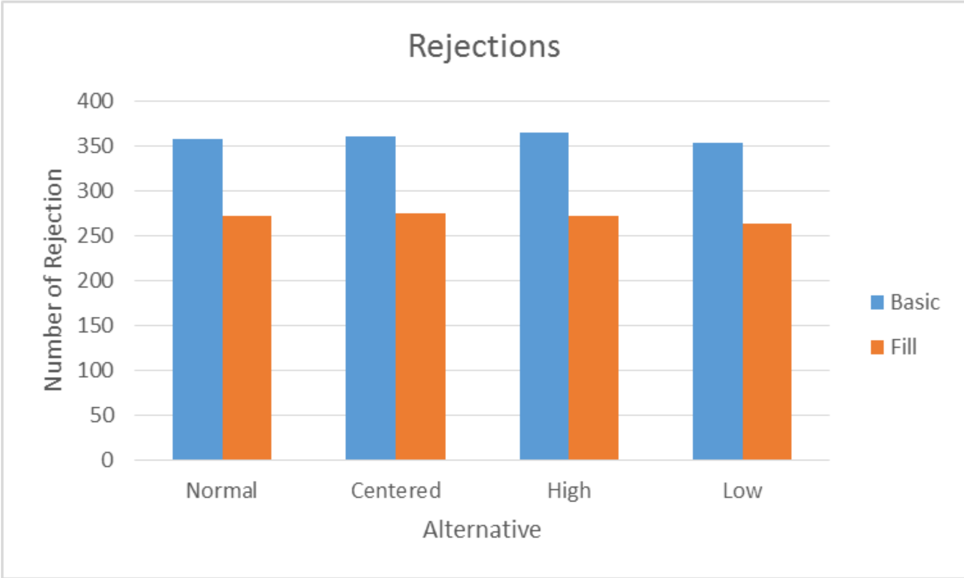



**Figure 31: Rejections for Changing Acuity Distribution on Arrival**

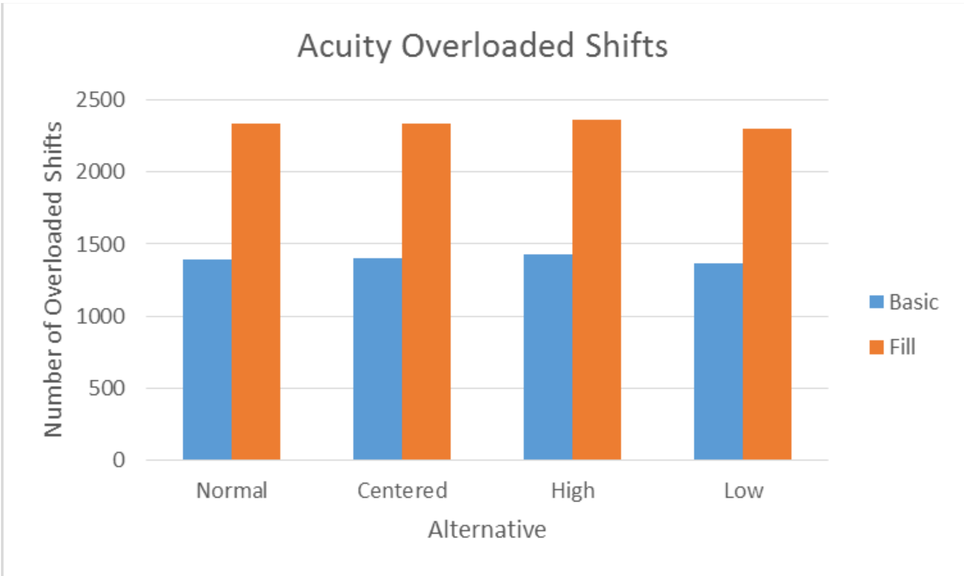



**Figure 32: Acuity Overloaded Shifts for Changing Acuity Distribution on Arrival**

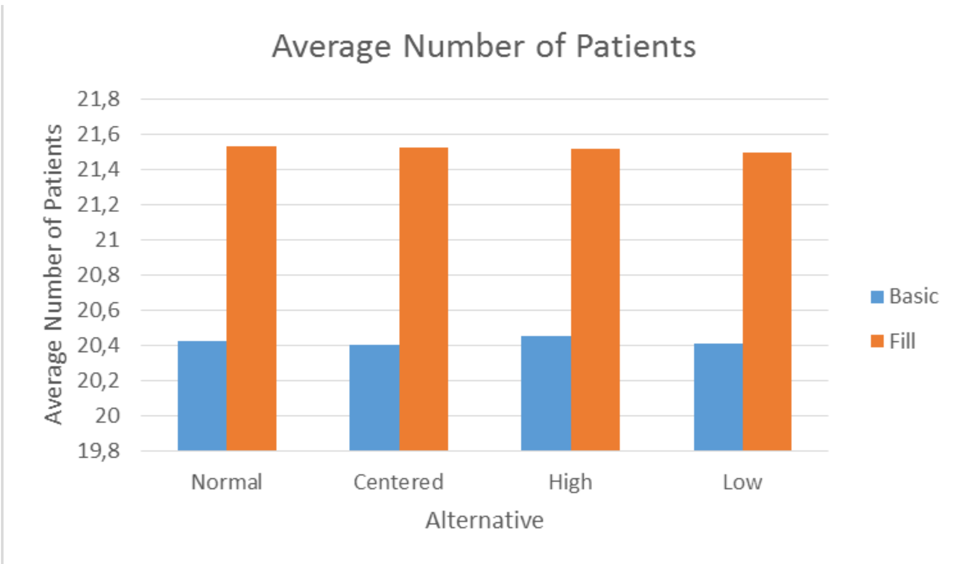



**Figure 33: Average Number of Patients for Changing Acuity Distribution on Arrival**

On basis of the figures, we verify visually that the outputs of all alternatives are not very different. We can assume that the acuity distribution among arrivals is not important for the absolute results, and therefore does not affect the conclusions and recommendations we draw from the experiments.

## 5.5 Conclusion

This chapter explained that the acuity measurement enables a simulation model to statistically compare several policies. The experiments in this chapter showed that using acuity as support for the decisions regarding patient placement and NICU capacity management has several implications for the performance of the NICU. When not minding the acuity at all and just focusing on the available beds, the units will end up with more patients, more busy shifts, but fewer rejections than when using acuity. When using acuity to decide to which unit the patient should be admitted, the hospital can choose between an equal filling level and a best fill option. There are more policies possible, but we chose to experiment with these two. The best fill option results in more busy shifts then the equal filling, but has fewer rejections and a higher average number of patients.

Because the acuity measurement enables nurses to identify the moments at which they help other units when they themselves have time to spare, the overloaded shifts in the best fill policy are likely to be coped with by simply transferring nurses between units during shifts. When one unit is quiet, it can spare one nurse to support a busy unit. The experiments in this simulation shows that the average number of patients can potentially rise with 1.12 patient, while the number of rejections can be reduced by 25%. Since one additional patient for one day results in an extra revenue of €2,521,70, the total amount of extra revenue per year can amount to a little over €1,000,000.

The level of acuity to which each unit is filled is a tradeoff between utilization and rejections, but this tradeoff is the same for both the best fill and equal filling options. The data we have gathered is slightly adjusted to enhance the validity of the dataset. The transition matrix that is used in the simulation is a little different from the observations. The other inputs, the arrival rate and the acuity distribution among new patients were proven to not be significantly important to impact the conclusions we have drawn above.

# 6. Conclusions and Recommendations

This chapter summarizes the previous chapters and provides the answers to the research questions. The limitations of this research will follow the conclusions. Practical recommendations for the NICU are given, as well as some recommendations for further research.

## 6.1 Research Questions

Chapter 1 discusses seven research questions that are answered throughout the other chapters. This section will summarize the conclusions of all chapters and answer the research questions.

In Chapter 2 we saw that the NICU is a complex work environment where prematurely born babies and babies born in need of IC care are treated. The organization of care is done by medical professionals, with help from supporting departments. Important decisions regarding patient logistics and scheduling are also made by medical experts. There are two important drawbacks of the current decision-making process: the medical experts having a limited knowledge of and insight in logistical processes, and the lack of objectivity in current workload approximations. Research question 1 is answered throughout this chapter. Research question 2 is answered by introducing the three stakeholders staff, patients, and management. Each of these stakeholders has its own performance indicator, but we conclude that a main problem of the NICU is that quality of work, the staff's measure of performance, cannot yet be measured.

Chapter 3 introduced acuity and patient classification models. A lot of models exist, but due to several requirements, only few are applicable to the WKZ. This was the answer to research question 3. The model we can use should be easy to use, quantifiable, accurately representing the nurses' workload, and be applicable to the entire perinatal division (research question 4). We combined two models to create a classification system that fulfills all requirements. Each patient will be scored for that shift for the number of similar patients a nurse can work on simultaneously, including several factors. This results in a total number of nurses that are needed for a unit or the entire division (research question 5).

The performance of the model can be measured by tests on alignment, reliability, and validity. These features are tested in a three-day pilot, followed by a two-week test period. Reliability means that the model is generalizable for all nurses. This is measured by the percentage of absolute agreement of pairwise comparisons of the patient classifications. This was 55.8% during the pilot, and 67.0% during the test period. Both were judged to be sufficient. Validity was measured by comparing the results of the classifications to the perception of workload. This proved to be significantly correlated for both tests. Alignment is the way the model's results agree with the actual performance. This answers research question 6.

Chapter 5 discussed the simulation experiments in which several policy changes were tested and compared statistically. Using an acuity measurement system enables the nurses to better use their capacity, and to identify idle time during which they can either help each other or work outside the ward. The experiments indicated that basing decisions on acuity causes fewer overloaded shifts, but costs utilization and rejections. These effects can be countered by not distributing the patients equally over all units and, instead using a best-fill policy. This way a higher utilization and a lower number of yearly rejections can be realized, while coping with the overloaded shifts by identifying idle nurse time. The fill level can be used to tune the actual situation, reach the maximum number of overloaded shifts accepted, and obtain the maximal utilization (research question 7).

## 6.2 Limitations and Assumptions

A couple of limitations to this research should be mentioned. The first limitation is the dataset that is used for the simulation experiments. It is proven that the reliability of the transition matrix is very important for the expected time a patient spends in the system, and can influence the experiments significantly. Section 5.2.5 assumes the effect to be comparable to changing the arrival rate, but this is not tested. It is hard to research the effect of changes in the matrix on the recommendations that can be made from the experiments. We have to assume that the transition matrix represents the patient flow throughout the year. This assumption could be verified by using a longer period of data gathering.

The experiments do not take into account that the NICU works with three shifts, which we have proven to differ significantly from each other in average acuity level. Another factor is the number of available nurses, which is fixed in the experiments, but in reality varies from shift to shift. The effects of these factors on the conclusions of this research cannot be predicted. The simulation also does not allow patients to be transferred over units when admitted, which happens sometimes.

## 6.3 Recommendations

From the conclusions from Section 6.1 we can draw several recommendations:

- <u>Introduce the acuity measurement system.</u> Tests have proven that the model is reliable and valid, and that it introduces several benefits on the operational planning level. Firstly, it prevents unjustified refusals and unjustified admittances. This helps the department plan the organization of care and reduce variability in demand. Secondly, the model helps the nurses identify time they can spend supporting others, doing administrative tasks, or working on projects. The accuracy and value of the system will improve over time as nurses get more acquainted to the classifications and agree on a benchmark or performance indicator based on the acuity measurement. For the implementation of the system are several factors to be coped with:
  - <u>Loss of autonomy.</u> During and after the test period were there nurses who were afraid that using acuity measurement would be leading in the determination of the requirements of nurses. Acuity measurement will not be introduced at the WKZ for this reason, but to better utilize the existing number of nurses. This should be emphasized when introducing the model and is crucial for the nurses to understand to secure their involvement.
  - <u>Scoring too busy.</u> When the nurses think that the measurement can have such an impact on the management that the number of nurses attending each shift will change can the nurses score too busy. When the average scores are higher than acceptable should be analyzed how this can be adjusted, but hiring more nurses should be considered a last option. The involvement of the nurses should make them understand that they themselves benefit the most from truthful ratings.
  - <u>Scoring too quiet.</u> When the nurses believe that the measurement will be used to evaluate their performance can they score too quiet, overestimating their own capacity. This is obviously undesirable. Because not every single nurse needs to score, but only the coordinating nurse, will this not be possible. This is important to communicate immediately to the nurses, since it can help reduce their resistance to using acuity measurement.

- Benchmark all performance indicators. In order to improve the performance of the NICU, it is important to not only measure the performance, but to also benchmark this performance. This research enables measurement of all performance indicators, so the recommendation is to do so, and agree on acceptable scores and target scores for all indicators. This helps setting goals, which makes improvements more easily accomplished.
- Use a best-fill policy. Because the use of the measurement system helps nurses support each other overloaded shifts can be better coped with. A best-fill policy comes with more overloaded shifts, but also leaves at least one unit with spare time. The benefits of introducing this assignment policy can be up to 30% less refusals and over €1,000,000 of raised revenue.
- Explore more research areas within healthcare logistics. This research was an exploratory first project to see whether the department could benefit from healthcare logistics. The introduction of the measurement system introduces several opportunities to do further research on the tactical planning level, all of which could be very valuable for the NICU. My experience on the NICU was that those involved with the research were enthusiastic and motivated to reach the research goals, but I also experienced the resistance against new research opportunities and change. This stretched the timespan of the research, particularly since the main motivation was to make an actual contribution to the department. I would like to emphasize the mission statement of the department, which clearly states that the department wants to "*deliver top care and subsequently academic research to both woman and baby*". I am convinced that this research contributes to facilitating top care, and would like to encourage the department to expand their efforts in this research area.

## 6.4 Further Research

As stated above, the department could benefit from more research in the field of healthcare logistics. The current research introduces the acuity measurement model, and explores the use of a best-fill policy, both of which are improvements. However, there are several other factors that can influence the NICU's performance and may be worth researching further, based on the results of this research.

- Include the MC and HC in the simulation. A lot of patients go to the MC and HC when transferred from the NICU. This means that availability at the MC and HC is a contributing factor in the patient flow. These units do not have the equipment or specialized nurses to provide all care necessary for NICU patients. Training these nurses and purchasing equipment may promote patient flow. These factors could contribute to a more efficient NICU, and may be worth researching.
- Shifting patients between units. This already happens sometimes, for instance to place twins next to each other. If for every admittance we allow a certain number of inter-unit transfers, could the units better be filled. This flexibility may be worth the trouble, but it is hard to predict how often the department will benefit from the transfers, and how large the benefits will be.
- Assigning some activities to the evening- and nightshifts. We have seen that nurses prefer the evening- and nightshifts over the dayshifts. Researching which activities can be shifted to the other shifts can ultimately lead to fewer overloaded shifts. This will in time allow the management to re-evaluate the fill-level, in order to raise utilization and further reduce rejections.

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# Appendix A: WANNNT

- Level 1 (0.25 nurse)
  - Postnatal care of healthy term newborn with or without phototherapy
  - Peripheral intravenous to heplock with two or less piggyback meds (i.e. antibiotics)
  - Has met discharge criteria
  - Healthy infant with significant social issues
- Level 2 (0.3 nurse)
  - $O_2$ therapy and oximetry
  - Cardio-respiratory monitoring
  - Peripheral intravenous with two or less solutions
  - Peripherally inserted central catheter (PICC)/cutdown central venous line
  - Total parenteral nutrition (TPN)
  - Uncomplicated gavage/breast/bottle feeds
  - Uncomplicated chronic stable ostomy
  - Neonatal abstinence scoring
  - Convalescing infant with parents requiring teaching
  - Hyperbilirubinemia with high potential for exchange transfusions
- Level 3 (0.5 nurse)
  - Stable nasal continuous positive airway pressure (NCPAP) or stable trach to continuous positive airway pressure (CRAP)
  - Frequent cardio-respiratory events
  - Umbilical venous line
  - Feeding: significant difficulty or intensive parent education
  - Complicated ostomy care/appliance changes/complex skin care
  - Unstable infant of a diabetic mother (IDM) with frequent blood glucose monitoring
  - Unstable with handling
  - Active neonatal withdrawal syndrome
- Level 4 (0.7 nurse)
  - Mechanical ventilation – stable with few changes and/or weaning
  - Unstable NCPAP potentially requiring intubation
  - Frequent significant cardio-respiratory events
  - Invasive pressure monitoring
  - Stable blood pressure on one vasopressor with few changes
  - Cardiac anomaly requiring prostaglandin infusion
  - Single chest tube
  - Seizures
  - Intensive oxygen management with >10 adjustments/hour
- Level 5 (1.0 nurse)
  - Isolation requiring 1 : 1 care
  - External ventricular drain requiring frequent adjustments
  - Mechanical ventilation endotracheal tube (ETT) or trach with unstable respiratory status requiring frequent blood gases and vent changes
  - Nitric oxide
  - Haemodynamically variable with up to two inotropes
  - Peritoneal or haemodialysis
  - Multiple chest tubes
  - Consistently high pain/agitation scores
  - End-of-life care/active advanced care planning
- Level 6 (1.5 nurse)
  - Haemodynamically extremely unstable requiring more than two inotropes with frequent changes, i.e. >one change/hour
  - Postoperative cardiac surgery (excluding patent ductus arteriosus (PDA)) for first 24 hours
  - Extracorporeal membrane oxygenation (ECMO)
  - Active disseminated intravascular coagulation (DIC) with frequent blood products
  - Continuous fluid boluses and changes

**Figure 34: WANNNT Classifications**

# Appendix B: PCS of Harper and McCulley

**Patient Classification System**
**Acuity Rating Scale**

Room: _____ Date: _____

Initials: _____ Time: _____

| ACUITY | 1 | 2 | 3 | 4 | Score |
|---|---|---|---|---|---|
| MEDICATIONS | 1-5 | 6-10 | 11-15 | >16 | ____ |
| COMPLICATED PROCEDURES | o Neuros Q4<br>o Foley<br>o Suction | o Picc<br>o NGT<br>o Central Line<br>o Incontinent<br>o Respiratory Monitoring<br>o PCA | o Neuros Q2<br>o Trach<br>o Freq. ____<br>o Wound/skin Care<br>o Telemetry<br>o Assist w/ADL<br>o CBI | o Total Care<br>o Isolation<br>o Restraints<br>o Feeder<br>o Confused<br>o Sundowners<br>o Falls Risk<br>o RRT | ____ |
| EDUCATION | o Standard | o CHF<br>o DM<br>o CAP<br>o Smoking | o Planned DC<br>o Family Educ.<br>o Pre/Post procedure | o New diagnosis<br>o Inability to comprehend<br>o Multiple chronicities | ____ |
| PSYCHOSOCIAL | o Depression | o Bipolar | o Palliative Care | o Personal/family dynamics | ____ |
| COMPLICATED IV'S & MEDS | o IDDM | o 2–5 IV meds | o K Rider<br>o Heparin<br>o >5 IV meds<br>o TPN<br>o Lipids | o Blood<br>o Tube feeding<br>o Cardiac drip | ____ |
| TOTAL | | | | | ____ |
| DIVIDED BY 5 | | | | | ____ |

Figure 35: PCS of Harper&McCulley

# Appendix C: Experiment Results

Some sections in the report refer to the results of the experiments or work with summaries of those results. To increase the understandability of those results will this section give the results of the basic situation of the first experiment as illustration for all experiments. Because it is unnecessary to fill over 20 pages with these results is chosen to only give the results of one experiment.

| Run number | Number of rejections | Acuity Overload | Average number of patients |
|---|---|---|---|
| 1 | 338 | 1358 | 20.38 |
| 2 | 280 | 1288 | 20.36 |
| 3 | 355 | 1375 | 20.4 |
| 4 | 420 | 1587 | 20.73 |
| 5 | 369 | 1386 | 20.41 |
| 6 | 364 | 1518 | 20.7 |
| 7 | 375 | 1449 | 20.54 |
| 8 | 383 | 1478 | 20.65 |
| 9 | 329 | 1365 | 20.5 |
| 10 | 338 | 1377 | 20.43 |
| 11 | 364 | 1381 | 20.25 |
| 12 | 383 | 1427 | 20.42 |
| 13 | 355 | 1487 | 20.47 |
| 14 | 389 | 1401 | 20.37 |
| 15 | 401 | 1401 | 20.31 |
| 16 | 300 | 1277 | 20.34 |
| 17 | 332 | 1383 | 20.46 |
| 18 | 329 | 1335 | 20.23 |
| 19 | 393 | 1457 | 20.55 |
| 20 | 346 | 1344 | 20.28 |
| 21 | 345 | 1405 | 20.34 |
| 22 | 363 | 1227 | 20.19 |
| | | | |
| Average | 356.86 | 1395.73 | 20.42 |
| St. Deviation | 32.77 | 81.21 | 0.14 |

**Table 21: Results Experiment 1: Basic**

# Appendix D: Transition Matrix

Every patient that is rated is categorized in one of the six levels. Each shift, due to patient characteristics or external factors, this level can change. For most patients will the patient characteristics improve over time, working towards a transfer from the NICU. To imitate this process has every patient in the simulation an attribute called “acuity”. This attribute represents the latest categorization of that patient. Every eight hours is this attribute changed, and with that attribute changes the total acuity level on the unit. The probabilities that a patient changes from one level to another the next shift is represented in the transition matrix.

In order to calculate these probabilities, all observations from nurses in adjacent shifts are compared, and each transition is noted in the observations matrix. This matrix is presented in Table 22. Cell [c,r] is the amount of times that a patient had an acuity level of c at time I, and r at time i+1. This resulted in a total of 280 observations, with the majority of the observations on levels 3 and 4.

| | 1 | 2 | 3 | 4 | 5 | 6 | Transfer | Total |
|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 2 |
| 2 | 1 | 8 | 20 | 9 | 0 | 0 | 1 | 39 |
| 3 | 0 | 26 | 67 | 25 | 1 | 0 | 5 | 124 |
| 4 | 1 | 12 | 44 | 32 | 4 | 2 | 2 | 97 |
| 5 | 0 | 1 | 6 | 6 | 3 | 0 | 0 | 16 |
| 6 | 0 | 0 | 1 | 5 | 0 | 0 | 0 | 6 |
| | | | | | | | | 280 |

**Table 22: The Observed Transitions**

Translated into probabilities, the transition matrix is given in Table 23.

| | 1 | 2 | 3 | 4 | 5 | 6 | Transfer |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0.5 | 0 | 0 | 0.5 |
| 2 | 0.025641 | 0.205128 | 0.512821 | 0.230769 | 0 | 0 | 0.02564103 |
| 3 | 0 | 0.209677 | 0.540323 | 0.201613 | 0.008065 | 0 | 0.04032258 |
| 4 | 0.010309 | 0.123711 | 0.453608 | 0.329897 | 0.041237 | 0.020619 | 0.02061856 |
| 5 | 0 | 0.0625 | 0.375 | 0.375 | 0.1875 | 0 | 0 |
| 6 | 0 | 0 | 0.166667 | 0.833333 | 0 | 0 | 0 |
| Transfer | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

**Table 23: The Transition Matrix**

See appendix B for the transition matrix adjustments.

# Appendix E: Absorbing Markov Chain Calculations

Each patient will over time be scored for several levels of acuity, until eventually the patient leaves the NICU. This process can be represented in a Markov chain. A Markov chain is a process that jumps from state to state within a predetermined series of states. For each state is there a different set of probabilities in which the process can be at the next moment. The transition matrix can be seen as a Markov Chain. Each patient finds itself to be in a certain state, and has a probability of being a different level of acuity the next shift.

The transition matrix is a special kind of Markov chain, it is an absorbing Markov chain. This means that there is one state where, once reached, the process never leaves that state. When a patient leaves the NICU, we end the chain and never leave that state again. Returning patients can be treated as new patients in this theory. For absorbing Markov chains can be calculated what the average amount of steps is from each single state to reach the absorbing state. Translating to the NICU can we calculate for each level of acuity what the expected time is for a patient to be in the ward.

The calculations for this amount of steps is as follows. First, name the probability matrix for all transient (non-absorbing) states, Q. Subtract this matrix from the pivot matrix I, and take the inverse:

$$N = (I - Q)^{-1}$$

These calculations are done in excel. Table 24 gives Q, Table 25 N.

| | 1 | 2 | 3 | 4 | 5 | 6 | Transfer |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0.5 | 0 | 0 | 0.5 |
| 2 | 0.025641 | 0.205128 | 0.512821 | 0.230769 | 0 | 0 | 0.025641 |
| 3 | 0 | 0.209677 | 0.540323 | 0.201613 | 0.008065 | 0 | 0.0403226 |
| 4 | 0.010309 | 0.123711 | 0.453608 | 0.329897 | 0.041237 | 0.020619 | 0.0206186 |
| 5 | 0 | 0.0625 | 0.375 | 0.375 | 0.1875 | 0 | 0 |
| 6 | 0 | 0 | 0.166667 | 0.833333 | 0 | 0 | 0 |

**Table 24: Q**

| | | | | | |
|---|---|---|---|---|---|
| 1.1093567 | 2.5880116 | 7.2655929 | 4.1707531 | 0.2837948 | 0.0859949 |
| 0.2318057 | 6.1900565 | 14.36429 | 7.0893683 | 0.5023829 | 0.1461725 |
| 0.2054099 | 5.1859766 | 15.362336 | 7.0263053 | 0.5090884 | 0.1448723 |
| 0.2187135 | 5.1760232 | 14.531186 | 8.3415063 | 0.5675897 | 0.1719898 |
| 0.2135804 | 5.2586196 | 14.901955 | 7.6381721 | 1.7663424 | 0.1574881 |
| 0.2164962 | 5.1776821 | 14.669711 | 8.1223061 | 0.5578395 | 1.1674702 |

**Table 25: N**

The expected number of steps from each transient state is now the sum of each row. See Table 26.

| Level | Number of steps |
|---|---|
| 1 | 15.50350409 |
| 2 | 28.52407553 |
| 3 | 28.43398818 |
| 4 | 29.00700819 |
| 5 | 29.93615798 |
| 6 | 29.91150485 |

Table 26: Expected Number of Steps

Each step is one shift, so the expected number of days is the expected number of steps divided by three. We also have the distribution of acuity levels on arrival. The expected length of stay should thus be the sum of the probability of arriving being a level times the expected number of days from that point. See Table 27. This results in an average length of stay of 9.68 days.

| Level | Number of days | Arrival probability | | |
|---|---|---|---|---|
| 1 | 5.167834698 | 0 | 0 | |
| 2 | 9.508025177 | 0.03 | 0.2852408 | |
| 3 | 9.477996061 | 0.4 | 3.7911984 | |
| 4 | 9.669002729 | 0.25 | 2.4172507 | |
| 5 | 9.978719327 | 0.25 | 2.4946798 | |
| 6 | 9.970501618 | 0.07 | 0.6979351 | |
| | | | 9.6863048 | Average stay |

Table 27: Average Stay Calculation

As stated in Chapter 5, the average length of stay at the NICU in the Netherlands in 2008 was 15 days. To approach this number have we taken a look at the matrix and adjusted the probabilities of leaving the NICU. These were overestimated because some transferals were included when there was no data available, but the patient was transferred in a later shift when the nurses did score the patients. Table 28 shows these adjustments.

| Level: | Old amount | New amount |
|---|---|---|
| 1 | 1 | 1 |
| 2 | 1 | 1 |
| 3 | 5 | 2 |
| 4 | 2 | 2 |
| 5 | 0 | 0 |
| 6 | 0 | 0 |
| Total: | 9 | 6 |

Table 28: Adjusted Probabilities

This resulted in a new probability matrix, which through the same calculations as explained above resulted in an average stay of 14.95, which is a close approximation of the average over 2008.

We can then calculate the new Q and N:

| | 1 | 2 | 3 | 4 | 5 | 6 | Transfer |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0.5 | 0 | 0 | 0.5 |
| 2 | 0.025641 | 0.205128 | 0.512821 | 0.230769 | 0 | 0 | 0.025641 |
| 3 | 0 | 0.214876 | 0.553719 | 0.206612 | 0.008264 | 0 | 0.0165289 |
| 4 | 0.010309 | 0.123711 | 0.453608 | 0.329897 | 0.041237 | 0.020619 | 0.0206186 |
| 5 | 0 | 0.0625 | 0.375 | 0.375 | 0.1875 | 0 | 0 |
| 6 | 0 | 0 | 0.166667 | 0.833333 | 0 | 0 | 0 |

Table 29: New Q

| | | | | | |
|---|---|---|---|---|---|
| 1.1668218 | 4.0388297 | 11.28357 | 6.1364179 | 0.4262164 | 0.1265241 |
| 0.3454158 | 9.0583665 | 22.307949 | 10.975545 | 0.7839545 | 0.2262999 |
| 0.3269137 | 8.2535798 | 23.857928 | 11.182498 | 0.8102239 | 0.230567 |
| 0.3336436 | 8.0776595 | 22.567141 | 12.272836 | 0.8524328 | 0.2530482 |
| 0.331443 | 8.2342924 | 23.142951 | 11.669811 | 2.0584534 | 0.2406147 |
| 0.3325219 | 8.1069795 | 22.782272 | 12.091113 | 0.8453979 | 1.2493013 |

Table 30: New N

| Level | Number of steps |
|---|---|
| 1 | 23.1783802 |
| 2 | 43.69752998 |
| 3 | 44.66171028 |
| 4 | 44.35676039 |
| 5 | 45.67756569 |
| 6 | 45.40758537 |

Table 31: New Expected Number of Steps

| Level | Number of days | Arrival probability | | |
|---|---|---|---|---|
| 1 | 7.726126732 | 0 | 0 | |
| 2 | 14.56584333 | 0.03 | 0.4369753 | |
| 3 | 14.88723676 | 0.4 | 5.9548947 | |
| 4 | 14.7855868 | 0.25 | 3.6963967 | |
| 5 | 15.22585523 | 0.25 | 3.8064638 | |
| 6 | 15.13586179 | 0.07 | 1.0595103 | |
| | | | 14.954241 | Average stay |

Table 32: New Average Stay Calculation

Which results in an average stay of almost 15 days. We see in the simulation that the average length of stay is 13.25 (see Section 5.4.2). Due to the rounding of the probabilities in the transition matrix that is used in the simulation changes the expected average stay significantly:

| | 1 | 2 | 3 | 4 | 5 | 6 | Transfer |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0.5 | 0 | 0 | 0.5 |
| 2 | 0.03 | 0,2 | 0.51 | 0.23 | 0 | 0 | 0.03 |
| 3 | 0 | 0,21 | 0.55 | 0.21 | 0.01 | 0 | 0.02 |
| 4 | 0.01 | 0.13 | 0.45 | 0.33 | 0.04 | 0.02 | 0.02 |
| 5 | 0 | 0.06 | 0.38 | 0.37 | 0.19 | 0 | 0 |
| 6 | 0 | 0 | 0.17 | 0.83 | 0 | 0 | 0 |
| Transfer | 0 | 0 | 0 | 0 | 0 | 0 | 1 |

**Table 33: The Rounded Transition Matrix**

| | | | | | |
|---|---|---|---|---|---|
| 1.1627388 | 3.563048 | 10.002219 | 5.584738 | 0.3992737 | 0.1116948 |
| 0.339616 | 8.0499382 | 19.622912 | 9.8117813 | 0.7267906 | 0.1962356 |
| 0.3175505 | 7.2432491 | 21.171063 | 10.025301 | 0.7564477 | 0.200506 |
| 0.3254776 | 7.1260961 | 20.004439 | 11.169476 | 0.7985474 | 0.2233895 |
| 0.322806 | 7.2494895 | 20.523483 | 10.532132 | 2.0080495 | 0.2106426 |
| 0.32413 | 7.1460121 | 20.202765 | 10.974966 | 0.7913905 | 1.2194993 |

**Table 34: N for Rounded Transition Matrix**

| Level | Number of days | Arrival probability | |
|---|---|---|---|
| 1 | 6.941237582 | 0 | 0 |
| 2 | 12.91575802 | 0.03 | 0.3874727 |
| 3 | 13.23803921 | 0.4 | 5.2952157 |
| 4 | 13.2158085 | 0.25 | 3.3039521 |
| 5 | 13.61553439 | 0.25 | 3.4038836 |
| 6 | 13.55292105 | 0.07 | 0.9487045 |
| | | | 13.339229 Average stay |

**Table 35: Average Stay Calculation for Rounded Transition Matrix**

Which results in an average length of stay of 13.34 days. Because it has been proven that the rounding can be of significant importance are the calculations in this appendix made with this many digits.

# Appendix F: Replications

Each experiment that is simulated runs for a certain amount of days, for a certain amount of runs. Each run is another simulation of that amount of days with different random numbers. To determine the amount of runs that is necessary for a reliable result, we use the replication/deletion method (Law, 2009).

In this method, start by determining a large number of runs, which we will do for one experiment. For the three outputs, we take the running mean of all runs so far, and compare the 95% confidence interval half-width to that running mean. When the confidence interval half-width is smaller than 5% of the running mean, we have a sufficient amount of runs.

The formula for the confidence interval half-width:

$$\delta(n,\alpha) = t_{n-1,1-\alpha/2}\sqrt{S_n^2 / n}$$

Where n is the run number, a is the confidence level, and $S_n$ is the standard deviation of the results up to run number n.

And we look for the first run to suffice:

$$\delta(n,\alpha) / \bar{X}_n \leq \gamma'$$

Where $X_n$ is the running mean until run n and gamma is the error (5%).

For our basic scenario, this resulted in Tables 36, 37, and 38

. The number of rejections needs the largest number of runs to suffice the error margin, so we use that number of replications, which is 22 (see Table 36).

| Run number | Number of rejections | Mean | d(n,a) | d(n,a)/mean |
|---|---|---|---|---|
| 1 | 255 | 262.1153846 | | |
| 2 | 189 | 259.4074074 | 419.3047563 | 1.888760163 |
| 3 | 261 | 259.4642857 | 99.24122386 | 0.42230308 |
| 4 | 325 | 261.7241379 | 88.43823028 | 0.343449438 |
| 5 | 272 | 262.0666667 | 60.30448995 | 0.231584063 |
| 6 | 272 | 262.3870968 | 45.85765576 | 0.17480682 |
| 7 | 290 | 263.25 | 38.13877534 | 0.143225015 |
| 8 | 271 | 263.4848485 | 31.94880739 | 0.119714501 |
| 9 | 250 | 263.0882353 | 27.8158015 | 0.104965289 |
| 10 | 240 | 262.4285714 | 25.0528161 | 0.095439299 |
| 11 | 246 | 261.9722222 | 22.56918788 | 0.086471984 |
| 12 | 273 | 262.2702703 | 20.47034528 | 0.078131089 |
| 13 | 276 | 262.6315789 | 18.78739035 | 0.071414057 |
| 14 | 303 | 263.6666667 | 18.31379117 | 0.068867332 |
| 15 | 289 | 264.3 | 17.24471842 | 0.064474271 |
| 16 | 228 | 263.4146341 | 16.87079679 | 0.063663384 |
| 17 | 229 | 262.5952381 | 16.38836812 | 0.062341074 |
| 18 | 248 | 262.255814 | 15.47618513 | 0.059056886 |
| 19 | 279 | 262.6363636 | 14.69721371 | 0.055894127 |
| 20 | 260 | 262.5777778 | 13.89400948 | 0.052869138 |
| 21 | 279 | 262.9347826 | 13.2691914 | 0.050343816 |
| 22 | 245 | 262.5531915 | 12.73474807 | 0.048471359 |
| 23 | 259 | 262.4791667 | 12.13953513 | 0.046234361 |
| 24 | 246 | 262.1428571 | 11.68108331 | 0.044605569 |
| 25 | 275 | 262.4 | 11.23071877 | 0.042799995 |

**Table 36: Replication/Deletion: Rejections**

| Run number | Acuity Overload | Mean | d(n,a) | d(n,a)/mean |
|---|---|---|---|---|
| 1 | 1023 | 1023 | | |
| 2 | 947 | 985 | 482.83578 | 0.490188609 |
| 3 | 1058 | 1009.333333 | 140.9697994 | 0.139666248 |
| 4 | 1206 | 1058.5 | 172.9706654 | 0.163411115 |
| 5 | 989 | 1044.6 | 123.0958159 | 0.117840145 |
| 6 | 1147 | 1061.666667 | 102.8782406 | 0.096902581 |
| 7 | 1103 | 1067.571429 | 84.01661952 | 0.078698827 |
| 8 | 1100 | 1071.625 | 70.96397035 | 0.066220898 |
| 9 | 1051 | 1069.333333 | 61.2612036 | 0.057289155 |
| 10 | 1023 | 1064.7 | 54.7641935 | 0.051436267 |
| <u>11</u> | <u>971</u> | <u>1056.181818</u> | <u>52.3527016</u> | <u>0.049567888</u> |
| 12 | 1081 | 1058.25 | 47.42779466 | 0.044817193 |
| 13 | 1138 | 1064.384615 | 45.20879347 | 0.042474114 |
| 14 | 1098 | 1066.785714 | 41.82382054 | 0.039205456 |
| 15 | 1017 | 1063.466667 | 39.30504189 | 0.036959355 |
| 16 | 978 | 1058.125 | 38.27068704 | 0.036168399 |
| 17 | 982 | 1053.647059 | 36.9930626 | 0.035109539 |
| 18 | 1041 | 1052.944444 | 34.74303344 | 0.032996075 |
| 19 | 1110 | 1055.947368 | 33.32767302 | 0.031561869 |
| 20 | 987 | 1052.5 | 32.31440637 | 0.030702524 |
| 21 | 1096 | 1054.571429 | 30.93668064 | 0.029335785 |
| 22 | 915 | 1048.227273 | 32.23116319 | 0.030748259 |
| 23 | 1037 | 1047.73913 | 30.72960475 | 0.029329443 |
| 24 | 958 | 1044 | 30.34959395 | 0.029070492 |
| 25 | 1078 | 1045.36 | 29.17865987 | 0.027912547 |

**Table 37: Replication/Deletion: Acuity Overloaded Shifts**

| Run number | Average number of patients | Mean | d(n,a) | d(n,a)/mean |
|---|---|---|---|---|
| 1 | 20.42 | 20.42 | | |
| 2 | 20.32 | 20.37 | 0.63531 | 0.031188524 |
| 3 | 20.46 | 20.4 | 0.179134 | 0.008781065 |
| 4 | 20.69 | 20.4725 | 0.249023 | 0.012163803 |
| 5 | 20.37 | 20.452 | 0.177649 | 0.008686148 |
| 6 | 20.66 | 20.48667 | 0.161172 | 0.007867157 |
| 7 | 20.52 | 20.49143 | 0.130184 | 0.006353109 |
| 8 | 20.63 | 20.50875 | 0.116396 | 0.005675431 |
| 9 | 20.62 | 20.52111 | 0.104086 | 0.005072144 |
| 10 | 20.42 | 20.511 | 0.094148 | 0.004590118 |
| 11 | 20.1 | 20.47364 | 0.11818 | 0.005772306 |
| 12 | 20.31 | 20.46 | 0.110714 | 0.005411252 |
| 13 | 20.43 | 20.45769 | 0.100942 | 0.004934165 |
| 14 | 20.48 | 20.45929 | 0.092727 | 0.00453225 |
| 15 | 20.31 | 20.44933 | 0.088319 | 0.004318941 |
| 16 | 20.33 | 20.44188 | 0.083626 | 0.004090938 |
| 17 | 20.29 | 20.43294 | 0.080391 | 0.003934363 |
| 18 | 20.29 | 20.425 | 0.077271 | 0.003783135 |
| 19 | 20.52 | 20.43 | 0.073537 | 0.003599445 |
| 20 | 20.2 | 20.4185 | 0.073551 | 0.00360216 |
| 21 | 20.35 | 20.41524 | 0.070056 | 0.003431549 |
| 22 | 20.21 | 20.40591 | 0.069361 | 0.003399058 |
| 23 | 20.49 | 20.40957 | 0.066527 | 0.003259606 |
| 24 | 20.07 | 20.39542 | 0.069952 | 0.003429798 |
| 25 | 20.31 | 20.392 | 0.067312 | 0.003300892 |

**Table 38: Replication/Deletion: Average number of Patients**