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MASTER

Reducing intensive care unit refusals at a trauma care hospital

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Reducing intensive care unit refusals at a trauma care hospital

by

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in partial fulfilment of the requirements for the degree of

Master of Science
in Operations Management and Logistics for Health Care

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PREFACE

This report presents the results of the graduation project I executed to conclude the master Operations Management and Logistics at the University of Technology Eindhoven. The project was executed at the St. Elisabeth Hospital in Tilburg.

During secondary school I always wanted to do "something" with technology or health care. After writing the final exams, I choose the direction of technology. After four years of studying I became Bachelor of Engineering in Industrial Engineering. As I did not feel ready to enter the working life already, I decided to start the pre-master of Operations Management and Logistics.

The master enabled me to study abroad in Singapore (so far away!) and Berlin (history!). I believe both experiences were amazing. That is why, I am very thankful that I was able to do this: meeting new friends and travel. Next to these periods, I really enjoyed my years studying together with my fellow students in Eindhoven.

I would like to thanks my first supervisor Nico Dellaert for his time, his valuable input and criticism, for listening to my complaints and above all his motivational support. Also, I would like to thank Pieter van Gorp for being the second assessor of this project.

Next to the people from the university, I would like to thank the people from the St. Elisabeth Hospital. First of all, my supervisors Marc Beerens, Marloes Hendriks and Willem Wiegersma. Furthermore, I would like to say "thanks" to Charlotte, Erica, Ingeborg, Liesbeth, Mark, Monique and Piet i.e. the lunch group.

Last but certainly not least, my last "thank you" goes out to my family: mom, dad and brother Rens for their unconditional support.

Rik Mols

Eindhoven, August 2013

ABSTRACT

This report is a result of a master thesis conducted at the St. Elisabeth Hospital based in the Netherlands. The hospital management wants to reduce the number of refusals at the intensive care unit. This is consistent with the status of the hospital, a trauma care center.

State dependent predictions are used to make short term demand predictions for the intensive care unit. Two options for meeting the IC demand are investigated: early cancellations (time) by means of adaptive cap policies and flexibility of ICU capacity.

A simulation model is developed that determines the appropriate number of elective surgical arrivals in a certain week. Also, flexible capacity decisions based on de demand predictions are investigated by means of a simulation model.

MANAGEMENT SUMMARY

Introduction

The St. Elisabeth hospital is a hospital in Tilburg, North-Brabant. The key themes of the hospital are: Compassionate, Lean, Quality and Safety. Next to these themes, the hospital focuses on both trauma and neuro care and wants to excel in these disciplines. The hospital is one of the ten trauma care centers in the Netherlands.

Intensive care unit

The intensive care unit of the St. Elisabeth hospital consists of 34 single rooms. 24 of the rooms are facilitated to provide intensive care and 10 of the room are facilitated to provide medium care. The intensive care differs from medium care as it is equipped with mechanical ventilation. Also, the nurse-patient ratio is larger for intensive care beds. 30 staffed beds can be operated structurally. The management question that can be seen as the trigger for this master thesis is formulated as follows.

Management question

How can the number of refusals be minimized, given the current budget?

Research questions

After conducting a literature review, the attentions was focused on the elective surgical admissions arriving from the operating theatre after surgery. These can be controlled to some extent. Also, flexibility of the ICU got attention. Research questions were formulated.

1. How should the adaptive cap policy, based on state dependent predictions, be designed for the St. Elisabeth Hospital?
    - What is the length of the scheduling horizon?
    - What is the length of the prediction horizon?
2. Can the adaptive cap policy reduce the number of refusals / late cancelled surgeries?
    - What are the advantages?
    - What are the disadvantages?
3. To what extent does the flexibility of the ICU capacity reduce the number of refusals/late cancellations?

The research questions were input for the qualitative and quantitative analysis.

Qualitative analysis

The total available operating time is divided across medical disciplines. The medical disciplines own their operating time (block schedule) and can schedule their patients freely. The medical disciplines in the hospital scheduled their patients independently of each other.

Medical disciplines neurosurgery, general surgery, orthopedics and urology accounted for respectively 53%, 24%, 7% and 6% of the elective surgical admissions in 2012. The surgery schedulers of these medical disciplines are interviewed regarding elective surgical IC patients.

One out of four surgery schedulers acknowledges the need to level the number of elective surgical IC patients. This scheduler's attention is limited to the own medical discipline. The other three schedules do not consider postoperative stay at the ICU as a decision variable. Overall, no coordination or communication takes place between the medical disciplines about this issue.

If a patient needs surgery an admission request is completed by a medical specialist. The medical specialist whether the postoperative stay at the IC is needed. A preliminary surgical date is agreed with the patient by a policlinic nurse. Also, the patient needs to undergo an assessment at the preoperative screening. Outcome of the assessment can be that the patient needs to stay at the ICU postoperative. Every day the schedulers finalize the surgical schedules (for tomorrow) and send it to the operating theatre (OT). At the OT, the schedules are consolidated to a day schedule.

The next morning (before schedule execution) the floor manager of the OT contacts the ICU to reach agreement about the number of elective surgical IC patients. The floor manager needs this to start the surgical schedule. If more patients needs IC than the ICU can award, these patients are processed by altering anesthetic treatment, change sequence of the schedule and wait for a freed bed at the ICU or cancel the surgery.

Quantitative analysis

Data on IC admission is collected and analyzed. Also, data on the number of surgeries and IC indicated surgeries is gathered and investigated. All data stem from 2012.

- Unscheduled admissions accounted for 62% of the admissions and 81% of the bed days.
- Scheduled admissions accounted for 38% of the admissions and 19% of the bed days.
- The number of IC indication was positively related to the number of surgeries.
- The number of IC indications did not match the number of elective surgical arrivals in around 2/3 of the surgical days.

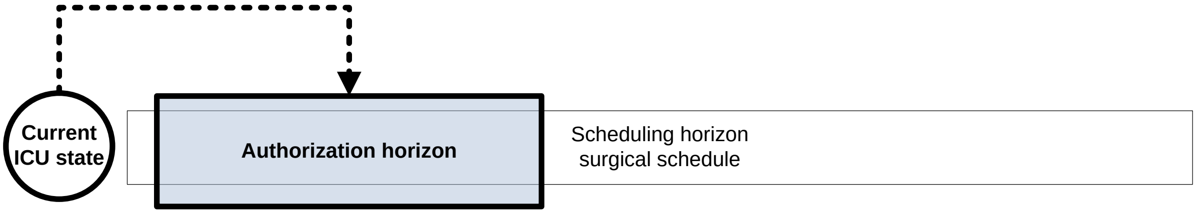
- The number of refusals/late cancellations was estimated to be around 60. The total number of admissions in 2012 was 2,381.

Results

The length of the scheduling horizon is between four to six weeks for most of the medical disciplines. Neurosurgery has a shorter scheduling horizon: two to three weeks.

The length of the prediction horizon i.e. time in the future that prediction is meaningful is considered to be seven days. The future state of the ICU depends on the current state of the ICU. However, as 90% of the patients stay shorter than one week, the future state in two weeks does not depend much on the current state.

The length of the prediction and scheduling horizon has consequences for the adaptive cap based policy. As the prediction horizon is rather short and patients are scheduled up to three weeks from now an authorization horizon was considered (see figure below).



Based on the current state and surgical schedule a number of simulations are executed. The outcome of simulation indicates whether the surgical schedule would cause capacity problems. As the capacity is considered fixed, the surgical schedule should be adapted accordingly by removing or adding patients. Removing would mean early cancelling. Early cancelling is always considered to be preferred over late cancelling.

The advantage of the adaptive cap policy is that it could reduce the refusals and late cancellations at the intensive care unit. Early cancellations could also mean that less operating time is lost (there is more time to fill the lost operating time).

The disadvantage is that the adaptive cap policy in its current form requires great flexibility of the medical disciplines. On the one hand, scheduled patients could be removed from the schedule within the authorization horizon. On the other hand, scheduled patients need to be added in case of low demand at the ICU.

All in all, the idea is that the variability in the demand for IC is buffered in the surgical schedules.

Having defined the patient categories, arrival and length of stay distribution, the demand distributions for the next seven days were calculated. These calculations can be input for decision about capacity.

A flexible ICU was assumed where beds are opened and closed based on state dependent predictions. Two important variables are the lead time and the buffer capacity that is needed. The lead time is the time needed to adapt the capacity. The buffer capacity is the number of beds in addition to the expected demand to buffer variability. A fixed capacity scenario was compared to four flexible scenarios. Results indicated that reduction in both late cancellations and refusals was possible, even with a smaller average number of staffed beds.

Recommendations

In the light of the status of the hospital, a trauma care center, it could be worthwhile implementing an adaptive cap policy. However, additional research is needed about patient that can be removed (postponed) from the schedule safely.

Although several researchers have concluded the usefulness of leveling the demand caused by the elective surgical schedule, this idea has not been implemented In the St. Elisabeth Hospital.

The demand caused by the elective surgical schedule should receive some extra attention. Currently, the number of IC indications per day deviates from the elective surgical IC admissions in 2/3 of the days. The number of elective surgical arrivals at the ICU is a function of the surgical schedule.

A first step would be to define the probability distribution for a particular surgical schedule. The second step would be to include the probability distribution in the demand predictions for the ICU. Input to the demand predictions should be patient categories with arrival and length of stay distributions. Based on the demand prediction a number of staffed beds could be chosen.

After describing the demand caused by the surgical schedule, a limit could still be imposed to level the resulting demand as much as possible. This would reduce the amount of flexibility that is needed for the capacity of the ICU.

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1 INTRODUCTION

This chapter introduces the field site, St. Elisabeth Hospital and its intensive care. The management question that can be seen as the trigger for this report is provided. After that, the structure of the report is given.

1.1 ST ELISABETH HOSPITAL

St. Elisabeth Ziekenhuis is located in the southeast of Tilburg. First, some facts and figures of the hospital of the year 2011:

- 3,143 employees
- 191 medical specialists
- 162 physician assistants
- 73 volunteers
- 28 medical disciplines
- 119,000 outpatient patients
- 20,000 admitted patients
- 16,500 day care patients
- € 231 M revenue

The hospital management has formulated four key themes: “Compassion, Lean, Quality and Safety” (Lief, Lean, Kwaliteit en Veiligheid). These themes have got attention in the last years. Next to these key themes, the hospital focuses on both trauma and neuro (neurosurgery and neurology) care. The hospital has a regional function for these two categories of care and wants to excel in these two disciplines. Formally, St. Elisabeth Ziekenhuis is one of the ten trauma centers in the Netherlands (St. Elisabeth Ziekenhuis 2012).

The hospital building is characterized by the long hallway. Medical disciplines can be found on both sides of this hallway. The emergency department, operating theatre and intensive care unit are physically aligned to facilitate handling of trauma patients (Figure 1.1).

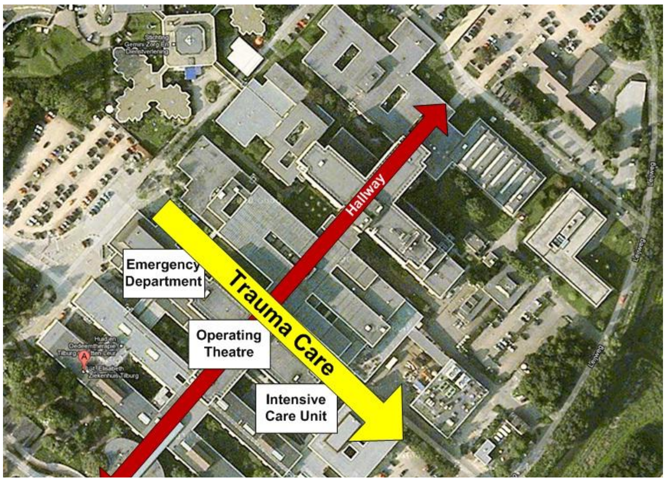


FIGURE 1.1 - ST. ELISABETH HOSPITAL BUILDING

Recently, the Dutch Competition Authority (Nederlandse Mededingingsautoriteit, NMa) has approved the intended merge between TweeSteden Ziekenhuis and St. Elisabeth Ziekenhuis.

1.2 INTENSIVE CARE

The European Society for Intensive Care Medicine (ESICM) has formulated recommendations on the basic requirements of intensive care units. In addition, it has stated the definition and objectives of an intensive care unit. According to (Valentin and Ferdinande 2011),

> *"The intensive care unit (ICU) is a distinct organizational and geographic entity for clinical activity and care, operating in cooperation with other departments integrated in a hospital."*
>
> *"The objectives of an ICU are the monitoring and support of threatened or failing vital functions in critically ill patients who have illnesses with the potential to endanger life, in order to perform adequate diagnostic measures and medical or surgical therapies to improve outcome."*

Intensive care units can be classified according to the level of care that is provided (Valentin and Ferdinande 2011). Three levels of care are defined. Each level is related to its own workload (i.e. patient-nurse ratio and number of FTE per ICU bed). The three levels of care are summarized below.

- Level III: Patients with multiple acute organ failure of an immediate life threatening character.
- Level II: Patients with one acute organ failure of an immediate life threatening character.
- Level I: Patients at risk of developing one or more acute organ failures. Also, patients recovering from one or more acute vital organ failures but whose condition is too unstable are included. If nursing workload is too high or complex to be managed on a regular ward, patients can recover at this level of IC.

1.3 INTENSIVE CARE UNIT

Every year, around 2,700 patients are admitted to the intensive care unit. The average length of stay is equal to three days. In October 2009, the intensive care unit was expanded from 24 to the current capacity of 34 beds. The intensive care unit is divided into four subunits. Three of these subunits have eight beds with the option of mechanical ventilation. The fourth subunit has ten beds without the option of mechanical ventilation. A schematic floor plan is given in Figure 1.2.

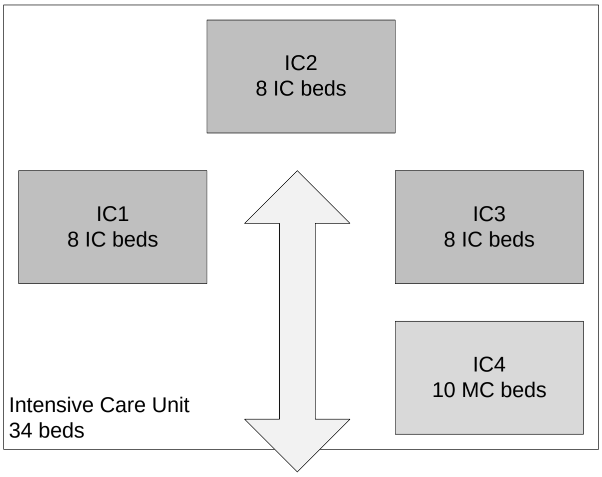


FIGURE 1.2 - SCHEMATIC FLOOR PLAN OF THE ICU

In 2010, the Dutch Association for Intensive Care (NVIC) has allotted the intensive care unit of St. Elisabeth Ziekenhuis a level III status. Level III is the highest attainable level of intensive care.

1.4 MANAGEMENT QUESTION

St. Elisabeth Ziekenhuis wants to be “best in class” when it comes to trauma care. The hospital is one of the ten trauma care centers in the Netherlands.

The intensive care unit is one of the shared resources in St. Elisabeth Ziekenhuis. Patients from different disciplines with different urgencies arrive at the intensive care unit and are in need for intensive care. Normally, patients are admitted to the ICU. However, some patients cannot enter the ICU due to a lack of IC capacity. These patients are refused.

The hospital management has to make a tradeoff between two perspectives of the intensive care unit, efficiency and service. One the on hand, the hospital wants to minimize the number of refused patients (service). On the other hand, the hospital wants to maintain certain utilization (efficiency).

The hospital management can simply decide to increase the number of staffed beds to reduce the number of refused patients. However, this will directly impact the efficiency of the intensive care unit. As a consequence, other possibilities of capacity management should be investigated.

Management question

“How can the number of refusals at the intensive care unit be minimized, given the current budget?”

2 LITERATURE REVIEW

In this chapter relevant literature for this master thesis is presented. This chapter is a summary of the literature review (Mols 2013) written as preparation for the master thesis.

Vissers and Beech (2005) defined three logistical perspectives for a hospital setting, namely unit logistics, chain logistics and network logistics (Figure 2.1). Unit logistics deals with the logistics of a single unit (e.g. OT, IC). Chain logistics concentrates on the logistics of a single chain (e.g. trauma or diabetic patients). Last but not least, network logistics is a combination of unit and chain logistics.

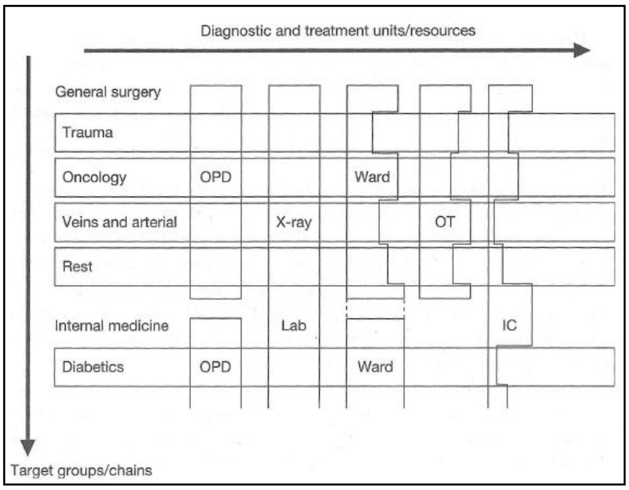


FIGURE 2.1 - UNIT, CHAIN AND NETWORK LOGISTICS

Vissers and Beech (2005) distinguished between leading and following resources. Leading resources trigger demand at the following resources. The ICU can be both a leading (acute admissions) and following resource (elective surgical admissions). In addition, the ICU is an example of a shared resource and is generally available for all specialties.

The importance of the incorporation of stochastic information and patient groups is confirmed in (Harper and Shahani 2002). They have demonstrated how a commonly adopted simple deterministic approach to capacity planning can result in misleading, often underestimating hospital requirements. They ran a model with varying settings. The first model considered seasonal demand and stochastic length of stay (LOS) distributions for many distinct patient groups. The fourth and last model assumed no seasonal demand and used the average LOS for elective and the average LOS for emergency patients, while ignoring the patient groups. The first model yielded the best results.

This chapter discusses articles that concentrate on the unit perspective, the two unit perspective (OT-ICU) and the network perspective.

2.1 UNIT PERSPECTIVE: ICU

Researchers studied the intensive care unit in isolation. This section concentrates on the papers that have investigated the ICU from the unit perspective.

The *number of staffed beds* is a decision variable in order to improve the service of the intensive care unit. Increasing the number of staffed beds decreases the refusal rate, but also the utilization in a non-linear fashion (Ridge, et al. 1998) (Harper and Shahani 2002) (McManus, et al. 2004) (Kokangul 2008). This is desirable from the service perspective, but not from the perspective of efficiency.

Besides the number of staffed beds, researchers have proposed *bed reservation policies* for the intensive care unit. Reserving IC beds for emergency patients has resulted in a small decrease in rejection of emergency patients. However, a significant increase in rejection of elective patients was found (Ridge, et al. 1998). Also, reserving IC beds for elective surgical patients was investigated. The goal was to reduce the number of cancelled surgeries. A dedicated unit was outperformed by the flexible reservation policies in the main unit. Furthermore, the reservation policies decrease the number of cancelled surgeries, but increase the waiting time (Kim, Horowitz and Young, et al. 2000). Bed reservation policies influence the performance of the intensive care unit. The type of reservation policy should be consistent with the objectives of the decision maker.

A distinction is made between random and controllable variation (Hopp and Spearman 2008). Controllable variation is a direct consequence of decisions, whereas random variation is beyond immediate control. Natural variability should be managed and artificial variability should be reduced (Litvak and Long 2000). In line with this argument, several researchers have directed the attention towards the *planning of elective surgical intensive care patients* (Ridge, et al. 1998) (Kim, Horowitz and Young, et al. 1999) (McManus, et al. 2004). In other words, attempts should be made to level the intensive care demand.

Aforementioned research has expressed the service perspective of the intensive care unit by waiting time and transfer (rejection) for emergency patients and cancelled surgeries or deferral for elective patients. This implicitly assumes that the currently admitted patients have priority over new arriving patients. In practice, this is not always the case. Dobson et al. (2010) formulated a model to investigated so-called *bumping*. Bumping means that the arriving patient is given priority over the current patient population. Currently admitted patients that are close to being discharged are discharged earlier.

2.2 TWO UNIT PERSPECTIVE: OT AND ICU

The need to investigate the relationship between the operating theatre and intensive care unit was indicated in the previous section. The papers discussed in this section have focused on the scheduling of elective surgical IC patients. In other words, emergency patients are not considered.

Van Houdenhoven et al. (2008) considered a cyclic surgery schedule to increase the operating theatre utilization and decrease the intensive care unit refusals. First, their model generates a surgical schedule (Operating Room Day Schedule, ORDS) for each day that maximizes OT utilization. Then, the ORDSs are put in the order that levels the intensive care demand throughout the cycle period.

Kim and Horowitz (2002) investigated the use of elective surgical quota. The elective surgical quota specifies how the elective surgical IC patients need to be scheduled throughout the week. This is another attempt at leveling the intensive care demand caused by the operating theatre.

Chaiwanon (2010) compared a uniform cap policy to service-specific cap policy. The uniform cap policy put a restriction on the maximum number of elective arrivals scheduled, whereas the service-specific cap policy incorporated information about the length of stay of the elective arrivals. The former policy aims at leveling the arrival of patients and the latter policy aims to level the elective bed demand in the ICU.

The research in this section has mainly focused on the tandem OT-ICU. Bountourelis et al. (2013) stated that the intensive care unit cannot and should not be studied in isolation. The researchers have mentioned the phenomenon *patient blocking*. Two relevant types of patient blocking exist: (1) a patient is blocked and cannot enter the intensive care unit (rejection, refusal, waiting time, canceled surgery and deferral) and (2) a patient is blocked and cannot leave the intensive care. That is, the patient cannot enter the ward (delayed discharge). The aforementioned research assumed that no patient blocking occurs at the moment of discharge.

2.3 NETWORK PERSPECTIVE

The papers discussed in this section deal with the network perspective of a hospital. In most of the papers, the operating theatre was identified to be the leading resource, generating demand at downstream resources like wards and the ICU.

Beliën & Demeulemeester (2007) evaluated several models for building cyclic surgery schedules with leveled resulting bed occupancy. The arrival and length of stay distributions were considered stochastic. The objective was to minimize the total expected bed shortage within the cycle length of the cyclic surgery schedule. Later, Beliën et al. (2009) presented a decision support system for the purpose of constructing cyclic surgery schedules. Operating blocks of four or eight hours were assigned to surgeons of several specialties. This surgical schedule generates demand at subsequent units i.e. wards. The decision support system was facilitated with a graphical user interface, visualizing the consequences regarding bed utilization at multiple wards.

The two papers mentioned above focused on the scheduling of the surgeons. Operating time allocated to surgeon S on a certain day generates work just before and after this certain day. The surgeon schedule leads to admissions, because a specific patient needs to be operated by a specific surgeon. Researchers recognized the importance of admission planning.

Cyclic patient admissions profiles have been investigated in (Adan and Vissers 2002), (Vissers, Adan and Bekkers 2005) (Adan, Bekkers, et al. 2009). The patient admission profiles specifies for a number of patient categories *when* and *how many* patients to admit. Each patient category demands a certain set of resources after admission (bill of resources). Based on this information, an optimal patient admission profile can be calculated. The optimal profile minimizes the deviation from the target utilization at multiple units (e.g. OT, ICU and Ward). Furthermore, the optimal profile accounts for the average demand of a certain patient category.

Based on the papers discussed previously, (Dellaert and Jeunet 2009) translated the tactical patient admission profile into an operational patient admission profile by means of slack planning, flexibility rules and updating. The impact of these strategies was measured by the performance criteria: waiting time, deviation from target utilization and plan changes.

The papers mentioned in this section have considered elective surgical (IC) demand only. In practice emergency patients arrive and demand the same resources as the elective surgical (IC) patient demand, like an IC bed and eventually a bed at the ward. The following paper also considered emergency patients.

Adan et al. (2011) presented their approach towards operational effectiveness of tactical master plans including both elective and emergency patients. The researchers defined a tactical, operational and executed plan. Again, the tactical plan was translated into an operational plan. The operational plan leaded to an executed plan after considering emergency patients. The constructs patient dissatisfaction and hospital inefficiency were used to measure the performance of the tactical plan in combination with slack planning and flexibility. Their main conclusion was that an increase in patient satisfaction can be realized by a decrease in hospital efficiency.

2.4 LITERATURE GAP

Researchers identified the need to control the elective surgical arrivals of the ICU. The main argument is that these arrivals can be controlled by the decision makers. Then, researchers simulated the use of leveled elective surgical schedules. Most of the researchers focused on the number of elective surgical patients and therefore ignored the impact of the length of stay in the intensive care unit. This can be called the homogeneous approach.

Given the homogeneous approach, a heterogeneous approach is researched by several researchers. The latter approach accounts for differences in the length of stay of elective surgical IC patients. The focus of the heterogeneous approach is not on leveling the number of arrivals, rather the approach focuses on a leveled elective demand for the intensive care unit. By leveling the demand caused by elective patients, the utilization and service rate of the ICU become dependent on the unscheduled demand. All of these approaches have been developed independent of the intensive care capacity status.

Chaiwanon (2010) introduced the idea of state dependent prediction. Based on the current ICU state, the future state of the ICU is predicted. In line with this idea, the author suggests the development of adaptive cap-based policies. It would be interesting to investigate the usefulness of adaptive cap-based policies. Applying such a policy is linking the elective scheduling process to the ICU's capacity status. The ultimate goal is to negatively correlate the elective surgical admissions with the number of patients in the unit. This would lead to the smallest number of refusals and improved unit utilization (Figure 2.2).

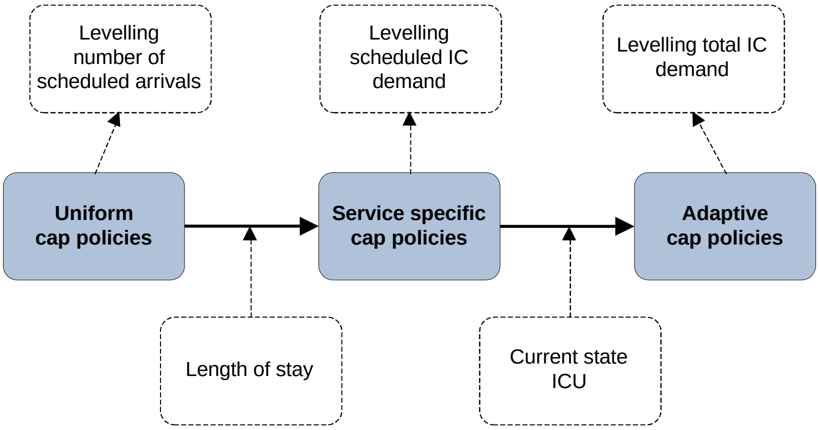


FIGURE 2.2 - OVERVIEW OF LITERATURE

3 RESEARCH PROJECT

This chapter provides the problem statements, the research objectives, research questions, the research scope and the model used to conduct the research.

3.1 PROBLEM STATEMENT

During the literature review, it became clear that several scheduling policies have been introduced at health care facilities to improve the efficiency and service of a health care unit. Previous research has focused on the ICU performance in terms of efficiency (e.g. utilization) and service (refusal and cancellation rates). The need for a uniform cap policy or a service specific cap policy was identified.

However, the hospital management does not want to impose a uniform or service specific cap on the scheduling of scheduled arrivals. Therefore, the hospital management seeks for alternatives.

An alternative could be a dynamic system where the number of scheduled arrivals allowed differs from time to time. Chaiwanon (2010) suggested investigation of adaptive cap based policies based on state dependent prediction. The adaptive cap policy allows more scheduled arrivals in times of low ICU occupancy and limits the number of scheduled arrivals in times of high ICU occupancy. In this way, the scheduled arrivals become dependent on the state of the ICU. Also, flexibility of the ICU capacity can be investigated. In the current situation, the capacity of the ICU can be considered fixed.

3.2 RESEARCH OBJECTIVE

The research objective is to develop models based on state dependent predictions, that reduce the number of refusals (unscheduled arrivals not admitted) and late cancellations (surgeries cancelled on the day of surgery). Two models will be investigated.

In the first model, an adaptive cap policy is developed based on the state dependent predictions. The second model incorporates flexibility of the ICU capacity. In both models, the effect on the number of refusals is investigated.

3.3 RESEARCH QUESTIONS

Based on the literature, the problem statement and the research objective three research questions are formulated.

1. How should the adaptive cap policy, based on state dependent predictions, be designed for the St. Elisabeth Hospital?

   - What is the length of the scheduling horizon?
   - What is the length of the prediction horizon?
2. Can the adaptive cap policy reduce the number of refusals / late cancelled surgeries?
   - What are the advantages?
   - What are the disadvantages?
3. To what extent does the flexibility of the ICU capacity reduce the number of refusals/late cancellations?

3.4 RESEARCH SCOPE

The intensive care unit is a resource shared by several medical disciplines and interacts with many different actors. Not all relations and interactions of the ICU are included in the research project. Therefore, the scope of the research project is described here.

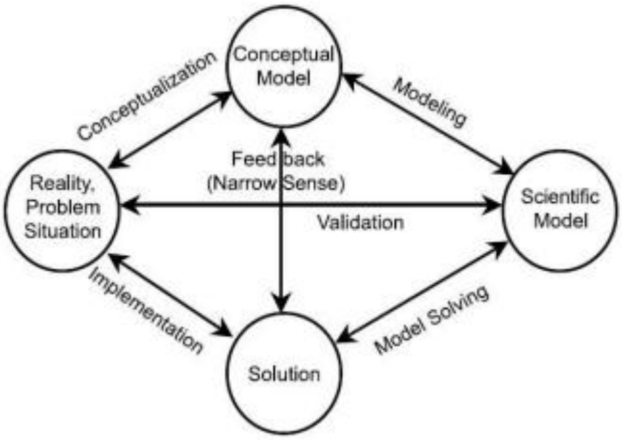


FIGURE 3.1 - RESEARCH MODEL BY MITROFF ET AL. (1974)

1. Both scheduled and unscheduled arrivals are considered.
2. The interaction between the ICU and the operating theatre belongs to the scope of the model. However, operating duration and surgeon schedules are not modeled explicitly.
3. Although discharge blocking (a patient that cannot leave the ICU) can occur, this was considered out of scope i.e. patient can always be discharged.

3.5 RESEARCH MODEL

The development of the two models was guided by the model of Mitroff et al. (1974) is based on the initial approaches used when operational research emerged as a field (Figure 3.1). Within this model the operational research approach consists of a number of phases:

- **Conceptualization**: In order to answer the research questions, the reality/problem/situation should be described first. This is done by conducting interviews with relevant actors with respect to the IC processes. In addition, data on IC admissions and refusals and elective surgeries is collected and analyzed.
- **Modeling:** The current situation is translated into a conceptual model. The conceptual model abstracts this reality and specifies the variables to be included, the scope and the model addressed (Bertrand and Fransoo 2002). More specifically, patient categories are defined; arrival and length of stay distribution are derived.

- **Model solving:** In the modeling phase, the actual mathematical model is constructed. In this research project MATLAB will be used for this purpose. In the scientific model, causal relationships are defined mathematically. The scientific model is solved given varying input parameters and leads to solutions. Based on the patient categories and arrival and length of stay distributions, simulation models are developed. Important aspects of the simulation models are the use of random variables, probabilities and statistics.
- **Feedback:** The solutions are compared to particular reference scenarios. For example, a situation without adaptive cap policy is compared to the situation with adaptive cap policy. In this way, the effect of introducing the adaptive cap policy can be observed.
- **Implementation:** If the solutions and conclusions from the model solving activity satisfy the stakeholders of the problem the desired interventions should be implemented. Furthermore, based on the solutions the conceptual model might be adapted. For example, the level of detail in the conceptual model is increased after observing the solutions.

3.6 STRUCTURE OF THE REPORT

After the introduction, the literature review and the research project, the result of the qualitative and quantitative analysis are provided in chapter 4 and 5 respectively.

The adaptive cap policy is conceptualized in chapter 6 and modeled in chapter 7. Chapter 8 presents the performance measures for several scenarios of the adaptive cap policy. In chapter 9 flexibility of the ICU capacity is assumed and evaluated. Conclusions and recommendations are provided in chapter 10. The main text of the report ends with a discussion and further research directions in chapter 11. After chapter 11, appendices can be found.

4 QUALITATIVE ANALYSIS

The literature about intensive care unit capacity management has directed the attention towards the elective surgical demand for intensive care. The main reason is that this demand can be planned and controlled to some extent. The operating theatre planning and scheduling process is described in this chapter.

4.1 OPERATING THEATRE PLANNING

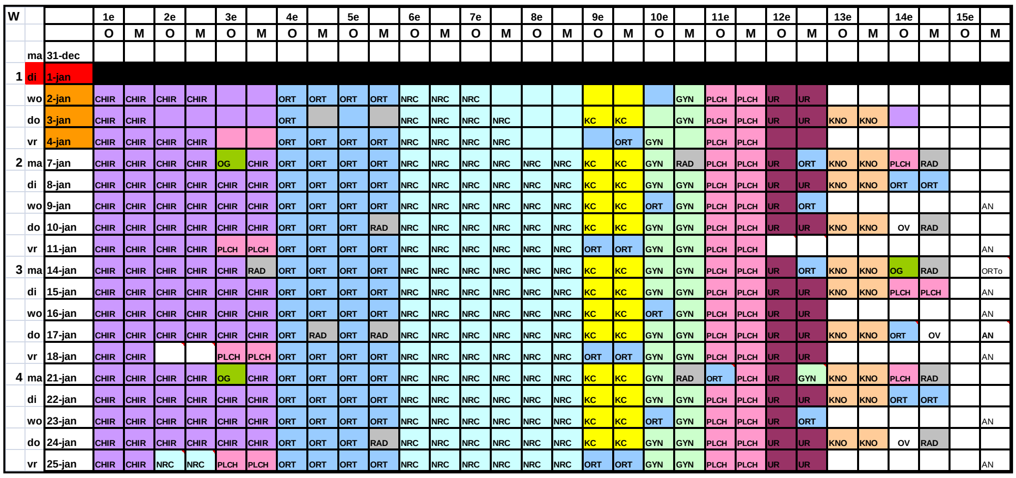
This chapter was written after interviewing relevant actors. The OT planners of the volume top 4 surgical groups were interviewed as well as actors working at the operating theatre.

Interviewees

1. OT planners of surgical groups
    - Neurosurgery
    - General surgery
    - Orthopedics
    - Urology
2. Specialist nurse – Preoperative screening
3. Care group manager of surgical groups
4. Head OT
5. Two OT floor managers independently

4.1.1 OPERATING THEATRE PLANNING

The operating theatre in St. Elisabeth Ziekenhuis consists of 15 operating rooms. The operating time is divided in blocks. A block is a combination of a room and a half day (a morning or an afternoon) (Figure 4.1). Each block is assigned to one of the 13 surgical groups. One surgical group can have more than one block (or room) at the same time. The planning horizon is six months ahead.



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	di	15-jan	CHIR	CHIR	CHIR	CHIR	CHIR	CHIR	ORT	ORT	ORT	ORT	NRC	NRC	NRC	NRC	NRC	NRC	KC	KC	GYN	GYN	PLCH	PLCH	UR	UR	KNO	KNO	PLCH	PLCH		AN
	wo	16-jan	CHIR	CHIR	CHIR	CHIR	CHIR	CHIR	ORT	ORT	ORT	ORT	NRC	NRC	NRC	NRC	NRC	NRC	KC	KC	ORT	GYN	PLCH	PLCH	UR	UR						AN
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	vr	18-jan	CHIR	CHIR			PLCH	PLCH	ORT	ORT	ORT	ORT	NRC	NRC	NRC	NRC	NRC	NRC	ORT	ORT	GYN	GYN	PLCH	PLCH	UR	UR						AN
4	ma	21-jan	CHIR	CHIR	CHIR	CHIR	OG	CHIR	ORT	ORT	ORT	ORT	NRC	NRC	NRC	NRC	NRC	NRC	KC	KC	GYN	RAD	ORT	PLCH	UR	GYN	KNO	KNO	PLCH	RAD		
	di	22-jan	CHIR	CHIR	CHIR	CHIR	CHIR	CHIR	ORT	ORT	ORT	ORT	NRC	NRC	NRC	NRC	NRC	NRC	KC	KC	GYN	GYN	PLCH	PLCH	UR	UR	KNO	KNO	ORT	ORT		
	wo	23-jan	CHIR	CHIR	CHIR	CHIR	CHIR	CHIR	ORT	ORT	ORT	ORT	NRC	NRC	NRC	NRC	NRC	NRC	KC	KC	ORT	GYN	PLCH	PLCH	UR	ORT						AN
	do	24-jan	CHIR	CHIR	CHIR	CHIR	CHIR	CHIR	ORT	ORT	ORT	RAD	NRC	NRC	NRC	NRC	NRC	NRC	KC	KC	GYN	GYN	PLCH	PLCH	UR	UR	KNO	KNO	OV	RAD		
	vr	25-jan	CHIR	CHIR	NRC	NRC	PLCH	PLCH	ORT	ORT	ORT	ORT	NRC	NRC	NRC	NRC	NRC	NRC	ORT	ORT	GYN	GYN	PLCH	PLCH	UR	UR						AN

FIGURE 4.1 - OPERATING ROOM AND TIME ASSIGNMENT

The operating time and room assignment is done centrally by the operating theatre management. Every week the planners of the surgical groups meet for an auction. Here, assigned blocks are traded between surgical groups. Low volume periods at one surgical group can be compensated by high volume periods at another surgical group.

4.1.1 PATIENT SCHEDULE CONSTRUCTION

After operating time and room assignment, patients can be scheduled (up to six weeks ahead). In the previous phase, planning activities are carried out on the surgical group level. The next phase will be called "schedule construction" and takes place at the patient level. A schedule is constructed as follows (Figure 4.2).

A patients' surgery needs to be planned on the elective surgical schedule after a medical specialist has decided that a patient needs surgery. Then, the patient and the polyclinic nurse agree upon a preliminary surgery date. In addition, an appointment is scheduled at the preoperative screening (POS).

The schedules are constructed independently at each surgical group's polyclinic or secretary. Every morning all surgical groups finalize their surgery schedule for the next day of surgery. Patients on the schedule should have completed the preoperative screening. In practice, this is not always the case.

The OT floor manager receives all surgical group schedules for the next day. The schedules are consolidated to one day schedule, one afternoon before schedule execution. The floor manager assesses whether the schedule is feasible, since some of the resources at the OT have restricted capacity (e.g. surgical sets, C-arms). Normally only the sequence of the schedule is changed by the floor manager of the OT.

After finalizing the schedule for the next surgical day, the final schedule is communicated to the relevant departments in the hospitals i.e. surgical group wards, intensive care unit, PACU etc.

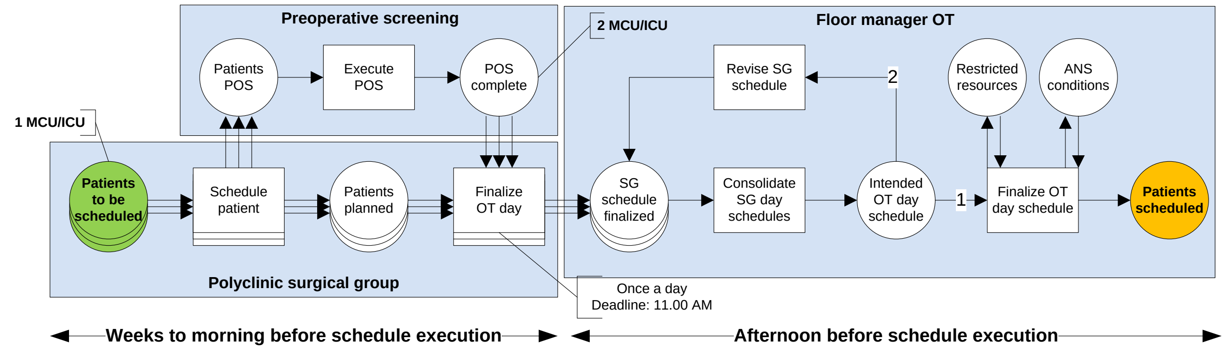


FIGURE 4.2 - SCHEDULE CONSTRUCTION PROCESS

Intensive care need

Normally, the need for intensive (or medium) care is indicated by the medical specialist of the surgical group. This IC indication is then related to the primary illness of the patient. An intensive care indication can also be the result of the preoperative screening. The IC indication is then mostly related to secondary health concerns of the patient. An example is the presence of obstructive sleep apnea.

The surgical group planners have indicated that the information about the postoperative stay at the ICU is rarely used as a decision variable in their surgery schedule. Answers varied from "I know I should not plan too many IC requiring patients" to "I do not use the IC information at all". In addition, the surgical group planners do not interact to coordinate IC demand.

4.1.2 PATIENT SCHEDULE EXECUTION

The schedule execution starts with a final operating day program i.e. the patients scheduled for surgery that day (Figure 4.3). The surgical group wards have received the day schedule, so they know which patient needs to undergo surgery first. The operating theatre secretary orders the patient at the surgical group wards.

The patient is then brought to the preparation by the ward nurses. The patient is prepared here and a last check is executed. The patient is then brought to the operating room, undergoes surgery and is brought to the PACU. The PACU has three boxes with beds. Patient with a postoperative stay at the ICU stay in box 3 for a while. After that, they are transported to the ICU.

Intensive care need

From the perspective of the intensive care unit, a distinction should be made between IC patients and non-IC patients. Around 7.15 AM, the OT floor manager contacts the medical specialist of the intensive care. The floor manager asks how many beds are available for elective surgical patients. Based on that information, the floor manager can start executing the schedule. In case not enough beds are available, the floor manager asks about the expectations for later that day. Beds might be available later that day, because patients are discharged during the day. The floor manager changes the order of the schedule to win time.

Above average demand for intensive care beds is handled by being flexible in anesthetic treatment and time (i.e. changing the order of the schedule). Next to that, all IC requiring patients are ranked. The rank indicates the urgency of the patient's IC need. The last option is to cancel the surgical procedure.

Sometimes the floor manager and the intensive care unit have contact about the coming days proactively. When one of the two observes a large number of patients scheduled to go to the ICU, then the floor manager contacts the specialists in order to adapt the schedule a few days in advance.

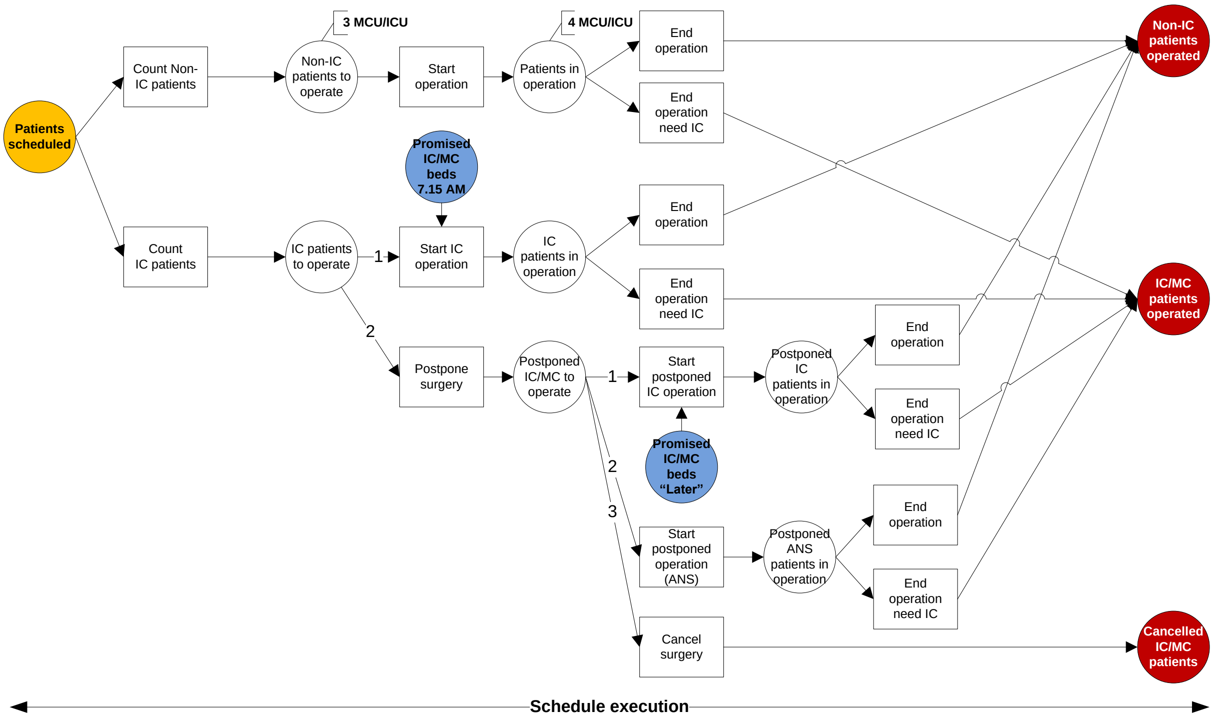


FIGURE 4.3 - SCHEDULE EXECUTION PROCESS

4.2 INTENSIVE CARE LOGISTICS

The patient logistics within the intensive care are described in this paragraph.

During the night, patient admitted to the ICU are identified to leave during the next discharge round. In the early morning, the ICU management communicates with the operating theatre about the expectations for today. The ICU management approves a number of IC beds to the operating theatre (the floor manager of the OT can start executing the surgical schedule). After that, patients are discussed during a multidisciplinary meeting. Around 11.00 hr and 14.00 hr, patients are discharged to the wards of the hospital. After discharge rounds, arrivals are admitted (Appendix VIII).

4.2.1 CONCLUSIONS

The conclusion is that most of the surgical group planners do not use the information about postoperative stay. Even if the planner uses the information, the attention is limited to their own surgical group. All interviewees have indicated that no communication or coordination takes place between the surgical groups about this issue.

Next to that, sometimes the planners cannot use postoperative stay information. A patient is given a preliminary surgery date and later the POS concludes postoperative stay at the ICU is needed. Currently, this is no reason to alter the schedule. The preliminary surgery date becomes the final surgery date.

The current practice demands flexibility during the schedule execution. Large intensive care demand is handled by postponing surgeries (i.e. change the sequence of the schedule, delay IC admission), altering treatment (i.e. no narcosis, extended stay at PACU) and cancellation of the surgery.

The conclusion can be generalized for all other shared resources like c-arms, surgical sets, surgical tables etcetera. No communication and coordination about the use of shared resources leads to variability in the demand for these shared resources like the intensive care. The demand variability will be buffered by a combination of time, inventory and capacity. The latter statement is one of the principles presented in the book Factory Physics (Hopp and Spearman 2008).

5 QUANTITATIVE ANALYSIS

The previous chapter provided a qualitative analysis of the schedule construction and schedule execution process. In this chapter, the results of the quantitative analysis are presented.

5.1 DATA SETS

Two data sets are extracted from the information systems of the hospital. First of all, data on all IC admissions is extracted from the database called Mediscore. Mediscore is used to report to National Intensive Care Evaluation (NICE). The goal of NICE is to monitor and improve the intensive care quality by continuous and complete registration. The research coordinator of the ICU maintains the database.

For the year 2012 the **registered IC admissions** data are extracted. Next to that, the **registered IC refusals** by the intensive care unit are also extracted. Last but not least, a handwritten sheet is collected at the operating theatre. The sheet contains the **registered late cancellations** from the perspective of the operating theatre. The extracted columns for the IC admissions, IC refusals and IC late cancellations can be found in Appendix I .

The second data set contains the number of surgeries executed per day in 2012 and the number of IC indications scheduled and executed.

5.2 ADMISSIONS

All IC admissions are assigned an admission type. Four IC admission types can be distinguished, namely “medical”, “emergency surgical”, “elective surgical” and “dead before admission” admissions (Figure 5.1).

- Medical IC admissions arrive from wards, emergency department or other hospitals. They have an acute character.
- Emergency surgical IC admissions arrive via the operating theatre and are also acute.
- Elective surgical IC admissions arrive via the operating theatre, but their surgery was scheduled.
- “Dead before admission” IC admissions are admitted to preserve organs for transplantation.

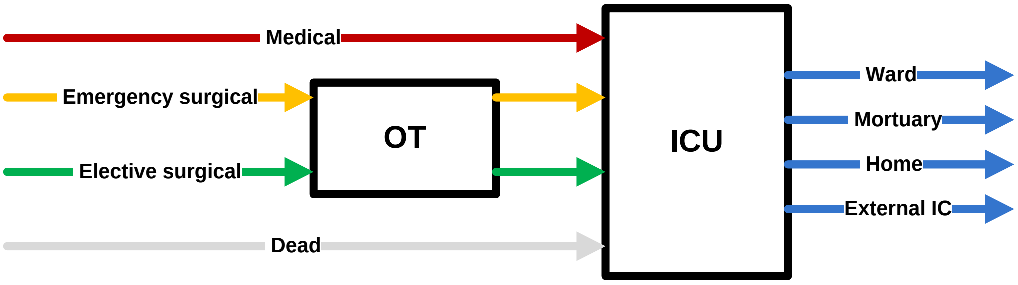


FIGURE 5.1 - ADMISSION TYPES

The data set contained information on all IC admissions from 01-01-2012 to 31-12-2012. This section presents the information of this year.

Table 5.1 presents the registered IC admissions according to medical discipline and admission type. More than 60% of the admissions had medical discipline neurosurgery or general surgery.

TABLE 5.1 - REGISTERED IC ADMISSIONS ACCORDING TO ADMISSION TYPE AND MEDICAL DISCIPLINE

2012	**Admission type**				
Medical discipline	**Elective surgical**	**Medical**	**Dead before**	**Emergency surgical**	**Total**
Neurochirurgie	484	241	2	119	846
Heelkunde	221	210	2	172	605
Inwendige geneeskunde		254	1	4	259
Longziekten	1	157		1	159
Neurologie	3	126	3	5	137
Cardiologie		89	1	1	91
Orthopedie	63	13		10	86
Urologie	59	7		2	68
Mondziekten en kaakchirurgie	29	3		2	34
Gynaecologie en verloskunde	15	3		11	29
Keel-, neus-, oorheelkunde	23	4			27
Plastische chirurgie	16			1	17
Psychiatrie		8			8
Revalidatie	1	7			8
Kindergeneeskunde		4			4
Nefrologie		2			2
Reumatologie		1			1
Total	**915**	**1,129**	**9**	**328**	**2,381**

Table 5.2 presents the registered IC admissions according to weekday and admission type. Just a few elective surgical admissions are registered during the weekend days. Obviously, this is because normally no elective surgical procedures are executed at the OT during the weekends.

TABLE 5.2 - REGISTERED IC ADMISSIONS ACCORDING TO ADMISSION TYPE AND WEEKDAY OF ADMISSION

2012	**Admission type**				
Weekday	**Elective surgical**	**Medical**	**Dead before**	**Emergency surgical**	**Total**
Sunday	7	169		50	226
Monday	130	156	1	50	337
Tuesday	222	166	2	50	440
Wednesday	175	179	2	44	400
Thursday	175	152	1	50	378
Friday	201	170	2	39	412
Saturday	5	137	1	45	188
Grand Total	**915**	**1,129**	**9**	**328**	**2,381**

Figure 5.2 presents the registered IC admissions per month for each admission type. In the summer months, the hospital productivity is lower due to the holiday period. The intensive care capacity is restricted in August.

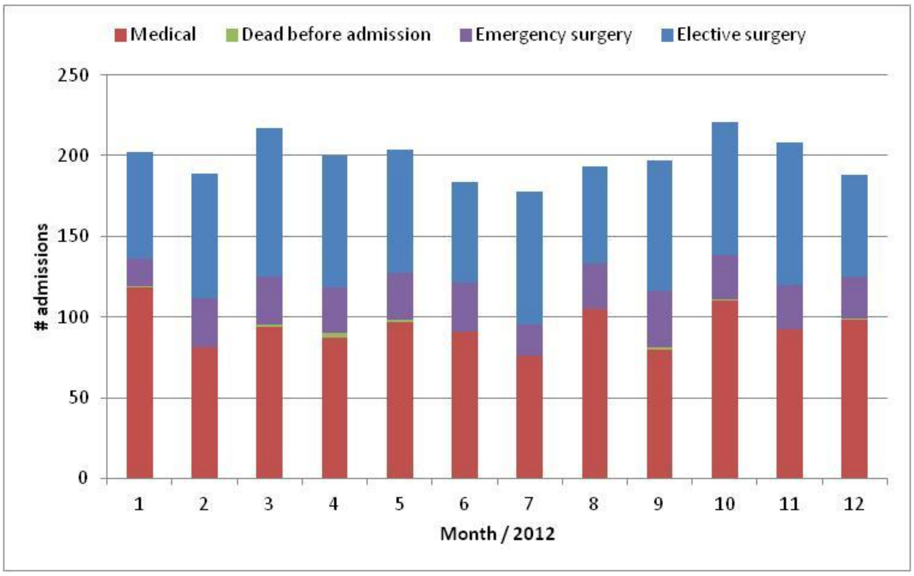


FIGURE 5.2 - REGISTERED IC ADMISSIONS PER ADMISSION TYPE PER MONTH IN 2012

Additional information on the admission and discharge distributions can be found in appendix VIII. For example, differences in arrivals per weekday and the timing of the admissions and discharges.

5.3 LENGTH OF STAY

Table 5.3 presents the statistics about the length of stay (LOS) for each admission type. The LOS distributions for the admission types elective surgical, medical and emergency surgical are not normally distributed. The length of stay distribution are positively skewed i.e. a long right tail. It has relatively few high values. Note that the table contains a negative minimum length of stay for medical admissions. This is probably an entry error since the discharge date cannot be before the date of admission.

TABLE 5.3 - LENGTH OF STAY STATISTICS PER ADMISSION TYPE

2012	**Admission type**				
Statistic (in days)	**Elective surgical**	**Medical**	**Dead before**	**Emergency surgical**	**Total**
Mean	1.58	3.82	0.33	5.74	3.21
Standard deviation	5.42	6.77	0.34	11.66	7.34
Minimum	0.02	-0.09	0.01	0.01	-0.09
Maximum	92.92	62.81	0.94	113.71	113.71
Sum	1,444	4,309	3	1,876	7,632
Count	915	1,129	9	328	2,381

The length of stay distribution for elective surgical admissions is given in Table 5.4 as an example.

TABLE 5.4 - LENGTH OF STAY DISTIBUTION FOR ELECTIVE SURGICAL ADMISSIONS

Length of stay – elective surgical admissions										
Days	0	1	2	3	4	5	6	7	>7	Total
Number of patients	23	771	58	16	12	9	4	4	18	915
Percentage	3%	84%	6%	2%	1%	1%	0%	0%	2%	100%

5.4 IC INDICATION

If a patient needs surgery, the medical specialist indicates that the patient might need intensive care after the surgical intervention. Another way to obtain an IC indication by means of the preoperative screening.

The number of IC indications registered in 2012 equals 930. As could be expected the number of IC indications per day is positively correlated with the number of elective surgeries per day (Figure 5.3).

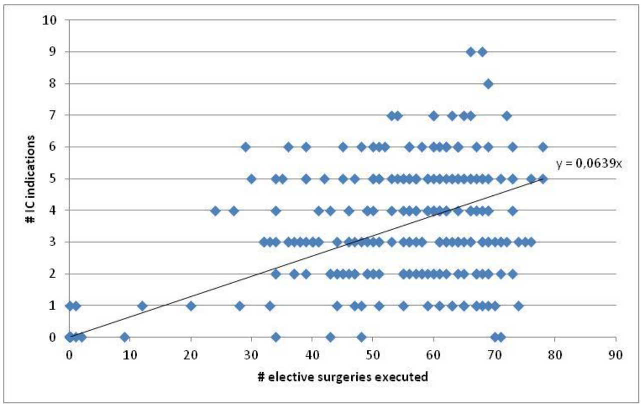


FIGURE 5.3 - RELATIONSHIP BETWEEN ELECTIVE SURGERIES AND IC INDICATIONS

The number of IC indications on a particular day is compared to the number of elective surgical admissions that day. Figure 5.4 depicts the number of IC indications minus the elective surgical IC admissions on weekdays. A positive value indicates that the number of IC indications was larger than the number of elective surgical admissions. A negative value indicates that the number of IC indications was smaller than the number of elective surgical admissions.

The differences between IC indication and actual arrivals are compared on an aggregate daily level. Comparing the differences on the patient level could only increase the differences between IC indication and IC admission. To clarify this idea, imagine four indicated surgical patients do not become IC admissions; instead four other patients become IC admissions. The result would be that the number of IC indications matches the IC admissions on the daily level. However, this would be a 100% mismatch between indication and realization.

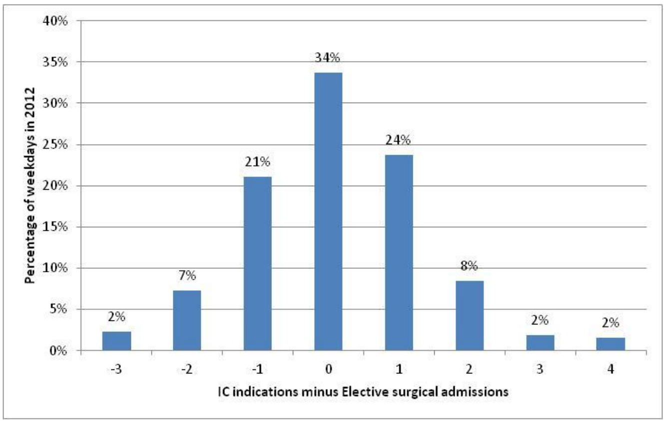


FIGURE 5.4 - IC INDICATIONS PER DAY MINUS ELECTIVE SURGICAL IC ADMISSIONS PER DAY

5.5 REFUSALS AND LATE CANCELLATIONS

Refusals are registered at the intensive care unit. Late cancellations are registered at the operating theatre (Table 5.5 and Table 5.6 respectively)

The registered refusals by the ICU are gathered from the database Mediscore. The medical manager has indicated that not all refusals over this period are registered. The medical manager thinks that the number of registered refusals should be multiplied by a factor two or three to obtain the total number of refusals.

The medical manager of the ICU also indicated that the unit starts refusing patients from 28 occupied beds on. In 2012, the 9 out of 366 days more than 28 beds were occupied. On average 6.5 patients arrive per day. The number of refusals and late cancellations is estimated to be around 60 (9 * 6.50 =58.5 patients).

TABLE 5.5 - REFUSALS REGISTERED BY THE ICU

#	Refusal date	Gender	Age	Arrival from	Via OT?	Referring specialism	Discharge location
1	18-2-2012	M	73	Chirurgie B1	Ja	Heelkunde	Chirurgie B1
2	4-6-2012	F	64	Chirurgie B1	Ja	Heelkunde	Interne Geneeskunde H2
3	7-6-2012	F	59	Dagbehandeling G3	Ja	Neurochirurgie	Dagbehandeling G3
4	15-6-2012	M	72	Spoedeisende hulp	Nee	Heelkunde	Neurologie G1
5	13-8-2012	F	81	Spoedeisende hulp	Nee	Heelkunde	Chirurgie B1
6	14-8-2012	F	68	Chirurgie B1	Ja	Heelkunde	Chirurgie B1
7	7-10-2012	M	7	Spoedeisende hulp	Nee	Kindergeneeskunde	Intensive Care elders
8	16-11-2012	F	75	Chirurgie B2	Ja	Heelkunde	Chirurgie B2
9	23-11-2012	F	64	Chirurgie B1	Ja	Heelkunde	Chirurgie B1
10	10-12-2012	M	47	Spoedeisende hulp	Nee	Heelkunde	Dagbehandeling G3

TABLE 5.6 - LATE CANCELLATIONS REGISTERED BY THE OT

#	Refusal date	Gender	Age
1	17-2-2012	M	50
2	6-3-2012	M	32
3	6-3-2012	M	38
4	7-3-2012	M	75
5	21-5-2012	F	63
6	4-6-2012	M	73
7	7-6-2012	M	65
8	7-6-2012	F	69
9	15-6-2012	M	51
10	15-6-2012	M	56
11	27-11-2012	Unknown	Unknown
12	27-11-2012	Unknown	Unknown
13	27-11-2012	Unknown	Unknown

The registered late cancellations by the OT are coming from a written list. The list contains the cancelled surgeries due to IC capacity. The floor manager makes sure a patient's surgery is not cancelled two times.

The refusals and late cancellations registered by both units can be compared by date, gender and age. The conclusion is that both registrations contain unique patients. However, refusals and late cancellations are registered in the same periods (i.e. beginning of June and end of November).

Figure 5.1 presents the registered late cancellations by the OT (OT-REF) and IC (IC-REF) in time. In addition, the bed usage is also considered in the figure. The bed usage was measured at the start of a day (i.e. midnight 00.00). Obviously, refusals are registered in periods with large numbers of beds used.

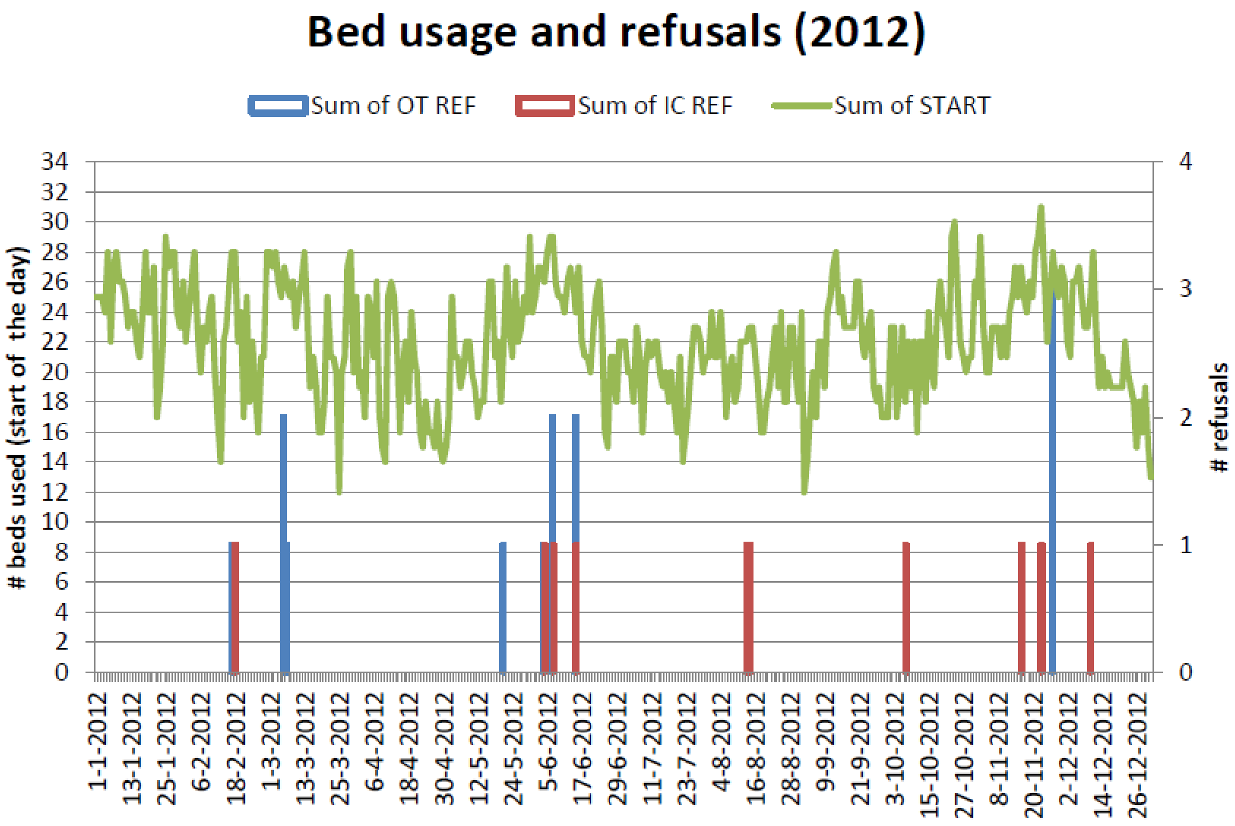


FIGURE 5.5 - BED USAGE AND REFUSALS

5.6 CONCLUSIONS

- The unscheduled patients (medical, emergency surgical) accounted for 62% of the admissions in 2012. 81% of the bed days are related to unscheduled patients.
- The elective surgical patients accounted for 38% of the admissions in 2012. As the length of these admissions is relatively short, the patients accounted for around 19% of the bed days.
- The number of IC indications is positively related to the number of scheduled surgeries.
- Clearly, the IC indication is not the best predictor for the number of elective surgical arrivals. In 66% of the surgical days, the number of indications did not equal the number of IC admissions.
- ICU staff interprets the whole surgical schedule and reasons that some of the IC indicated patients will not become an arrival to the unit.
- The number of refusals and late cancellations is estimated to be around 60.

6 ADAPTIVE CAP POLICY - CONCEPTUAL MODEL

In this chapter, the answers to the first research question are provided.

> "How should the adaptive cap policy, based on state dependent predictions, be designed for the St. Elisabeth Hospital?"

Sub questions are formulated that can be answered after the qualitative and quantitative analysis. Two sub questions are considered relevant.

- What is the length of the scheduling horizon?

The scheduling horizon is the time that schedulers can or do schedule in the future. The scheduling horizon varies across medical disciplines. The scheduling horizon is between 4 and 6 weeks for most of the medical disciplines.

- What is the length of the prediction horizon?

The prediction horizon is the time that the state dependent predictions are meaningful. Chaiwanon (2010) concluded that the state of the system in the near future is likely to be dependent on the current state and that the effect of current state information on the future system state diminishes with time. In case of the St. Elisabeth hospital, the prediction horizon is shorter than the scheduling horizon. The length of stay of 90% of the patient is smaller than or equal to seven days.

Ideally, the adaptive cap policy would specify the allowed number of scheduled arrivals *before* patients are scheduled. However, the scheduling horizon is generally longer than the prediction horizon. As a consequence, the focus of the project is on adapting the surgical schedule *after* patients are scheduled. Basically, based on the ICU state it is predicted whether the observed surgical schedule could cause refusals (or cancellations).

Therefore, the goal is to authorize the surgical schedule within the authorization horizon based on the current state information (Figure 6.1). The outcome would be an early signal that the IC demand would be too large.

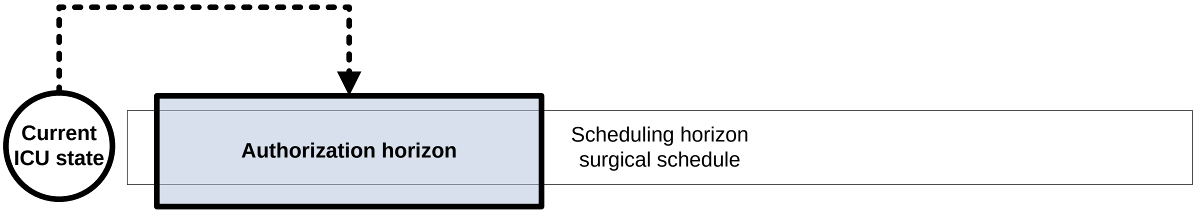


FIGURE 6.1 - AUTHORIZATION HORIZON AND SCHEDULING HORIZON

Relevant actors could then act according to the authorization by opening or closing beds (ICU), early cancel surgeries and add surgeries with IC need to the schedule (medical disciplines). The intensive care management has several options to meet the demand. For example: altering the number of beds, bump or early discharge a patient (Dobson, Lee and Pinker 2010), cancel a surgery or refuse unscheduled arrivals.

Consideration of an authorization horizon for the surgical schedule enables the option of early cancelling elective surgeries. The argument for early cancelling surgeries is that early cancellation is always preferred over a late cancellation. In case of late cancellation, the patient will be dissatisfied and operating time is lost. In case of early cancellation, the patient is informed earlier (probably still dissatisfied) and another not IC requiring patient can be scheduled in the freed operating time. Furthermore, some elective surgeries do not require immediate surgery and can be postponed (to some extent).

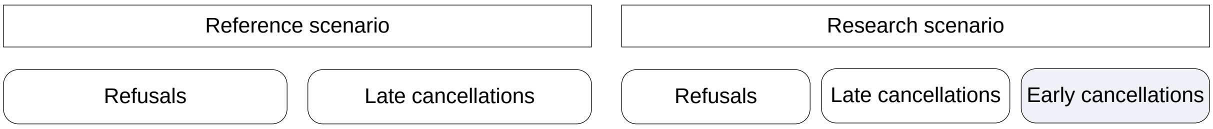


FIGURE 6.2 - REFERENCE VERSUS RESEARCH SCENARIO

In this report, the option of early cancelling elective surgeries is investigated. The reference scenario considers only two options, namely refusing admission of unscheduled arrivals or late cancellations (on the day of surgery) of an elective surgical arrival. The research scenario considers the option of early cancelling a surgery to overcome potential capacity problems (Figure 6.2).

6.1 FUNCTIONAL REQUIREMENTS

In consultation with the hospital management, requirements are formulated for the design of the adaptive cap policy.

1. The hospital management does not want to impose a uniform or service specific cap policy. Instead, an adaptive cap policy is desired.
2. The hospital management does not want to alter their scheduling construction procedure.
3. The capacity of the ICU is fixed.
4. The model takes account of the current state of the ICU and observed surgical schedule.
5. The model signals peak demand periods (i.e. refusals and cancellations) and removes scheduled arrivals from the schedule.

6. The model respects the observed schedule as much as possible. This leads to a minimum number of removals.
7. The model signals low demand periods and identified opportunities to schedule scheduled arrivals.

The objective of the policy is to determine in advance the number of scheduled arrivals that can be admitted. This could lead to early cancellations rather than waiting for late cancellations. Next to identifying early cancellations, possibilities to schedule extra scheduled arrivals are identified. For example, a scheduled arrival is (early) cancelled on Tuesday, but can be scheduled on Wednesday.

6.2 TIME

- A time period starts at 8.00 am in the morning and lasts until 8.00 am the next morning.
- The week starts Sunday morning. A decision has to be made about the surgical schedule for the next week (seven days or time periods).

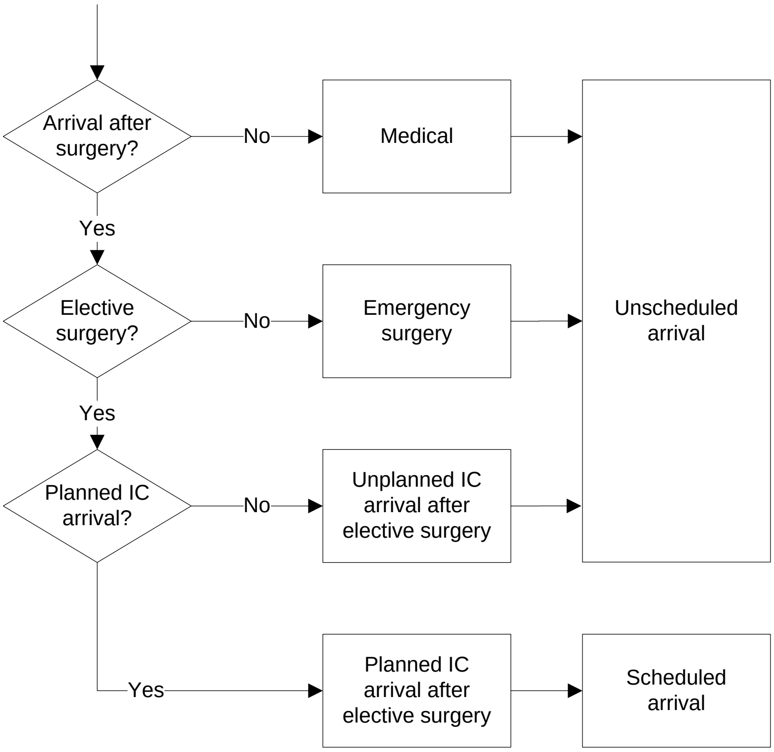


FIGURE 6.3 - PATIENT CATEGORIES CONSIDERED

6.3 PATIENT CHARACTERISTICS

- Two patient categories are considered: unscheduled (including elective surgery without indication) and scheduled patients (Figure 6.3).
- The number of unscheduled arrivals follows a Poisson distribution with parameter λ_u.

- The length of stay of unscheduled patients follows a geometric distribution with parameter $1-\mu_u$.
- The number of scheduled arrivals is known for at least one week. The number of scheduled arrivals on the schedule is sampled from a Poisson distribution with parameter λ_s.
- The length of stay of unscheduled patients follows a geometric distribution with parameter $1-\mu_s$.
- No scheduled arrivals appear on the surgical scheduled on Saturdays or Sundays.

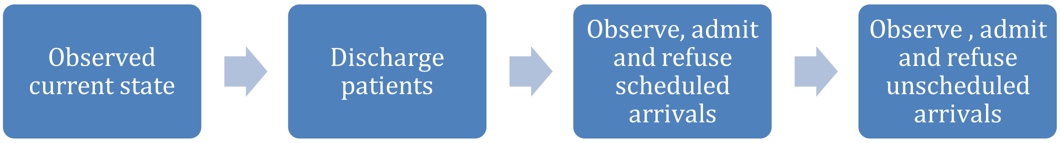


FIGURE 6.4 - DAILY ACTIVITIES AT THE ICU

6.4 ADMISSION POLICY

- Patients are discharged, scheduled arrivals are approved and then the unscheduled arrivals are observed (Figure 6.4).
- Without adaptive cap policy, the ICU management approves a number of scheduled arrivals up to level S. Capacity minus S is the number of beds reserved for unscheduled arrivals.
- With adaptive cap policy, the ICU management approves all scheduled arrivals as the schedule was approved earlier.
- After approving a number of scheduled arrivals, the unscheduled arrivals are observed, admitted and refused (if applicable).

7 ADAPTIVE CAP POLICY - SIMULATION MODEL

Chaiwanon (2010) predicts the future state of the ICU based on the current state of the ICU in combination with a uniform cap policy. In the hospital under study, a uniform cap policy is not implemented. As a result, the predictions should be based on the observed surgical schedule rather than a uniform cap policy.

The capacity of the intensive care unit is finite. The capacity of the ICU should be taken into account for any future state predictions. A refusal today has consequences for the future occupancy of the ICU.

7.1 SIMULATION PROCEDURE

The simulation procedure (Figure 7.1) distinguishes between three schedules, namely the observed schedule, the accepted scheduled and the possible schedule. The observed schedule is the schedule that results from the schedule construction process executed by the medical disciplines. In the prediction procedure, one week is simulated a number of times from the current state with the observed schedule. The outcome of the prediction procedure is compared to a predefined risk condition. If the risk condition is violated, the removal procedure is started. If else, the observed schedule becomes the accepted schedule. It could be possible to add scheduled arrivals to the accepted schedule. If there is no option left to add scheduled arrivals, then the accepted schedule becomes the possible schedule. If else, the addition procedure is started to identify possibilities for additional scheduled arrivals.

The simulation procedure is implemented in MATLAB R2013a. In the next sections, the prediction procedure, removal procedure and addition procedure are discussed in detail (Figure 7.1).

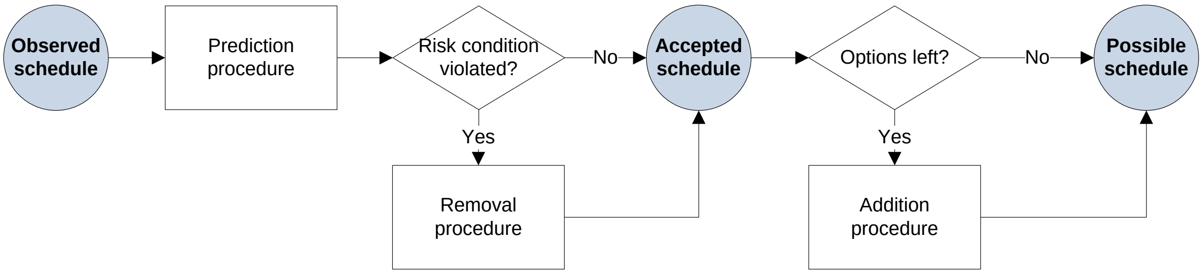


FIGURE 7.1 - SIMULATION PROCEDURE

7.1.1 PREDICTION PROCEDURE

The prediction procedure is an important procedure in the simulation. Given a current state and observed schedule, one week is simulated a number of times. One week elapses as follows:

1. Observe current ICU state
2. Discharge patients
3. Observe, admit and refuse scheduled arrivals
4. Observe, admit and refuse unscheduled arrivals
5. Observe ICU state
6. End of the week? If no, go to 2. If yes, stop.

The future ICU states (step 5) are registered and used to calculate the probability that the ICU is full. For example, one week is simulated 100 times given a current state and observed schedule. 49 out of 100 times, the ICU is full i.e. the observed state equals the capacity. The probability that the unit is full is considered to be 0.49.

The probability that the unit is full is compared to the risk condition. If this probability is smaller than or equal to the risk condition, the observed schedule becomes the accepted schedule. If this probability is larger than the risk condition, the removal procedure is started.

7.1.2 REMOVAL PROCEDURE

The removal procedure (Figure 7.2) is started if the risk condition is violated for at least one day. The objective of the removal procedure is to remove scheduled arrivals from the surgical schedule so that the risk condition is not violated anymore.

The removal procedure does not randomly remove scheduled arrivals from the schedule. Instead, the days of risk condition violation are identified. A schedule arrival is removed on the day (that violated the risk condition) closest to the current time. This was called the first come first serve approach (starting at the beginning of the week). Alternatively, a last come first serve approach (starting at the end of the week) and biggest gap approach were considered. By using a FCFS approach, unnecessary removals are avoided.

After removing a scheduled arrival, the prediction procedure is executed again. If the risk condition was violated, another scheduled arrival was removed. This continues until a schedule is found that does not violate the risk conditions or no scheduled arrivals could be removed anymore. An accepted schedule is obtained.

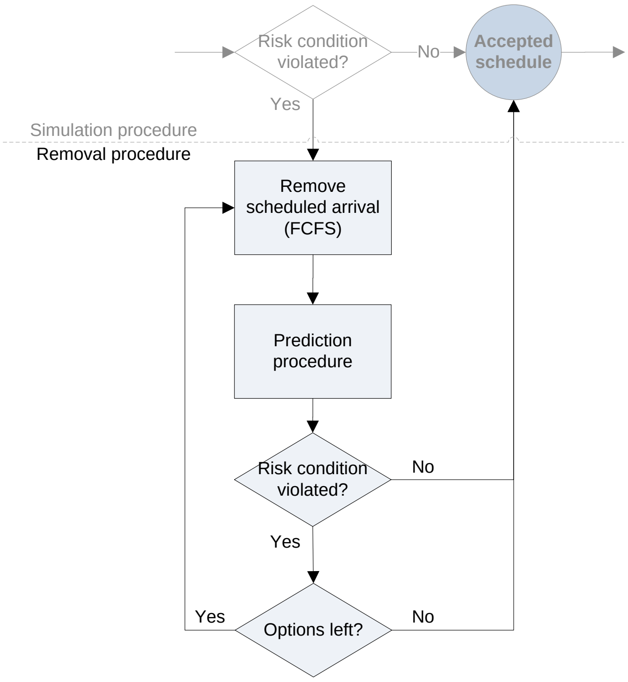


FIGURE 7.2 - REMOVAL PROCEDURE AS PART OF THE SIMULATION PROCEDURE

If scheduled arrivals are removed from every surgical day of the week, there was not need to check for additional scheduled arrivals. Consequentially, the accepted schedule became the possible schedule. However, if no scheduled arrivals are removed on a certain surgical day, it could be possible to add scheduled arrivals to the schedule on that day. The addition was started in that case.

7.1.3 ADDITION PROCEDURE

The objective of the addition procedure (Figure 7.3) is to identify possibilities to add scheduled arrivals to schedule. Even if scheduled arrivals are removed by the removal procedure, it could still be possible to add some scheduled arrivals on other days. The addition procedure works as follows.

The days at which scheduled arrivals are removed is excluded first (there is no need to check these). Given the remaining days, a scheduled arrival is added to the day with the largest difference (biggest gap) between the risk condition and probability that the unit was full. The chance to succeed is largest here. The prediction procedure is executed with the accepted schedule including the addition. If the risk condition is violated, the addition is not approved and the option is excluded. If the risk condition is not violated, the addition is approved. Then, the next option is chosen for the addition of a scheduled arrival. If the schedule does not violate the risk condition and no more options are left, the possible schedule is obtained.

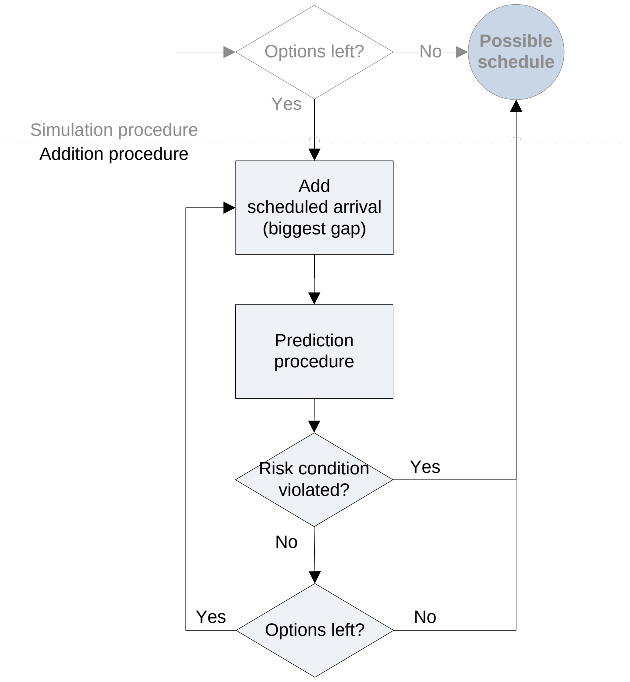


FIGURE 7.3 - ADDITION PROCEDURE AS PART OF THE SIMULATION PROCEDURE

7.2 MODEL PARAMETERS

The model parameters for the simulation model are specified below.

t	Time period
c	Patient category (s=scheduled, u=unscheduled)

Input parameters

λ_c	Arrival rate of patient category c
μ_c	Probability of stay another period of patient category c
B	# staffed beds i.e. capacity
RB	# staffed beds reserved for unscheduled arrivals
RL	Risk condition

Variables

$N_{c,t}$	# patients in the ICU of category c at the end of period t
$D_{c,t}$	# patients discharged from the ICU of category c at the end of period t
$A_{c,t}$	# observed arrivals of category c in time period t
$Q_{c,t}$	# admitted arrival of category c in time period t
$R_{c,t}$	# refused arrivals of category c in period t

Performance measures

Z	# rescheduling actions
P	# scheduled arrivals admitted
R	# refused arrivals/late cancellations
REM	# removals
ADD	# additions
U	Utilization of the unit

7.3 RELIABILITY

Experiments indicated that the accepted and possible schedules are not stable given similar initial conditions. To improve the reliability and stability of the outcomes, a solution is implemented. The solution can be found in appendix II.

8 ADAPTIVE CAP POLICY - PERFORMANCE EVALUATION

The ICU can be in a variety of states with a variety of surgical schedules. As a consequence, scenario analysis is done to assess the performance of the adaptive cap policy. First of all, the scenarios assessed are described. After that, the performance measures are defined.

8.1 INITIAL SETTINGS

Initial scenarios are input to the simulation model. Below, the initial settings are provided.

$$\lambda_u = 4, \lambda_s = 4, \mu_u = 0.76, \mu_s = 0.36$$

8.2 SCENARIOS

In the scenario analysis, 3 x 3 scenarios are considered for combination of capacity and service level. Three current states (high 90%, medium 75% and low 60%) are evaluated with three surgical scheduled (heavy, medium, light). The current states are described in Table 8.1 below. The state [7,18] means that 7 scheduled patients and 18 unscheduled patients are in the unit.

TABLE 8.1 - NINE SCENARIOS CONSIDERED

Level	Initial utilization (Cap = 26)	Current state
High	Approximately 96%, 25	[7,18]
Medium	Approximately 77%, 20	[6,14]
Low	Approximately 54%, 14	[4,10]

Three surgical schedules (Table 8.2) are selected as follows. 100 surgical schedules are generated by sampling five times from a Poisson distribution with parameter λ_s. The generated schedules were sorted on the number of scheduled arrivals per week. Then, a random schedule is taken from the light schedules (schedules 1-20), from the medium schedules (40-60) and from the heavy schedules (80-100).

TABLE 8.2 - SURGICAL SCHEDULES CONSIDERED

Weight	# scheduled arrivals / week	Surgical schedule
Light	16	[0 4 2 4 1 5 0]
Medium	20	[0 5 3 6 3 3 0]
Heavy	26	[0 3 8 7 3 5 0]

8.3 PERFORMANCE MEASURES

The scenarios are compared on the performance measures in the table below.

TABLE 8.3 - PERFORMANCE MEASURES OF ADAPTIVE CAP POLICY

Performance measure	Definition
Utilization	# beds occupied at the end of the time period
# late cancellations	# surgeries cancelled on the day of surgery execution
# removals	# surgeries cancelled before the day of surgery execution
# additions	# surgeries added before the day of surgery execution
# refusals	# number of refused unscheduled arrivals
# surgeries executed	# scheduled arrivals admitted

8.4 OBSERVED SCHEDULE PERFORMANCE

In this section, the performance of the observed schedule is evaluated. The nine scenarios are evaluated on four performance measures, namely utilization, scheduled admissions, late cancellations and refusals.

Simulation of the observed schedule meant that no schedule changes were applied. Instead, the number of scheduled arrivals remained unchanged until the day of surgery. Table 8.4 presents the median values of the performance measures for each of the nine scenarios.

Reservation policy

The ICU management decides on the number of scheduled arrivals to approve (and later admit) in the early morning. The decision has to be made without any knowledge about unscheduled arrivals, but with “some” knowledge about the number of discharges. A simple reservation policy is assumed and implemented in the model. A numerical example is given.

The capacity of the unit is 26 beds. The ICU management desires to reserve *four* beds for unscheduled arrivals. In the morning, 20 patients are observed in the unit. It turns out that *five* patients can be discharged. This means that a maximum of *seven* scheduled arrivals can be approved, because 20-5+7 = 22 beds. The remaining *four* beds are reserved for unscheduled arrivals.

TABLE 8.4 - PERFORMANCE MEASURES FOR THE OBSERVED SCHEDULE

Median values		Capacity = 26 beds								
		Reservation = 0			Reservation = 4			Reservation = 8		
		Schedule			Schedule			Schedule		
Occupancy	Perform. measure	Light	Medium	Heavy	Light	Medium	Heavy	Light	Medium	Heavy
Low	Utilization	17,70	18,52	19,41	17,68	18,49	19,42	17,48	18,16	18,70
	Scheduled admissions	16,00	19,99	25,96	15,82	19,71	24,92	14,45	17,52	20,03
	Late cancellations	0,00	0,01	0,04	0,18	0,29	1,08	1,56	2,48	5,97
	Refusals	0,39	0,61	1,57	0,27	0,43	0,94	0,08	0,10	0,13
Medium	Utilization	19,32	20,02	20,73	19,27	20,02	20,78	18,92	19,47	19,83
	Scheduled admissions	15,99	19,98	25,89	15,68	19,41	23,99	13,40	15,83	17,57
	Late cancellations	0,01	0,02	0,11	0,32	0,59	2,01	2,60	4,17	8,43
	Refusals	0,66	1,08	2,45	0,47	0,74	1,33	0,13	0,16	0,18
High	Utilization	20,72	21,32	21,86	20,70	21,33	21,94	20,11	20,48	20,78
	Scheduled admissions	15,99	19,96	25,73	15,37	18,82	22,64	11,62	13,32	14,64
	Late cancellations	0,01	0,04	0,27	0,63	1,18	3,37	4,38	6,68	11,36
	Refusals	1,22	1,88	3,61	0,86	1,21	1,78	0,25	0,26	0,29

The simulation is also carried out for 28 beds. The performance measures can be found in appendix III.

Interpretation of the performance measure yields the following general results.

- Utilization decreases with an increased number of beds reserved.
- The number of late cancellations increases with increasing schedule weight, increasing occupancy and number of beds reserved.
- The number of refusals increases with an increasing schedule weight and increasing occupancy.
- The number of refusals decreases with an increasing number of beds reserved.

8.5 ACCEPTED AND POSSIBLE SCHEDULE PERFORMANCE

In the previous section, the performance of the observed schedules is evaluated. In that case, no schedule intervention was done. In this section, the observed schedule is the starting point. The observed schedule is simulated and schedule interventions are done. For example, removing or adding a scheduled arrival to the surgical schedule.

The number of beds reserved for unscheduled arrivals is set to zero. The idea was that all scheduled arrival (on the accepted or possible schedule) should be admitted if the ICU had the option to intervene in the surgical schedule.

The performance outcomes of nine scenarios (3 occupancy levels and 3 schedules) are evaluated for one capacity level (26 beds) and two risk levels (0.05 and 0.25). In each scenario, an observed schedule (A) is transformed into an accepted schedule (B) and possible schedule (C) afterwards. The three schedules are provided for each scenario in the tables below. Table 8.5 shows the schedules for the scenarios in which the risk level was set to 0.25. This implies that the ICU management accepts that the unit is full with a probability of 25%. A similar table for risk level 0.05 can be found in appendix IV.

TABLE 8.5 - OBSERVED (A), ACCEPTED (B) AND POSSIBLE (C) SCHEDULES IF RL = 0.25

Capacity = 26, Reservation = 0, Risk level = 0.25												
Occupancy	Schedule	Phase	1	2	3	4	5	6	7	Removals	Additions	Net change
Low	Light	A	0	4	2	4	1	5	0	0		
		B	0	4	2	4	1	5	0		14	
		C	0	10	5	5	5	5	0			14
	Medium	A	0	5	3	6	3	3	0	0		
		B	0	5	3	6	3	3	0		10	
		C	0	10	4	6	5	5	0			10
	Heavy	A	0	3	8	7	3	5	0	-2		
		B	0	3	8	5	3	5	0		2	
		C	0	3	8	5	5	5	0			0
Medium	Light	A	0	4	2	4	1	5	0	0		
		B	0	4	2	4	1	5	0		10	
		C	0	7	5	5	4	5	0			10
	Medium	A	0	5	3	6	3	3	0	-1		
		B	0	5	3	5	3	3	0		6	
		C	0	7	5	5	4	4	0			5
	Heavy	A	0	3	8	7	3	5	0	-5		
		B	0	3	6	4	3	5	0		1	
		C	0	3	6	4	4	5	0			-4
High	Light	A	0	4	2	4	1	5	0	0		
		B	0	4	2	4	1	5	0		3	
		C	0	4	4	4	2	5	0			3
	Medium	A	0	5	3	6	3	3	0	-3		
		B	0	4	3	4	3	3	0		3	
		C	0	4	4	4	4	4	0			0
	Heavy	A	0	3	8	7	3	5	0	-8		
		B	0	3	4	4	3	4	0		2	
		C	0	4	4	4	4	4	0			-6

In the low-light scenario, the observed schedule does not violate the risk condition. As a consequence, the observed schedule becomes the accepted schedule. Next, additional scheduled arrivals could be scheduled on Monday, Tuesday, Wednesday and Thursday.

In the low-medium scenario, the observed schedule does not violate the risk condition. As a consequence, the observed schedule becomes the accepted schedule. Next, additional scheduled arrivals could be scheduled on Monday, Tuesday, Thursday and Friday. Note that the possible schedules of low-light and low-medium are different. In the latter case, the six scheduled arrivals on the observed schedule do not need to be removed.

The possible schedule (C) of medium-light scenario is expected to be similar to the possible schedule (C) of the medium-medium scenario. However, this was not the case. It turned out that the schedule [0 7 5 5 4 5 0] violates the risk condition sometimes.

The removal and addition procedure aims at generating accepted and possible schedules by respecting the observed schedule as much as possible. For example, a possible schedule [0 4 4 4 4 4 0] in case of the low-heavy scenario is undesirable as it removes a scheduled arrival on Friday and adds some on Thursday. The better possible schedule is [0 4 4 4 2 5 0] as it respects the observed schedule.

Compared to the situation where RL is 0.25, more removals (Figure 8.1) and fewer additions (Figure 8.2) are registered

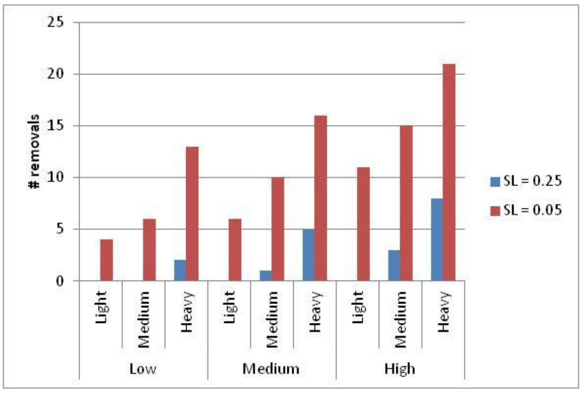


FIGURE 8.1 - NUMBER OF REMOVALS

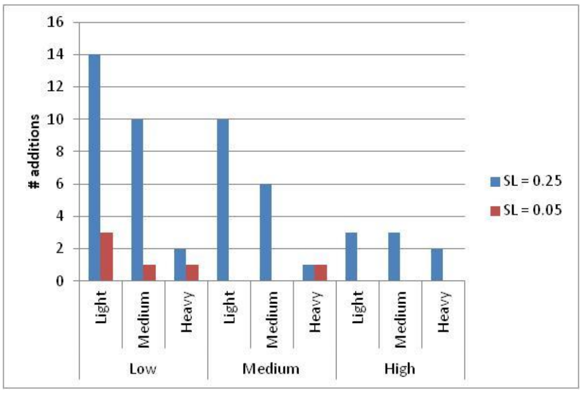


FIGURE 8.2 - NUMBER OF ADDITIONS

Interpretation of the performance measure yields the following general results.

- The number of removals increases as the weight of the schedule increases.
- The number of additions decreases as the weight of the schedule increases.
- The number of removals increases as the initial occupancy of the unit increases.

The performance measures of the schedules generated for risk level 0.25 are presented in Table 8.6. The performance measures of the schedules generated for risk level 0.05 are presented in appendix V

TABLE 8.6 - PERFORMANCE MEASURES FOR RL = 0.25

Median values		Capacity = 26, Reservation = 0, Risk level = 0.25								
		Schedule								
		Light			Medium			Heavy		
Occupancy	Performance measure	A	B	C	A	B	C	A	B	C
Low	Utilization	17,70	17,69	20,28	18,52	18,51	20,27	19,41	19,15	19,50
	Scheduled admissions	16,00	16,00	29,99	19,99	19,99	29,99	25,96	23,98	25,98
	Late cancellations	0,00	0,00	0,01	0,01	0,01	0,02	0,04	0,02	0,02
	Refusals	0,39	0,39	1,54	0,61	0,61	1,61	1,57	1,13	1,42
	Schedule changes	-	-	14,00	-	-	10,00	-	-2,00	2,00
Medium	Utilization	19,32	19,30	21,01	20,02	19,90	20,85	20,73	20,17	20,33
	Scheduled admissions	15,99	15,99	25,98	19,98	18,99	24,99	25,89	20,98	21,98
	Late cancellations	0,01	0,01	0,02	0,02	0,01	0,01	0,11	0,02	0,02
	Refusals	0,66	0,67	1,81	1,08	0,87	1,63	2,45	1,24	1,38
	Schedule changes	-	-	10,00	-	-1,00	7,00	-	-5,00	1,00
High	Utilization	20,72	20,68	21,18	21,32	20,90	21,38	21,86	21,06	21,37
	Scheduled admissions	15,99	15,99	18,99	19,96	17,00	19,99	25,73	17,99	19,99
	Late cancellations	0,01	0,01	0,01	0,04	0,01	0,01	0,27	0,01	0,01
	Refusals	1,22	1,19	1,56	1,88	1,25	1,70	3,61	1,41	1,70
	Schedule changes	-	-	3,00	-	-3,00	3,00	-	-8,00	2,00

Evaluation of the performance measures

- The number of removals increased with the weight of the schedule. Heavier schedule required more removals.
- The number of additions decreased with the weight of the schedule. Heavier schedules accepted fewer additions.
- The number of removals increased with the initial occupancy of the ICU. Higher occupancy was related to more removals.
- The number of additions decreased with an increase in initial occupancy of the ICU. Higher occupancy was related to fewer additions.
- Variability of the observed schedule was found to be related to the number of removals and additions. For example, the observed schedule [0 0 15 0 0 0 0] would lead to many more removals and additions compared to observed schedule [0 3 3 3 3 3 0].

8.6 PARAMETER SETTING

The conclusion of the performance evaluation is that the number of refusals and late cancellation is quite stable for a given risk level. The risk level is an important parameter to the model as it specifies the risk the hospital management wants to bear. Also, the risk level is important regarding performance measures refusals and late cancellations. Waiting time is not explicitly taken into account, but the issue is discussed below.

8.6.1 WAITING TIME

A smaller risk level is associated with fewer accepted scheduled arrivals. A risk level set too small could cause problems in terms of waiting time. On average, the number of elective arrivals should be around 930 per year. Assuming 48 operating weeks of five days per year, this would mean 3.875 scheduled arrivals per working day. In the current setting, the number of scheduled arrivals could be reduced until zero. To overcome the issue of waiting time, the setting could be adapted to a minimum of four per day.

8.6.2 REFUSALS, EARLY AND LATE CANCELLATIONS

The risk level is associated with the number of refusals, early and late cancellations. A smaller risk level is associated with fewer refusals and late cancellations compared to a larger risk level. The reduction on these two measures is paid by the early cancellations (schedule removals) and additions.

8.7 CONCLUSIONS

Conclusions are formulated with respect to the model. Given the observations and conclusions above, it can be concluded that the model produces intuitive results.

- The model took account of the current ICU state and observed schedule. Based on this information, alternative schedules (accepted and possible) were derived to influence the performance of the ICU.
- The number of removals increased with a higher occupancy and heavier schedule.
- It was possible to (almost) eliminate the number of late cancellations. Also, the number of refusals was found to be quite stable across all scenarios. However, the reduction in late cancellations and stable number of refusals came at the cost of an increased number of removals (i.e. early cancellations).
- The accepted and possible schedule is dependent on the current state of the ICU and also desired service level.
- Irrespective of the risk level chosen. The removal and addition procedure always try to end up with a relatively leveled schedule. This suggests adoption of a uniform cap policy.

Essentially, the variability in the IC demand is buffered in the surgical schedules. This is just one of the options the ICU management has in order to meet the demand. Patient can be discharged early or IC beds opened (e.g. quality loss). A major drawback of the adaptive cap policy in its current form is that it requires great flexibility of the medical disciplines. The medical disciplines have to remove and add patient regularly.

Flexibility in capacity can be seen as the alternative for the adaptive cap based policy. Flexibility is investigated in the next chapter.

9 EXPECTATIONS MODEL: FLEXIBILITY OF THE ICU

In the simulation model, it was assumed that the scheduled arrivals (elective surgery with IC indication) needed postoperative stay with certainty. Unscheduled arrivals after elective surgery (without IC indication) are incorporated into the unscheduled arrivals. Inspired by the idea of Beliën et al. (2007) in which the demand resulting from a surgical block is considered dependent on the surgeon and hospital unit, the following approach is adopted (Figure 9.1) .

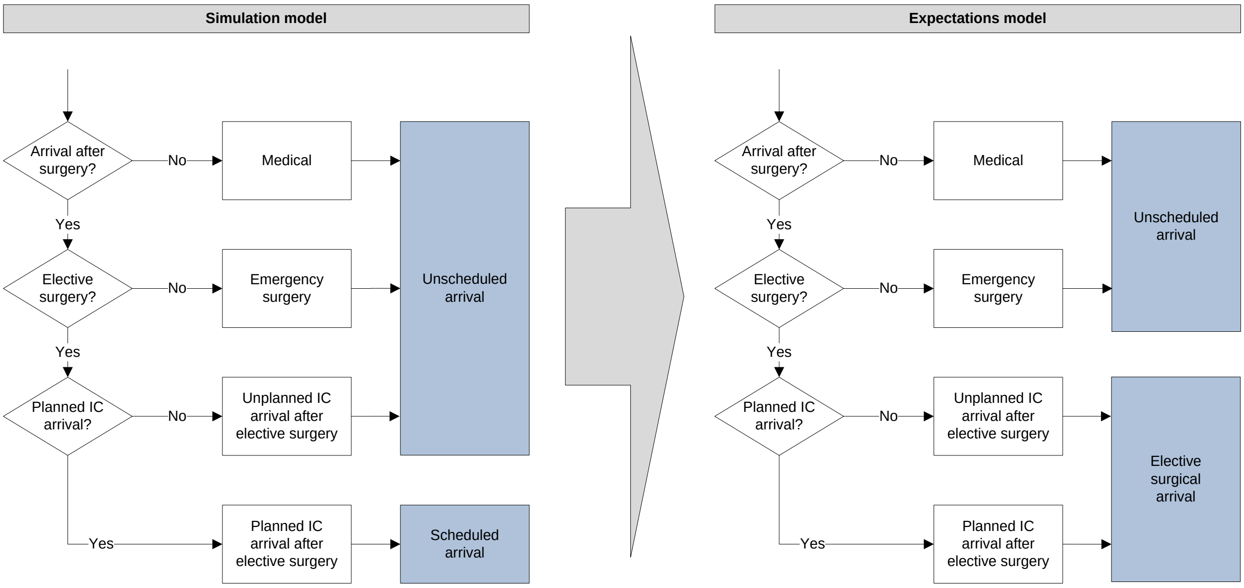


FIGURE 9.1 - CHANGE IN PERSPECTIVE OF PATIENT CATEGORIES

All arrivals at the ICU after elective surgery are considered to be the "elective surgical arrivals". This could be a patient with or without IC indication. Medical and emergency surgical arrivals remain in the "unscheduled arrivals" category.

The number of surgical arrivals at the ICU is a function of the surgical schedule. The surgical schedule consists of surgical sessions in which a surgeon operates a patient. Each session is associated with a certain probability to result in an arrival at the intensive care unit. The probability depends on several variables, for example the surgical intervention, the surgeon and patient specific characteristics.

In this chapter, the value of flexibility in the IC capacity is investigated. Flexible IC capacity is compared to a fixed level of staffed beds with reservation policies. In the flexible scenario, the number of staffed beds is determined as follows. The expected demand for the next seven day is calculated. The number of staffed beds to operate equals the expected demand plus a fixed number of beds to buffer the variability in the demand.

The ideal scenario would be that the capacity is increased just before a patient arrives. However, the capacity of the IC is physically restricted to 34 beds. Also, the number of staffed beds cannot be increased on a short notice. That is, it takes time to increase the capacity of the ICU (lead time).

9.1 MODEL INPUT

Compared to the theoretical model in chapter 6, the model input is changed in order to approach the real situation of the ICU in the St. Elisabeth Hospital.

- Ten unscheduled patient categories instead of one.
- A time varying unscheduled arrival rate instead of a fixed unscheduled arrival rate.
- A time varying scheduled arrival rate instead of a fixed scheduled arrival rate.
- Empirical length of stay distributions.

9.1.1 TEN UNSCHEDULED PATIENT CATEGORIES

In the simple model, two patient types are considered: unscheduled and scheduled patients. For the application of the model, the unscheduled patient type was broken down into ten patient categories.

Based on the data set, ten patient categories are defined for the unscheduled demand (Table 9.1). A patient category is a combination of arrival type and medical discipline with at least 50 arrivals in 2012. Combination with less than 50 arrivals in 2012 were grouped in patient categories 7 and 10 i.e. “Other”.

TABLE 9.1 - UNSCHEDULED PATIENT CATEGORIES

Patient category	Arrival type	Medical discipline	Arrivals (2012)
1	Medical	Inwendige geneeskunde	254
2	Medical	Neurochirurgie	241
3	Medical	Heelkunde	210
4	Medical	Longziekten	157
5	Medical	Neurologie	126
6	Medical	Cardiologie	89
7	Medical	Other	52
8	Emergency surgical	Heelkunde	172
9	Emergency surgical	Neurochirurgie	119
10	Emergency surgical	Other	37

9.1.2 TIME VARYING UNSCHEDULED ARRIVAL RATE

The unscheduled arrival rate includes the medical and emergency surgical (Table 9.2). The unscheduled arrival rate varies per week day as the number of operating rooms per weekday varies. The arrival distributions are assumed to follow a Poisson distribution. Test indicated that this assumption holds for the number of unscheduled arrivals per day (appendix VI). It is assumed that the Poisson assumption also hold for a certain weekday.

TABLE 9.2 - UNSCHEDULED ARRIVAL RATES PER WEEKDAY

Arrival rate per day	**Weekday**						
Patient category	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1	0,7692	0,7308	0,7885	0,7308	0,5192	0,8269	0,5192
2	0,7308	0,4808	0,6731	0,7115	0,7692	0,6731	0,5962
3	0,6346	0,5192	0,5192	0,7500	0,6154	0,5769	0,4231
4	0,5577	0,4615	0,3846	0,5000	0,3654	0,2115	0,5385
5	0,3077	0,4231	0,2885	0,4423	0,1731	0,5000	0,2885
6	0,0769	0,2692	0,4423	0,1731	0,3269	0,3077	0,1154
7	0,1731	0,1154	0,0962	0,1346	0,1538	0,1731	0,1538
8	0,5000	0,4038	0,5385	0,4423	0,3846	0,4231	0,6154
9	0,3462	0,5000	0,3269	0,2885	0,4038	0,2308	0,1923
10	0,1154	0,0577	0,0962	0,1154	0,1731	0,0962	0,0577
Sum	**4,2115**	**3,9615**	**4,1538**	**4,2885**	**3,8846**	**4,0192**	**3,5000**

9.1.3 ELECTIVE SURGICAL ARRIVAL RATE

The number of elective surgical arrivals is a function of the surgical schedule. The number of surgical sessions scheduled each weekday varies as a consequence of surgeon schedules and the number of productive operating rooms.

Empirical distributions were constructed for the number of surgical sessions scheduled (Figure 9.2). The red box was the lower quartile and the green box was the higher quartile. The median was in between the lower and higher quartile.

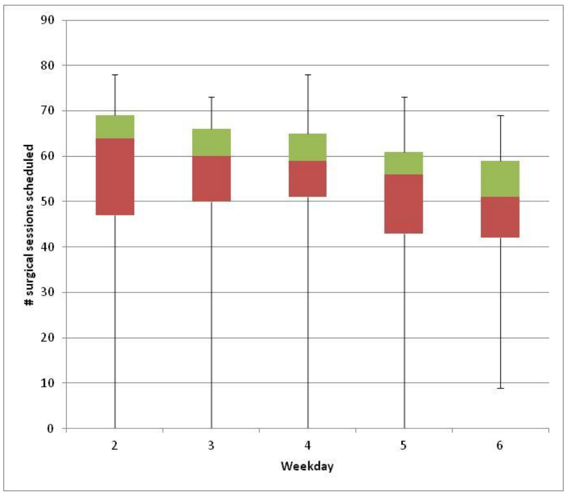


FIGURE 9.2 - NUMBER OF SUGRICAL SESSIONS SCHEDULED PER WEEKDAY (2 = MONDAY)

Before surgery, the patient's health status is checked at the preoperative screening. Each and every surgical session could result into an arrival at the ICU with a certain probability. The probability of going to the ICU is conditional on the IC indication (Table 9.3).

The probability that a surgical session have an IC indication on a Tuesday is larger than the probability on Monday. This implied that more severe surgeries are performed on Tuesdays compared to Mondays. Furthermore, the probability of IC arrival given IC indication varied from day to day. For example, the probability of IC arrival given an IC indication is 0.9716 on Tuesdays and 0.8041 on Mondays.

TABLE 9.3 - PROBABILITY OF IC INDICATION AND IC ARRIVAL

Weekday	P(IC indication)	P(no IC indication)	P(IC arrival|IC indication)	P(IC arrival|no IC indication)
1	n/a	n/a	n/a	n/a
2	0.0491	0.9509	0.8041	0.0024
3	0.0713	0.9287	0.9716	0.0048
4	0.0642	0.9358	0.8579	0.0040
5	0.0612	0.9388	0.9006	0.0052
6	0.0673	0.9327	0.8894	0.0029
7	n/a	n/a	n/a	n/a

The number of surgical sessions is sampled from an empirical distribution. Each surgical session of the surgical schedule had a probability to obtain an IC indication. Alternatively, the surgical sessions did not have an IC indication (Figure 9.3). This can be regarded as a Bernoulli trial.

Multiple Bernoulli trials with equal probabilities can be modeled by a binomial distribution. A binomial distribution is used to derive the number of surgeries with IC indications and the number of surgeries without IC indication. For both groups sampling is done from a binomial distribution

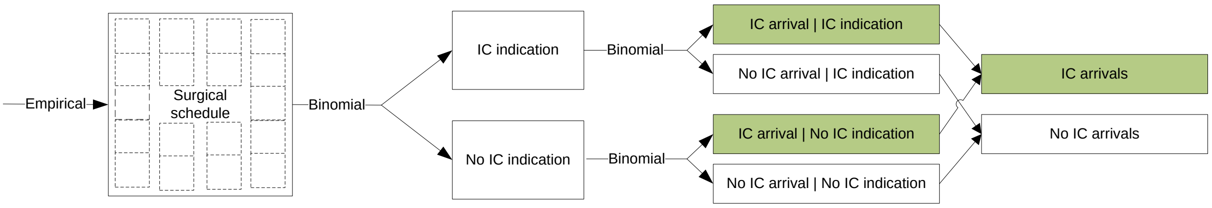


FIGURE 9.3 - PROBABILITY OF IC INDICATION AND CONDITIONAL IC ARRIVAL

9.1.4 EMPIRICAL LENGTH OF STAY DISTRIBUTIONS

In chapter 7, the performance of the model is evaluated assuming geometrically distributed length of stays for scheduled and unscheduled patients. In the application to the ICU, empirical length of stay distributions is used. After seven days, the probability of being discharged is considered constant (geometric distribution). The constant is set by taking the average length of stay after seven days. Patients in the dataset that were discharged on the day of arrivals (period 0) are included in period 1.

TABLE 9.4 - CONDITIONAL DISCHARGE PROBABILITIES

Conditional discharge Probabilities per period	**Period**							
Patient category	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**>7**
1	0,7115	0,3973	0,2273	0,2941	0,1667	0,2000	0,3125	0,1447
2	0,2780	0,1954	0,2143	0,1818	0,3000	0,0794	0,0862	0,0969
3	0,5048	0,2885	0,2027	0,2373	0,1111	0,1750	0,1212	0,1007
4	0,4268	0,3222	0,1311	0,2642	0,2051	0,1290	0,1852	0,1158
5	0,5079	0,2258	0,1458	0,1951	0,2424	0,1200	0,1818	0,0942
6	0,6292	0,2727	0,2083	0,1053	0,2353	0,1538	0,0909	0,0885
7	0,6923	0,3125	0,0909	0,1000	0,3333	0,0000	0,1667	0,0725
8	0,5029	0,3412	0,0714	0,1923	0,0238	0,0488	0,1538	0,0801
9	0,3697	0,2133	0,2373	0,2444	0,1176	0,0333	0,1379	0,0542
10	0,7297	0,2000	0,0000	0,3750	0,0000	0,0000	0,4000	0,0326
11 (elective surgical patients)	0,8028	0,2974	0,5401	0,1905	0,4118	0,1333	0,3077	0,0453

9.2 EXPECTATIONS

Recall that a time period is 24 hours and lasts from 8 am in the morning to 8 am the next morning. The total demand at the end of a time period t (D_t) is the sum of the remaining demand at the end of time period t (R_t), the unscheduled demand at the end of period t (U_t) and elective surgical demand at the end of period (S_t). The total demand at the end of a time period t (D_t) for t>0 is assumed to follow a normal distribution (Figure 9.4).

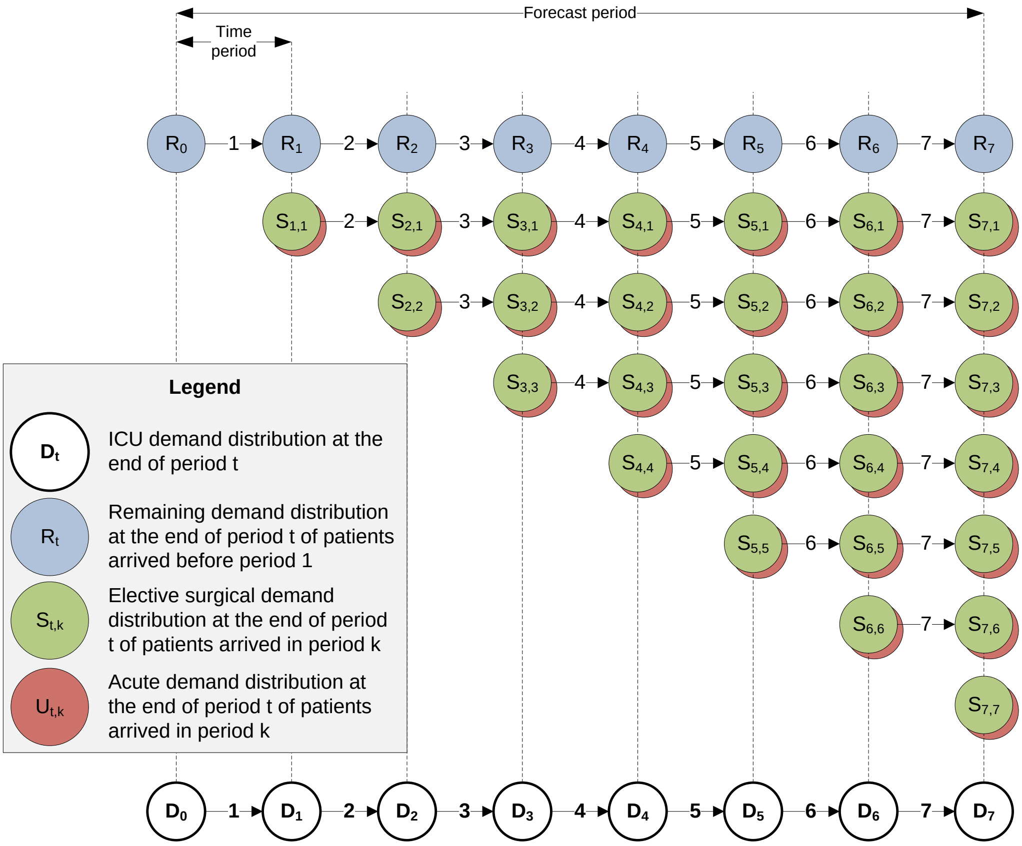


FIGURE 9.4 - DESCRIPTION OF DEMAND COMPONENTS BASED ON ICU STATE

In this model, only the expected demand of the demand distribution at the end of each period is considered. The formulae for the calculation of the expected demand at the end of a time period are provided in appendix VII.

9.3 DECISION

The expected values of the demand distribution at the end of the next seven time periods are calculated and used to decide about the number of staffed beds to have in the near future. The current patient population expected unscheduled arrivals and expected elective surgical arrivals are taken into account. Two variables play a dominant role in the decision about the number of staffed beds (Figure 9.5).

- L denotes the lead time of the capacity change. For example, today is a Monday. If L = 2, this means that the number of staffed beds for Wednesday is determined. L says something about the time needed to alter the capacity.
- V denotes the buffer capacity that is kept in addition to the expected demand. Staffing a number of beds based on the expected value only would lead to many refusals and late cancellations.

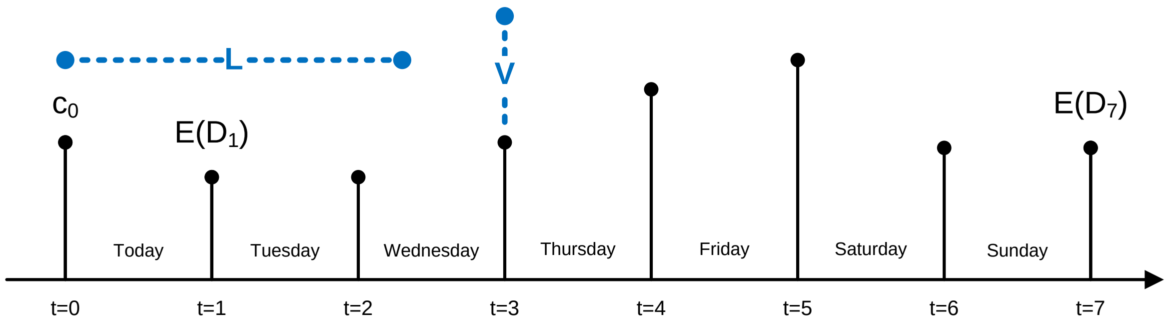


FIGURE 9.5 - EXPECTED DEMAND IN RELATION TO LEAD TIME AND BUFFER

For example, if L = 2 and V = 6 and today is a Monday. The expected demand at the end of Wednesday equals 20.5 patients. The number of staffed beds on Wednesday should equal $\lceil 20.5 + 6 \rceil = 27$. The six beds are needed to buffer the variability of the demand.

A day elapses as in the adaptive cap policy (i.e. discharge, observe and admit elective surgical arrivals, observe and admit unscheduled arrivals). If four unscheduled patients arrive and three beds are available from them, one patient is refused by random selection. This patient is transferred to another IC and thereby lost. A late cancellation is added to the surgical schedule one week from now. Variable R, the number of reserved beds for unscheduled arrivals is used to determine the priorities of the ICU.

9.4 SCENARIOS AND PERFORMANCE EVALUATION

The performance of several scenarios is evaluated in this paragraph. One scenario is simulated for 18,250 days. The first 365 days is considered to be the warm up period. Consequentially, performance measures are reported from day 366 to day 18,250.

Five scenarios are investigated (Table 9.5). The reference scenario is a fixed number of staffed beds. This number is set to 30. Four flexible scenarios are investigated, namely with a capacity lead time of 2 and 5 and a buffer of 6 and 8. The maximum number of beds is set to 34 beds (the physical restriction of the ICU).

TABLE 9.5- SCENARIOS CONSIDERED

Scenario	L	V	R
Fixed 30 beds	N/a	N/a	0,4,6 and 8
Flexible, max 34 beds	2	6	0,4,6 and 8
	5	6	0,4,6 and 8
	2	8	0,4,6 and 8
	5	8	0,4,6 and 8

9.4.1 REFUSALS AND LATE CANCELLATIONS

Two important performance measures are the late cancellations and the refusals. Figure 9.6 presents both measures for the five simulated scenarios.

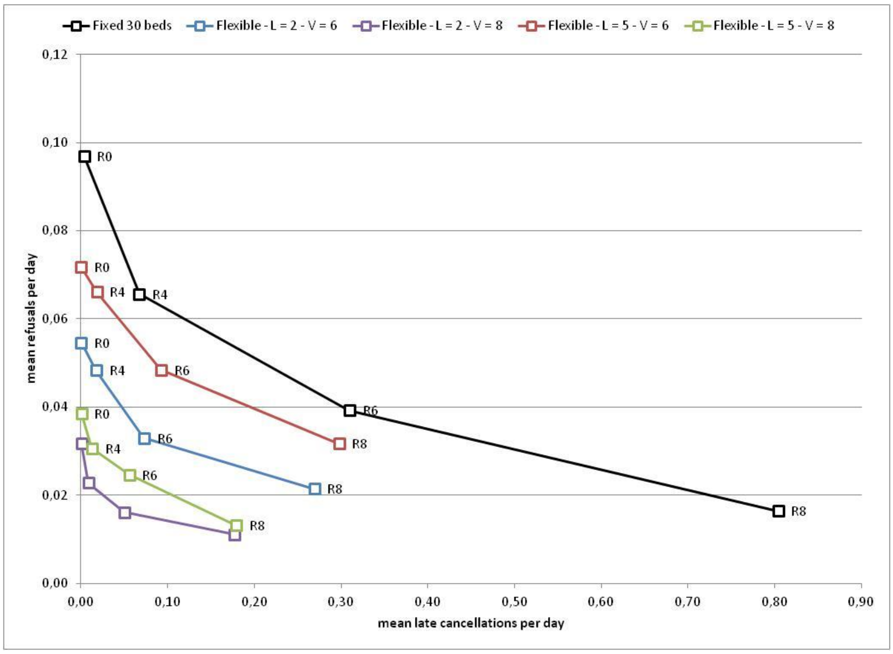


FIGURE 9.6 - REFUSALS AND LATE CANCELLATIONS FOR FIVE SCENARIOS

Three conclusions can be drawn the figure above.

1. A shorter capacity lead time is related to fewer late cancellations and refusals. A shorter capacity lead time enables the ICU to wait and react on nearby (more reliable) expectations.
2. A larger buffer capacity V is related to fewer late cancellations and refusals. This is simply because the ICU is operated more risk averse than in case V = 6.
3. A larger number of beds reserved for unscheduled patients is related to fewer refusals but more late cancellations.

9.4.2 UTILIZATION AND INVESTMENT

Figure 4.1 shows the mean utilization and mean number of staffed beds for R = 4. The utilization of the fixed 30 beds scenario is compared to the flexible scenarios. The flexible scenarios with buffer V = 6 have a larger mean utilization and require less investment compared to the other scenarios. That is, the number of staffed beds per day is smaller.

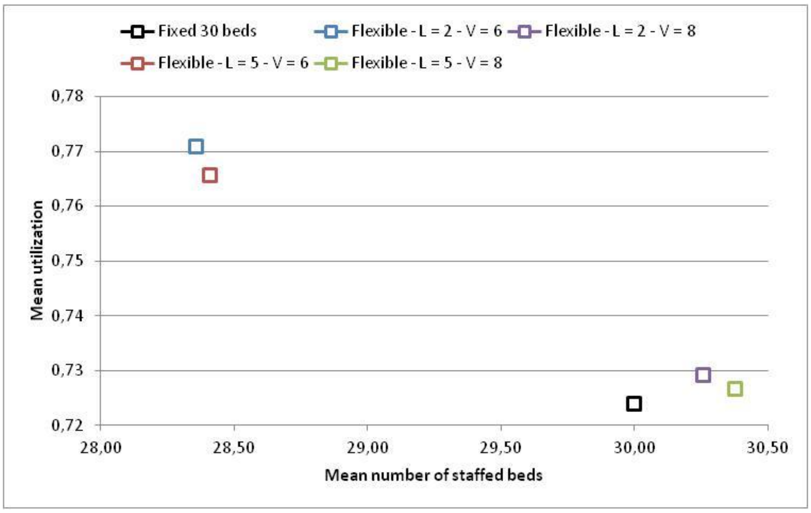


FIGURE 9.7 - MEAN NUMBER OF STAFFED BEDS VERSUS MEAN UTILIZATION

9.4.3 FLEXIBILITY OF INTENSIVE CARE SUPPLY

In the simulation it is assumed that the number of staffed beds can be easily in- and decreased. This is an extreme situation, resulting in plus or minus six beds from day to day. In practice, a staffing schedule is made well more than one month before the realization. This provides stability towards the IC personnel.

The intensive care capacity is considered to be fixed throughout the report. In practice however, the number of staffed IC beds can be in- and decreased by the ICU management. Regarding this issue, several restrictions have to be dealt with. For example, physical restrictions (maximum amount of IC capacities like beds, monitors, rooms and personnel), but also labor restrictions (how quickly can the IC capacity be increased).

As a consequence of this flexibility, the costs of the permanent capacity can possibly go down. The reduction in permanent staff could be invested into availability of flexible staff.

10 CONCLUSIONS AND RECOMMENDATIONS

In this chapter, conclusions and recommendations are provided. The chapter provides an overview of the work done and discusses the insights gathered during project execution.

The intensive care unit can be seen as a production system. (Hopp and Spearman 2008) state that variability in a production system will be buffered by some combination of time, inventory and capacity. Also, these authors state that: "Flexibility reduces the amount of variability buffering that is needed." In this report, an application of both time and flexibility is given.

10.1 TIME

Time and capacity is currently applicable to the ICU of the St. Elisabeth hospital. If a patient is refused, the patient is transferred to another facility (capacity) or if a patient is cancelled late (time).

An attempt is made to develop an adaptive cap policy for the ICU of the St. Elisabeth hospital. Instead of specifying the number of scheduled arrivals *before* any scheduling activities is undertaken, the focus was on early cancelling surgical sessions *after* scheduling activities are undertaken. This would enable the option of early cancelling an elective surgical arrival. The downside of this policy is that it demands great flexibility of the medical disciplines. The policy early cancels elective surgeries in case of peak IC demand and asks for more elective surgical arrivals in low IC demand periods.

Also, structural cancellation of surgical arrivals will increase the waiting list for these patients. The performance of the ICU would improve, but at the cost of decreased hospital performance (e.g. production figures). This is an important issue when parameters will be set.

The schedules generated by the adaptive cap based policy suggest that the elective surgical arrivals should not be variable. Instead, a leveled surgical schedule is desired. This is confirmed by other researchers.

The performance of the adaptive cap policy can possibly be improved by shortening the scheduling horizon and lengthen the prediction horizon for the ICU states. The goal is to make these horizons equally long.

10.2 FLEXIBILITY

As mentioned above, implementation of the adaptive cap policy requires flexibility of the medical disciplines. Patients will need to be removed and added regularly.

Flexibility could also be introduced at the capacity of the ICU. This issue is investigated in the expectations model. One of the conclusions is that the amount of investment (mean number of beds open) can be reduced. Also, the refusals and late cancellations decrease according to the considered model. As prediction of future ICU states is difficult for the distant future, the focus should be on short term flexibility and a sufficient buffer capacity should still be kept at hand.

10.3 DEFINE AND DESCRIBE DEMAND

Both time and flexibility can be used to improve the performance of the intensive care unit. For both situations, information about future demand is needed.

From the quantitative analysis, it can be concluded that the number of IC indications does not match the number of elective surgical arrivals on around 2/3 of the surgical days. The qualitative analysis indicated that a lot of flexibility is offered on the day of schedule execution.

This suggests the need for a better prediction of the elective surgical IC arrivals (distribution). Each surgical session has some probability to result into an IC arrival. Based on historical information, the weight of the surgical schedule could be determined. After that, it could be possible to impose limits on the weight of the schedule and determine the capacity (level the elective surgical demand).

All in all, the demand should be defined and described as a starting point. Based on the predictions, time and flexibility should be applied to the ICU, together with other option of the ICU management (e.g. early discharge).

11 DISCUSSION AND FURTHER RESEARCH

In this project, the surgical schedule is used to buffer the variability in the intensive care demand. The reason is that the surgical schedule can be influenced and elective surgeries can be postponed to some extent. Also flexibility is investigated.

Prioritization of elective surgeries

The model presented in this thesis assumed that all elective surgical arrivals belong to one homogenous group. An elective surgical patient could be removed from the surgical schedule with certainty. In practice however, a share of elective surgeries is semi urgent and could not be removed safely i.e. the patient needs timely surgery. Prioritization of the elective surgeries that indicates which patients' surgery could be postponed safely from the schedule would be an improvement to the model.

Surgical schedule IC demand distribution

The elective surgical demand per day is a function of the surgical schedule that day. To improve the state dependent predictions, the demand distribution of a particular surgical scheduled should be defined. Each individual surgical session is associated with a particular probability to result into IC demand. Instead of a binary IC indication (yes or no), a continuum could be developed capturing the IC arrivals without IC indication.

Trend and/or seasonality

The unscheduled arrival rate per day was assumed to be fixed (detailed simulation) and fixed per weekday (expectation model) per patient category. That is, the probability distribution of unscheduled arrivals on a Monday in January was considered equal to the probability distribution of unscheduled arrivals on a Monday in September. Investigation of a trend or seasonal component within the unscheduled arrival demand distribution was absent in this study, but could be a topic in future studies.

Adaptive cap policy

Ideally, the adaptive cap policy would specify the number of elective surgical arrivals *before* any patient is scheduled. However, the prediction horizon is rather short (most of the patients today leave within seven days. This means that the current state of the ICU does not say much about the state of the ICU in two or three weeks. Alternatively, an adaptive cap policy is introduced that observes the surgical schedule and authorizes (part) of the surgical schedule in light of the current ICU state. The argument for an adaptive cap based policy is that early cancellations are preferred over late cancellations. Shortening the scheduling horizon would reduce the number of early cancelations as the number of elective surgical arrivals authorized is specified *before* any scheduling took place.

Independence assumption

Throughout the study, the assumption of independent discharge probabilities was adopted. As the ICU management can decide to discharge a patient early for capacity reasons, the assumption does not hold anymore. The discharge probability is then not independent of other patients, but depends on the utilization in the unit.

12 BIBLIOGRAPHY

Adan, I., en JMH Vissers. „Patient mix optimisation in hospital admission planning: a case study." *International journal of operations \& production management* (MCB UP Ltd) 22, nr. 4 (2002): 445--461.

Adan, I., J. Bekkers, N. Dellaert, J. Jeunet, en J. Vissers. „Improving operational effectiveness of tactical master plans for emergency and elective patients under stochastic demand and capacitated resources." *European Journal of Operational Research* (Elsevier) 213, nr. 1 (2011): 290--308.

Adan, I., J. Bekkers, N. Dellaert, J. Vissers, en X. Yu. „Patient mix optimisation and stochastic resource requirements: A case study in cardiothoracic surgery planning." *Health care management science* (Springer) 12, nr. 2 (2009): 129--141.

Beliën, J., E. Demeulemeester, en B. Cardoen. „A decision support system for cyclic master surgery scheduling with multiple objectives." *Journal of scheduling* (Springer) 12, nr. 2 (2009): 147--161.

Beliën, J., en E. Demeulemeester. „Building cyclic master surgery schedules with leveled resulting bed occupancy." *European Journal of Operational Research* (Elsevier) 176, nr. 2 (2007): 1185--1204.

Bertrand, J.W.M., en J.C. Fransoo. „Operations management research methodologies using quantitative modeling." *International Journal of Operations \& Production Management* (MCB UP Ltd) 22, nr. 2 (2002): 241--264.

Bountourelis, Theologos, M Yasin Ulukus, Jeffrey P Kharoufeh, en Spencer G Nabors. „The Modeling, Analysis, and Management of Intensive Care Units." 153--182. Springer, 2013.

Chaiwanon, Wongskorn. *Capacity Planning and Admission Control Policies for Intensive Care Units.* Boston: Massachusetts Institute of Technology, 2010.

Dellaert, N.P., en J. Jeunet. *Hospital admission planning to optimize major resources utilization under uncertainty.* Eurandom, 2009.

Dobson, Gregory, Hsiao-Hui Lee, en Edieal Pinker. „A model of ICU bumping." *Operations research* (INFORMS) 58, nr. 6 (2010): 1564--1576.

Harper, PR, en AK Shahani. „Modelling for the planning and management of bed capacities in hospitals." *Journal of the Operational Research Society* (JSTOR), 2002: 11--18.

Hopp, Wallace J., en Mark L. Spearman. *Factory Physics.* New York: McGraw-Hill, 2008.

Kim, S.C., en I. Horowitz. „Scheduling hospital services: the efficacy of elective-surgery quotas." *Omega* (Elsevier) 30, nr. 5 (2002): 335--346.

Kim, S.C., I. Horowitz, K.K. Young, en T.A. Buckley. „Analysis of capacity management of the intensive care unit in a hospital." *European Journal of Operational Research* (Elsevier) 115, nr. 1 (1999): 36--46.

Kim, S.C., I. Horowitz, K.K. Young, en T.A. Buckley. „Flexible bed allocation and performance in the intensive care unit." *Journal of Operations Management* (Elsevier) 18, nr. 4 (2000): 427--443.

Kokangul, A. „A combination of deterministic and stochastic approaches to optimize bed capacity in a hospital unit." *Computer methods and programs in biomedicine* (Elsevier) 90, nr. 1 (2008): 56--65.

Litvak, E., en M.C. Long. „Cost and quality under managed care: Irreconcilable differences.” *Am J Manag Care* 6, nr. 3 (2000): 305--12.

McManus, M.L., M.C. Long, A. Cooper, en E. Litvak. „Queuing theory accurately models the need for critical care resources.” *Anesthesiology* (LWW) 100, nr. 5 (2004): 1271--1276.

Mitroff, I.I., F. Betz, L.R. Pondy, en F. Sagasti. „On managing science in the systems age: two schemas for the study of science as a whole systems phenomenon.” *Interfaces* 4 (1974): 46-58.

Mols, Rik. *Capacity Management of an Intensive Care Unit.* Eindhoven: University of Technology Eindhoven, 2013.

Ridge, JC, SK Jones, MS Nielsen, en AK Shahani. „Capacity planning for intensive care units.” *European journal of operational research* (Elsevier) 105, nr. 2 (1998): 346--355.

St. Elisabeth Ziekenhuis. „(Jaar)documenten.” *St. Elisabeth Ziekenhuis.* 12 07 2012. http://www.elisabeth.nl/ik_ben_professional/(jaar)documenten/ (geopend 11 07, 2012).

Valentin, A., en P. Ferdinande. „Recommendations on basic requirements for intensive care units: structural and organizational aspects.” *Intensive care medicine* (Springer) 37, nr. 10 (2011): 1575--1587.

Van Houdenhoven, M., et al. „Fewer intensive care unit refusals and a higher capacity utilization by using a cyclic surgical case schedule.” *Journal of critical care* (Elsevier) 23, nr. 2 (2008): 222--226.

Vissers, J., en R. Beech. *Health Operations Management.* New York: Routledge, 2005.

Vissers, JMH, I. Adan, en JA Bekkers. „Patient mix optimization in tactical cardiothoracic surgery planning: a case study.” *IMA Journal of Management Mathematics* (IMA) 16, nr. 3 (2005): 281--304.

Appendix I: Extracted data sets

Two data sets are extracted from the databases of the hospital.

First data set: Data on admissions in 2012 was gathered from the database MediScore. The data contained the following information for each unique admission.

1. Gender
2. Age
3. Admission number
4. Hospital Admission date
5. Hospital Discharge date
6. ICU Admission date
7. ICU Admission time
8. ICU Discharge date
9. ICU Discharge time
10. ICU Admission length of stay
11. Admission type
12. Referring specialism
13. Admission source
14. Admission via OT (Y/N)
15. Discharge sink
16. Mechanical ventilation at admission
17. Mechanical ventilation within 24 hrs after admission
18. APACHE II score
19. APACHE IV score
20. APACHE IV mortality

Second data set: Date on the emergency and elective surgeries. Also, IC indications are provided.

Per day in 2012:

1. Number of emergency surgeries
2. Number of elective surgeries
3. Number of elective surgeries IC indicated

Appendix II: Improving reliability of simulation model

In this section, the reliability of the simulation procedure is evaluated. How many simulated weeks are needed? Does the simulation procedure produce the same results in similar situations? These questions are answered in this section.

Prediction procedure variance

The prediction procedure's output is a 1x7 vector with the probability that the ICU is full. The prediction procedure was run 100 times with a varying number of simulated paths (i.e. 10, 100, 1000 and 3000) and current state [7,15] and observed schedule [0 4 4 4 4 4 0].

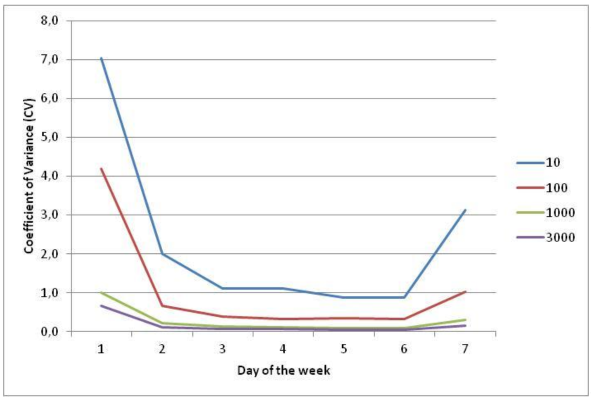


FIGURE A - COEFFICIENT OF VARIACE PER CASE

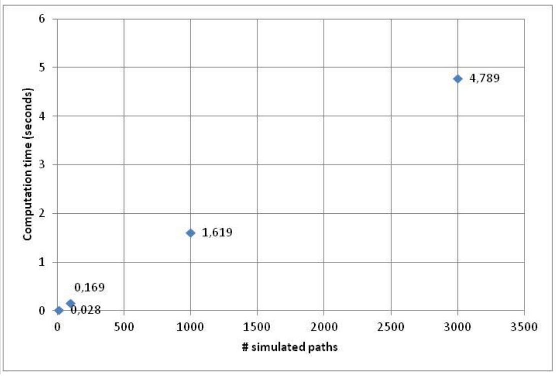


FIGURE B – COMPUATION TIME

The coefficient of variation in the probability that the unit is full is assessed. The mean probability that the unit is full is considered to be independent of the number of simulated paths. However, the variance was not. This is indicated by figure A. Increasing the number of simulated paths was associated with a decreasing variance.

Decreasing the variance in the prediction outcome is desirable, but comes at the cost of computation time. The prediction procedure is a key procedure in the simulation. In some scenarios the prediction procedure is used many times. A tradeoff has to be made between the decrease in variance and the computation time (Figure B).

Unique accepted schedules

If the observed schedule violates the risk condition, the removal procedure is executed to remove scheduled arrivals from the surgical schedule. Again, simulations are run to assess whether stable results are obtained from the simulation procedure.

The simulation procedure is executed 100 times with 10, 100 and 1000 simulated paths. This means that 100 accepted schedules were generated. The current state was [7, 15] with observed schedule [0 6 8 3 6 5 0]. For this scenario, the number of unique accepted schedules was counted. The results can be found in the table below.

TABLE A: UNIQUE SCHEDULES

# simulated paths	# unique accepted schedules SL = 0.05	# unique accepted scheduled SL = 0.5
10	85/100	55/100
100	27/100	18/100
1000	16/100	4/100

The number of unique accepted schedules decreases with an increasing number of simulated paths. Furthermore, the number of unique accepted schedules decreases with an increasing service level. Even with 1000 simulated paths, multiple unique accepted schedules are found.

The scenario with 1000 simulated paths and service level 0.5 is investigated.

Given the current state and observed schedule, the removal procedure approaches schedule 1 and predicts the outcome. In 3/100 simulations, schedule 1 does not violate the risk condition. However, in 97/100 simulations the schedule is not accepted. Scheduled arrival is removed from either Monday or Thursday.

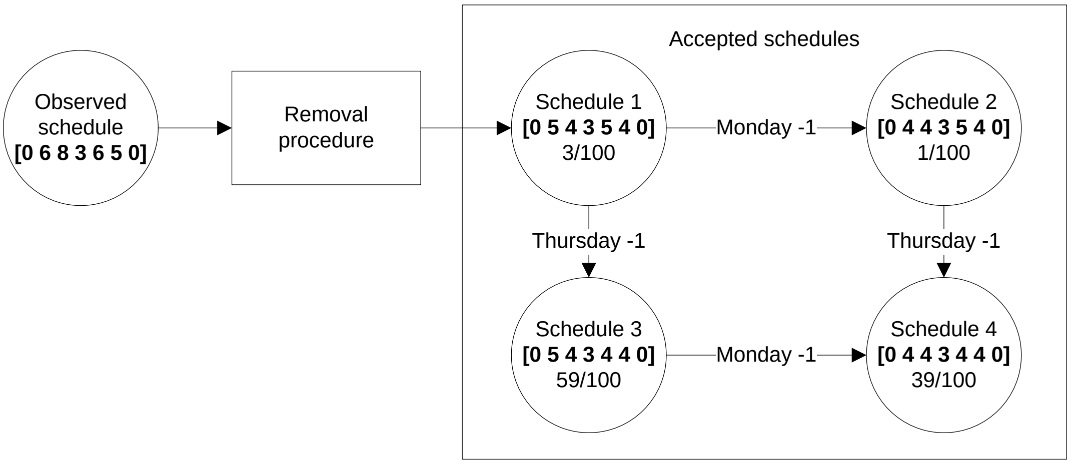


FIGURE C – UNIQUE ACCEPTE SCHEDULES

The conclusion is that the accepted schedule varied although the input i.e. current state and surgical schedule is the same. In some cases, schedule 3 is regarded as the accepted schedule and in other cases schedule 4 was regarded as the accepted schedule.

The prediction outcomes of 1 time 1000 simulated paths varied and therefore yielded different accepted schedules. The accepted schedules need to be based on some more stable measure. So instead of relying on just one prediction outcome, more prediction outcomes were needed. Therefore, the following solution is proposed and implemented.

Stable outcomes

The prediction procedure is run 50 times 1000 simulated paths (figure D). The probability that the unit is full is assumed to be normally distributed. A one tailed t-test is conducted to check whether the surgical schedule violates the risk condition i.e. the probability that the unit is full is significantly smaller than the risk condition.

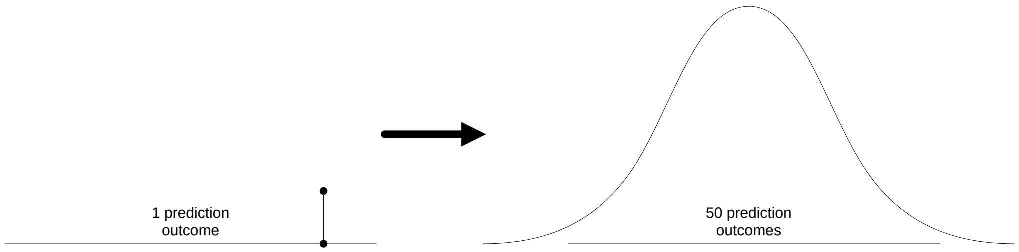


FIGURE D - ONE PREDICTION OUTCOME TO 50 PREDICTION OUTCOMES

For example: Given an observed schedule, the prediction outcomes indicate that the probability that the unit is full violates the risk condition on day 2 (figure E). More specifically, the probability that the unit is full is not significantly smaller than the risk condition.

As a consequence, one scheduled arrival on day 2 is removed from the schedule and again a prediction is made (50 x 1000 paths). The prediction outcomes indicate that the risk condition is not violated after removal of one scheduled arrival on day 2. More specifically, the probability that the unit is full is significantly smaller than the risk condition (figure F)

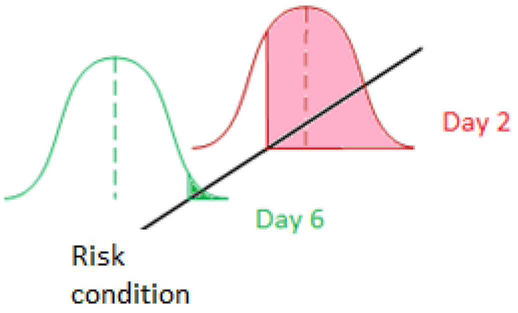


FIGURE E - SCHEDULE VOILATES RISK CONDITION

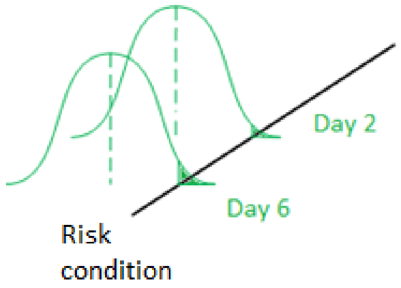


FIGURE F - SCHEDULE DOES NOT VIOLATE RISK CONDITION

Appendix III: Performance measures for 28 beds

Median values		Capacity = 28								
		Reservation = 0			Reservation = 4			Reservation = 8		
		Schedule			Schedule			Schedule		
Occupancy	Perform. measure	Light	Medium	Heavy	Light	Medium	Heavy	Light	Medium	Heavy
Low	Utilization	17,76	18,64	19,72	17,76	18,66	19,74	17,68	18,49	19,32
	Scheduled admissions	16,00	20,00	25,99	15,95	19,91	25,59	15,37	18,91	22,81
	Late cancellations	0,00	0,00	0,01	0,05	0,09	0,41	0,63	1,09	3,19
	Refusals	0,15	0,24	0,74	0,11	0,18	0,50	0,03	0,05	0,08
Medium	Utilization	19,44	20,26	21,19	19,44	20,25	21,21	19,27	19,98	20,60
	Scheduled admissions	16,00	20,00	25,97	15,90	19,79	25,15	14,89	17,98	20,98
	Late cancellations	0,00	0,00	0,03	0,10	0,21	0,85	1,11	2,02	5,02
	Refusals	0,27	0,47	1,27	0,20	0,34	0,79	0,05	0,07	0,10
High	Utilization	20,96	21,72	22,47	20,94	21,71	22,53	20,64	21,24	21,69
	Scheduled admissions	16,00	19,99	25,91	15,79	19,55	24,39	13,88	16,32	18,68
	Late cancellations	0,00	0,01	0,09	0,21	0,45	1,62	2,12	3,68	7,32
	Refusals	0,50	0,89	2,08	0,39	0,61	1,13	0,10	0,13	0,15

Appendix IV: Surgical schedules for risk level 0.05

Capacity = 26, Reservation = 0, Risk level = 0.25												
Occupancy	Schedule	Phase	1	2	3	4	5	6	7	Removals	Additions	Net change
Low	Light	A	0	4	2	4	1	5	0	-4		
		B	0	4	2	3	1	2	0		3	
		C	0	6	2	3	2	2	0			-1
	Medium	A	0	5	3	6	3	3	0	-6		
		B	0	5	3	2	2	2	0		1	
		C	0	6	3	2	2	2	0			-5
	Heavy	A	0	3	8	7	3	5	0	-13		
		B	0	3	4	2	2	2	0		1	
		C	0	4	4	2	2	2	0			-12
Medium	Light	A	0	4	2	4	1	5	0	-5		
		B	0	4	2	2	1	2	0		0	
		C	0	4	2	2	1	2	0			-5
	Medium	A	0	5	3	6	3	3	0	-11		
		B	0	3	2	2	1	1	0		0	
		C	0	3	2	2	1	1	0			-11
	Heavy	A	0	3	8	7	3	5	0	-17		
		B	0	3	2	2	1	1	0		1	
		C	0	4	2	2	1	1	0			-16
High	Light	A	0	4	2	4	1	5	0	-11		
		B	0	1	1	1	1	1	0		0	
		C	0	1	1	1	1	1	0			-11
	Medium	A	0	5	3	6	3	3	0	-15		
		B	0	1	1	1	1	1	0		0	
		C	0	1	1	1	1	1	0			-15
	Heavy	A	0	3	8	7	3	5	0	-21		
		B	0	1	1	1	1	1	0		0	
		C	0	1	1	1	1	1	0			-21

Appendix V: Performance measures for risk level 0.05

Median values		Capacity = 26, Reservation = 0, Risk level = 0.05								
		Schedule								
		Light			Medium			Heavy		
Occupancy	Performance measure	A	B	C	A	B	C	A	B	C
Low	Utilization	17,70	16,97	17,61	18,52	17,37	17,60	19,41	17,18	17,34
	Scheduled admissions	16,00	12,00	15,00	19,99	14,00	15,00	25,96	13,00	14,00
	Late cancellations	0,00	-	-	0,01	-	-	0,04	-	-
	Refusals	0,39	0,15	0,21	0,61	0,19	0,22	1,57	0,19	0,20
	Schedule changes	-	-4,00	3,00	-	-6,00	1,00	-	-13,00	1,00
Medium	Utilization	19,32	18,17	18,18	20,02	18,19	18,19	20,73	18,19	18,39
	Scheduled admissions	15,99	10,00	10,00	19,98	10,00	10,00	25,89	10,00	11,00
	Late cancellations	0,01	-	-	0,02	-	-	0,11	-	-
	Refusals	0,66	0,24	0,24	1,08	0,24	0,24	2,45	0,24	0,27
	Schedule changes	-	-6,00	-	-	-10,00	-	-	-16,00	1,00
High	Utilization	20,72	18,71	18,72	21,32	18,70	18,70	21,86	18,70	18,70
	Scheduled admissions	15,99	5,00	5,00	19,96	5,00	5,00	25,73	5,00	5,00
	Late cancellations	0,01	-	-	0,04	-	-	0,27	-	-
	Refusals	1,22	0,29	0,29	1,88	0,28	0,28	3,61	0,28	0,28
	Schedule changes	-	-11,00	-	-	-15,00	-	-	-21,00	-

Appendix VI: Tests for the Poisson assumption

To test whether the use of Poisson distributed arrival patterns was tested with the Chi-square Goodness of fit test.

H_0: The number of arrivals per day follows a Poisson distribution.

H_1: The number of arrivals per day does not follow a Poisson distribution.

The chi-square test statistic for determining whether the data follow the Poisson distribution is given by

$$\chi^2_{\mathrm{k-p-1}} = \sum_{\mathrm{k}} \frac{(\mathrm{f_o} - \mathrm{f_e})^2}{\mathrm{f_e}}$$

where

$f_o = observed\ frequency$

$f_e = expected\ frequency$

$k = number\ of\ categories$

$p = number\ of\ parameters\ estimated$

The degrees of freedom is equal to $k - p - 1 \;=\; 5 - 1 - 1 \;=\; 3$ degrees of freedom

Reject H_0 if $\chi^2 > 7.81$; otherwise do not reject H_0

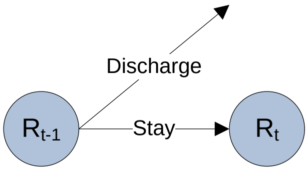
Patient Category	Kind	Arrival type	Medical specialty	Test statistic	Conclusion
1	Acute	Medical	Inwendige geneeskunde	1.11	Do not reject
2	Acute	Medical	Neurochirurgie	2.16	Do not reject
3	Acute	Medical	Heelkunde	3.39	Do not reject
4	Acute	Medical	Longziekten	1.57	Do not reject
5	Acute	Medical	Neurologie	3.72	Do not reject
6	Acute	Medical	Cardiologie	2.56	Do not reject
7	Acute	Medical	Other	0.19	Do not reject
8	Acute	Emergency surgical	Heelkunde	3.09	Do not reject
9	Acute	Emergency surgical	Neurochirurgie	0.37	Do not reject
10	Acute	Emergency surgical	Other	0.41	Do not reject

The test used does not provide evidence that the empirical unscheduled arrivals distribution differs from a Poisson distribution.

Appendix VII: Expectations model formulae

Remaining expected demand

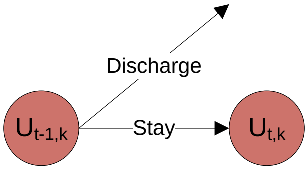
A certain patient population is observed at the end of a time period. Some members of the patient population will leave the ICU in the next time period. The expected demand at the end of the next period is equal to the observed number of patients in the unit minus the expected discharges in the next period. The probability of discharge in the next period depends on the patient category and current length of stay of the patient.

Conceptual representation	Mathematical representation
	$E(R_t) = E(R_{t-1}) * P(Discharge_t)$

Unscheduled expected demand

- Ten unscheduled patient categories are incorporated into the model.
- The new unscheduled demand at the end of period 1 is the sum of the unscheduled arrivals rates.
- The new unscheduled demand at the end of period 2 is the sum of the unscheduled arrival rates (the patients that arrive IN period 2) plus the unscheduled patients that arrived in period 1, but were not discharged in period 2. Etcetera.

$U_{t,k}$ denotes the unscheduled demand distribution at the end of period t caused by unscheduled arrivals in period k.

Conceptual representation	Mathematical representation
	$E(U_{t,k}) = E(U_{t-1,k}) * P(Discharge_{t-k})$

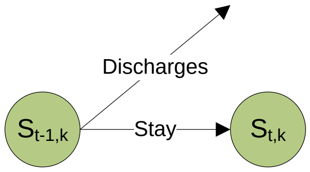
Elective surgical expected demand

- The new elective surgical demand at the end of period 1 is the sum of the elective surgical arrivals.
- The new unscheduled demand at the end of period 2 is the sum of the unscheduled arrival rates (the patients that arrive IN period 2) plus the unscheduled patients that arrived in period 1, but were not discharged in period 2. Etcetera.

A denotes IC arrival, A = 1 if arrival and A = 0 if no arrival.

I denotes IC indication, I = 1 if IC indication and I = 0 if no IC indication.

$E(S_{t,k,w})$ denotes the expected demand at the end of period t of arrivals in period k when period k was weekday w.

Conceptual representation	Mathematical representation
	$E(S_{t,k}) = E(S_{t-1,k}) * P(Discharge_{t-k})$

If t < k

$$E(S_{t,k,w}) = 0$$

If t = k

$$E(S_{t,k,w}) = E(S_{k,k,w}) = n_{I,t} \cdot P(A = 1 \mid I = 1 \ \cap w) + n_{I,t} \cdot P(A = 1 \mid I = 0 \ \cap w)$$

If t > k

$$E(S_{t,k,w}) = E(S_{t-1,k,w}) \cdot (1 - P(D = t - k))$$

The expected elective surgical demand at the end of period t is calculated by:

$$E(S_t) = \sum_{k=1}^{7} E(S_{t,k})$$

Appendix VIII: Admission and discharge information

The number of admitted scheduled arrivals varies between zero and seven. The average number of admissions per day equals 915 admissions / 261 surgical days = 3.51.

Arrivals approach the intensive care unit 24 hours per day. Elective surgical patients arrive during or after "office hours". In contrast, discharges normally take place during office hours. Discharges outside office hours are associated with deceased patients.