Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Economics and Management
Dept. of Industrial Economics and Technology Management

Tore Bjørseth Berdal
Erlend Moian Nydal

Emergency Department Layout Planning Using A Simulation And Optimization Approach

Master's thesis in Industrial Economics and Technology Management
Supervisor: Henrik Andersson, Bjørn Nygreen, Anders N. Gullhav,

January 2020

NTNU
Norwegian University of
Science and Technology

Tore Bjørseth Berdal
Erlend Moian Nydal

Emergency Department Layout Planning Using A Simulation And Optimization Approach

Master's thesis in Industrial Economics and Technology Management
Supervisor: Henrik Andersson, Bjørn Nygreen, Anders N. Gullhav,
January 2020

Norwegian University of Science and Technology
Faculty of Economics and Management
Dept. of Industrial Economics and Technology Management

NTNU
Norwegian University of
Science and Technology

Preface

This master thesis is written within Managerial Economics and Operations Research at the Department of Industrial Economics and Technology Management and Faculty of Economics at the Norwegian University of Science and Technology (NTNU). This thesis is motivated by the operations at the ED at Kalnes Hospital and written in collaboration with Sykehusbygg HF and Kalnes Hospital.

We appreciate the help and guidance in completing this thesis, both from the faculty at NTNU and industry contacts. We would especially like to thank our supervisors, Prof. Henrik Andersson, Prof. Bjørn Nygreen, and Ass. Prof. Anders N. Gullhav at NTNU for their valuable guidance throughout the process. We would also like to thank Unni Dahl, Gunn Håberget and Rita Konstante at Sykehusbygg HF for their input from meetings and e-mail correspondence, and Sissel Hagen at Kalnes Hospital for helping us understand the workings of an ED.

Tore Bjørseth Berdal and Erlend Moian Nydal

Trondheim, January 16, 2020

Abstract

Several factors affect the functioning of an ED, among others, talented staff, sufficient staff capacity, reasonable distribution of work, and plans to handle a variety of urgent situations. However, without a satisfactory internal layout, various challenges, like overcrowding and long waiting times, may still exist. To avoid these challenges, sufficient room capacity of different functions is essential. Besides, the internal layout and room placement have a significant influence on efficient working procedures, operational costs, reduced walking-distances for patients and staff, and improved patient flow. A consequence of these improvements is the ability to save more lives, which is the main purpose of every ED.

This master thesis is written in collaboration with Sykehusbygg HF and Kalnes Hospital. Sykehusbygg is the public enterprise responsible for the planning of major hospital construction and rebuilding projects in Norway. Kalnes Hospital is a large Norwegian hospital situated in the southeast of Norway. At this hospital, and more specifically, its ED, there are problems with overcrowding and long waiting times. These challenges are observable by looking at the Key Performance Indicators (KPIs) used to measure the performance at this ED. The most widely used KPI is Length of Stay (LOS), which is the consumed time from a patient arrives at the ED until the patient leaves the ED. When planned and built, the goal for the ED Kalnes was having an average LOS under 2 hours for all patients. However, today this metric is above 4.5 hours.

The focus of this thesis is to propose solutions to the Emergency Department Layout Problem (EDLP), with the overall aim to improve KPIs of the Kalnes ED by producing better layouts. EDLP is the planning of the internal layout of an ED, a problem of great importance and high complexity. When solving an EDLP, the functions of the ED, such as care rooms, triage, x-ray, and trauma, are placed at some particular locations. In this thesis, the total area and footprint of the ED are considered known, including the placement of hallways, as well as other static structures, such as stairs and elevators. The ED consists of locations where the different functions can be placed. In the model, the locations are discretized into blocks of equal size with the size of a normal-sized care room.

A function covers a discrete set of locations, and every location within the ED is assumed to be able to host any function. However, there are requirements for certain areas within the ED and other function-specific placement rules. Such rules are, for example, requirements for proximity to the entry or a specific function, access to a hallway, or the need for windows. A location can only be covered by one function, and consequently, no functions can overlap. Functions covering several locations are, like the functions covering one location, given only one center-location, close to its geographic center. Dependent on the center-location, these functions can take on different configurations. Patients and staff move between different functions, creating flows, and thereby dependencies between the functions. In a well-working layout, functions that are highly dependent on each other should be located close, while less connected functions may be located farther apart.

EDs have several dynamic aspects of their nature. Patient arrivals change over time, and seasonal variations in diseases and damages demand a vast variety of resources. When analyzing such a complex system, like an ED, simulation stands out as the preferred technique. However, Nolan and Sovereign (1972) outlines that simulating an ED with multiple experimental layouts may require considerable computational power. In comparison, optimizing an ED with complete details may be challenging to solve in a reasonable time. By combining simulation and optimization, the simulation model captures the complex behavior of the system, while the optimization model is able to find promising solutions to large-scale combinatorial problems.

In this thesis, a simulation-optimization framework is developed to solve the EDLP for the Kalnes ED. The simulation model evaluates layouts by measuring some particular KPIs and creates staff and patient flows. Following this, the optimization model creates a new and improved layout by minimizing the walking distances of the patients and staff, weighted by the priority of the patients acuity, and an emphasis on either patients or staff walking distances. The simulation and optimization model are run iteratively until a convergence criterion is reached.

The objective in the optimization model has similarities to the quadratic assignment problem, where functions are allocated while still considering the connection between them. Even though the simulation model captures the stochasticity, the quadratic nature of the problem makes solving it a challenging task. As a result, the optimization model is linearized and divided into several stages. In this formulation, only a smaller part of the problem is solved in the different stages. In every stage, some particular functions are locked before the stage, while other functions are locked in this or in a later stage. When a function is locked, this function is given a specific center-location and configuration in all the following stages. Since the functions to be locked in a later stage are only included in the stage to help to locate the functions of interest, the binary constraints on their respective variables are relaxed.

Several different aspects of the simulation-optimization framework are tested on both small instances and the Kalnes ED. When introducing a multi-stage optimization model, reasonable subsets of functions are to be locked in the various stages. Therefore, several different locking strategies are tested, with the purpose of finding the best possible layout. Other interesting perspectives are the prioritization of the different triage levels and among patients and staff. When testing different prioritization levels, overall performance measures, but also the safety of the most acute patients are taken into consideration.

Following this, the developed framework is utilized to produce three different layouts at the Kalnes ED. Compared to today's situation, the new layouts show significant improvements in the KPIs. These improvements are a result of having functions with high interaction close, and less dependent functions farther apart.

This master thesis is a proof of concept, showing how Operation Research (OR) can be utilized to solve problems within the health care sector, and more specifically, an ED. By taking advantage of this framework, the management at the ED Kalnes will receive more insight when considering strategic layout decisions.

Sammendrag

Flere faktorer påvirker hvordan et akuttmottak fungerer, blant annet dyktige ansatte, tilstrekkelig kapasitet av ressurser og ansatte, fornuftig arbeidsfordeling samt gode planer for å håndtere kritiske situasjoner. Men, selv om alle disse faktorene skulle fungere tilfredsstillende, kan en ineffektiv planløsning fortsatt gi utfordringer knyttet til fullt mottak og lange ventetider. En planløsning har stor påvirkning på arbeidsprosedyrer, driftskostnader og pasientflyt. En forbedret planløsning kan gi bedre pasientsikkerhet, samt at forholdene ligger mer til rette for å redde livet til pasienter i kritiske situasjoner.

Denne masteroppgaven er skrevet i samarbeid med Sykehusbygg HF og Kalnes Sykehus. Sykehusbygg er et offentlig norsk helseforetak med ansvar for planleggingen av større sykehusbyggprosjekter i Norge. Kalnes Sykehus er et stort norsk sykehus som ligger sør-øst i Norge. Kalnes opplever i dag store problemer med fullt mottak og lange ventetider. Disse utfordringene kan observeres ved å se på nøkkeltallene (KPI'ene) som brukes for å måle hvordan akuttmottaket fungerer. Det mest brukte KPI'en er total tid på mottak (LOS), som er gjennomsnittstiden en pasient er på akuttmottaket. Da mottaket ble bygget var målet at LOS skulle være under 2 timer, men i dag er den over 4,5 timer.

Hovedfokuset til denne oppgaven er å løse planløsningsproblemet til et akuttmottak (EDLP) ved hjelp av operasjonsanalyse, med det overordnede målet å forbedre KPI'ene til akuttmottaket på Kalnes. EDLP er et viktig, men vanskelig problem å løse. Når dette problemet løses plasseres funksjonene til akuttmottaket, som for eksempel behandlingsrom, triage, og røntgen på bestemte steder. I denne oppgaven blir det totale arealet og fotavtrykket til akuttmottaket på Kalnes brukt som utgangspunkt. For å gjøre problemet lettere å løse, er lokasjonene i mottaket diskretisert til like store rektangler med størrelse lik et vanlig behandlingsrom.

En funksjon dekker et bestemt antall lokasjoner, og alle lokasjoner kan i utgangspunktet bli dekket av hvilken som helst funksjon. Imidlertid er det noen spesifikke regler knyttet til plasseringen av enkelte funksjoner. Slike regler er for eksempel at en funksjon må ligge nær en annen bestemt funksjon, eller at det må være et vindu

på rommet der funksjonen er plassert. En lokasjon kan bare dekkes av én funksjon, og i tillegg kan ingen funksjoner overlappe hverandre. Funksjoner som dekker flere lokasjoner har en bestemt senterlokasjon, definert nær det geografiske sentrumet. I tillegg kan funksjoner som dekker flere lokasjoner ha forskjellige konfigurasjoner. Med en konfigurasjon menes ulike kombinasjoner av lokasjoner en funksjon dekker. Pasient- og personalflyten måler avhengighetene mellom funksjonene. I en godt fungerende planløsning bør svært avhengige funksjoner være i nærheten av hverandre, mens mindre avhengige funksjoner kan være plassert lengre fra hverandre.

Et akuttmottak har flere dynamiske aspekter. Pasientankomster endres over tid, og sesongvariasjoner i sykdommer og skader krever at ressursene er tilstrekkelig for å dekke behovene til pasientene. Når man analyserer et så komplekst system fremstår simulering som den mest fornuftige teknikken å bruke. Imidlertid beskriver Nolan and Sovereign (1972) at gjentatte eksperimentelle simuleringer av et akuttmottak krever stor datakraft. Til sammenligning kan det være vanskelig å løse EDLP med matematiske optimeringsmetoder der alle detaljer er tatt med i løpet av en fornuftig tid. Ved å kombinere simulering og optimering kan simuleringsmodellen ta hånd om den komplekse oppførselen til systemet, mens optimeringsmodellen er i stand til å finne gode løsninger på vanskelige kombinatoriske problemer.

I denne oppgaven utvikles et simulering-optimering-rammeverk for å løse EDLP på Kalnes. Simuleringsmodellen evaluerer planløsninger ved å måle noen spesielle KPI'er, og i tillegg blir personal- og pasientstrømmer laget. Optimeringsmodellen generer en ny og forbedret planløsning ved å minimere objektivet, som er de vektede gangavstandene til pasientene og ansatte. Simulering og optimeringsmodellen kjøres iterativt til stoppkriteriet er oppfylt.

Objektivet i optimeringsmodellen har likheter med det kvadratiske tildelingsproblemet (QAP), der funksjoner blir plassert basert på avhengighetene mellom dem. Selv om simuleringsmodellen fanger opp stokastisiteten, blir problemet vanskelig å løse på grunn av det kvadratiske objektivet. På grunn av den store kompleksiteten i problemet, blir optimeringsmodellen linearisert og delt inn i flere steg. I denne formuleringen løses bare en mindre del av problemet i de forskjellige stegene. I hvert steg er noen spesielle funksjoner låst på forhånd, mens andre funksjoner blir låst i dette eller i et senere steg. Når en funksjon er låst, får denne funksjonen den samme senterlokasjonen og konfigurasjonen i alle de følgende stegene. Funksjonene som skal låses i et senere steg er bare med for å plassere de funksjonene som skal plasseres og låses i dette steget til bedre lokasjoner, og de tilhørende variablene til disse funksjonene blir relakseres fra binære til kontinuerlige.

Flere aspekter av simulering-optimerings rammeverket testes på både små instanser og på hele akuttmottaket ved Kalnes. Siden rammeverket utnytter seg av en flerstegsmodell, skal fornuftige undergrupper av funksjoner låses i de forskjellige stegene. Forskjellige låsestrategier testes, med det formål å finne en best mulig planløsning. Andre interessante perspektiver er prioritering av de forskjellige triagenivåene samt prioriteringen mellom pasienter og ansatte. Når man tester forskjellige prioriteringsnivåer, blir de generelle resultatmålene, men også sikkerheten til de mest akutte pasientene tatt i betraktning.

Rammeverket blir brukt til å produsere tre forskjellige planløsninger for akuttmottaket på Kalnes. Sammenlignet med dagens situasjon, viser de nye planløsningene store forbedringer i KPI'ene. Disse forbedringene er et resultat av at funksjoner med stor avhengighet plasseres nærme hverandre mens mindre avhengige funksjoner blir plassert lenger fra hverandre.

Denne masteroppgaven er et konseptbevis, som viser hvordan matematiske optimeringsmetoder kan brukes til å løse problemer innen helsevesenet, og nærmere bestemt et akuttmottak. Rammeverket kan benyttes som et beslutningsverktøy ved framtidige strategiske beslutninger rundt planløsninger på mottaket.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

Health care services are experiencing increased demand, both due to an aging population and a growth in chronic disorders (Sentralbyrå, 2011). Compared to today's level, Sykehuset Østfold (2018) estimates an increase of 58.6% in health related activities within 2030. Meeting this higher demand, while at the same time trying to control cost will be one of the main challenges in the future. Already, the total costs for health care services in Norway have risen from 8.0% of GDP in 2007 to 10.4% in 2017 (OECD, 2019b).

In the effort to decrease costs, Norwegian authorities have implemented a strategy of larger and fewer hospitals. The primary purpose of building larger hospitals is to gather expertise. Today, there are 39 hospitals with an Emergency Department (ED), a reduction of 16 compared to the 55 hospitals in 2002 (Jensen, 2014). A consequence of fewer hospitals, in combination with increased demand for health care services, are more patients assigned to each hospital.

The ED is a highly important unit of any hospital, and often the first point of entry for a patient. This observation is especially true for the most acute patients. Consequently, the ED has a critical role in saving lives. The quality of care at an ED is highly influential of the public's view on the health care system as a whole (Uriarte et al., 2017). While the cost for health care services is on the rise, the number of acute beds per 1 000 population has fallen from 5.3 in 2004 to an all-time low of 3.7 in 2016 (OECD, 2019a). This mismatch creates several problems like overcrowding, long waiting times, and high workloads, affecting the quality and timelines of care, as well as patient safety. To combat these challenges, health care services need to deliver the required care more efficiently. Solving such problems can be achieved through the utilization of Operational Research (OR) methods.

Emergency Department Layout Planning (EDLP) is the planning of the internal layout of an ED, a problem of great importance and high complexity. The results of a well designed and carefully planned ED is better efficiency, reduction in staff down time, cost reduction, improved recourse utilization, and ultimately improve patient safety. Research within the field of Facility Layout Problems (FLPs) suggests methods for utilizing optimization in several types of layout planning problems. The problem is well established within traditional industries. However, FLPs in the context of Health Care are not extensively explored in the existing literature.

At an ED, patients and staff move between *functions* to receive and provide the necessary examination and treatment before the patients are discharged, admitted, or transferred to another department. When summarized, these movements can be seen as *flows* of patients and staff between functions. The amount of flow, both of patients and staff, give an accurate assessment of the dependencies between different functions. Every function is located at a specific *location* throughout the ED. Both from patients' and employees' point of view, the distances between relevant locations is preferred minimized. The distance between different workplaces for employees should be as short as possible, so that focus can be directed to core tasks rather than unnecessary walking. Short walking distances for patients are desirable both in a patient safety context and due to the obvious immobilities of arriving patients.

Identifying the *flow* of both patients and staff between different functions is a complex task due to the variability and stochastic nature of the different processes involving patients, staff, and resources. In literature, simulation stands out as the preferred methodology for this task. The main advantage of utilizing simulation to analyze EDs is conforming to Vanbrabant et al. (2019), the high level of detail that can be taken into account, such as individual patient characteristics. However, Nolan and Sovereign (1972) outline that finding the best layout using only simulation requires very high computational power. Without any smartness to the search, the simulation alone is forced to explore every possible layout. Running a standalone optimization model for the entire problem is also time-consuming for today's computers, because of the increased complexity when including the stochastic behaviors in an ED.

By combining simulation and optimization, the simulation model can capture the complex behavior of the system, while the optimization model is able to find promising solutions to large-scale combinatorial problems. Therefore, a simulation-optimization framework is, in this thesis, utilized to solve the EDLP and improve the Key Performance Indicators (KPIs) of the ED. The simulation model evaluates layouts and produces input data to the optimization model, while the optimization model creates a new and improved layout. This iterative process continues until a convergence criterion is reached.

This thesis is motivated by a collaboration with Sykehusbygg HF and Kalnes Hospital. Sykehusbygg is a Norwegian public enterprise organizing major construction- and rehabilitation projects of hospitals while at the same time developing best-practice standardized plans for hospitals. The case of this thesis is Kalnes Hospital, and more specifically, its ED. Kalnes Hospital is a relatively new hospital in the south-east of Norway, completed in 2015. Even though this hospital is relatively new, and its ED is one of the largest in Norway, this department suffers from overcrowding and long waiting times. The purpose of this thesis is to illustrate how a combination of simulation and optimization can capture the complex nature of an ED and propose better layouts. The model should place functions at locations while minimizing the distance between them weighted by the dependency given by the flows of staff and patients.

Chapter 2 provides the required background information for this thesis. Here, basic terminology, the Norwegian health care organization, Sykehusbygg HF, and Østfold hospital are presented. Following this, relevant literature within the field of solving EDLP with a simulation-optimization framework is reviewed in Chapter 3. In Chapter 4, the description of this problem is given. From this, general assumptions and the mathematical model is presented in Chapter 5. Chapter 6 describes the simulation model in detail with a brief review of the development process. In Chapter 7, the simulation-optimization framework is given, in addition to some required simplifications of the mathematical model. Further, in Chapter 8, key aspects of the optimization model are tested. A case study focusing on the Kalnes ED, solving a real-world case, and the presentation of the final layout is given in 9. Finally, 10 concludes on the main findings of the thesis, and 11 suggests the focus for possible further research and extensions of the work.

Chapter 2

Background

This chapter introduces background information relevant to this thesis. First, some basic terminology for this thesis is presented in Section 2.1. Following this, the Norwegian health care system is introduced in Section 2.2. The motivation is to give the reader an understanding of the health system, both pre-hospital and in-hospital care. Finally, the two industry partners of this report, Sykehusbygg HF and the Østfold Hospital department Kalnes, is introduced in Section 2.3 and 2.4. The majority of the information about Kalnes Hospital is gathered through meetings and correspondence with staff at the hospital and Sykehusbygg. Besides, Section 2.4 presents the Emergency Department at Kalnes, with a description of today's layout and the current state of the ED.

2.1 Terminology

The terminology presented in this section is useful for understanding the background information of this thesis. The terms listed are highlighted in italic letters the first time they occur in the subsequent sections.

Emergency Department Layout Problem - The emergency department layout problem is the process of determining the internal layout in an emergency department. The decision-maker is supposed to achieve predefined goals by placing functions to well-suited locations in the ED.

Key Performance Indicators - Key performance indicators (KPI) are referred to as different metrics to evaluate the performance of an ED. KPIs are divided into four categories; time metrics, proportion metrics, utilization and productivity measures, and budget-related measures. The most widely used KPI is time metrics. In this thesis, the following time-metrics are used; length of stay, time to triage, door to doctor time, and ready to transfer. Furthermore, KPIs are subdivided into qualitative KPIs and quantitative KPIs. Qualitative KPIs are descriptions or opinions of an object or process, for example, patient satisfaction and patient safety. In contrast, quantitative KPIs are measurable for anything involving numbers.

Length of Stay - Length of stay (LOS) is the consumed time from a patient arrives at the ED until the patient leaves the ED.

Time to Triage - Time to triage (TTT) is the consumed time from a patient arrives at the ED until the first medical examination. A physician or nurse conducts the examination.

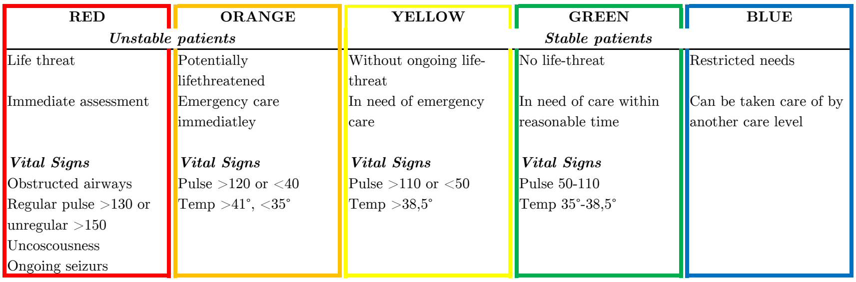
Door to Doctor Time - Door to doctor time (DTDT) is the consumed time from a patient arrives at the ED until the first medical examination by a physician.

Ready to Transfer - After the examination and treatment of a patient, the patient is clarified to go home or being transferred to another department. Ready to transfer (RTT) is the consumed time to transfer a clarified patient to another department.

Triage - Triage is defined as the process of determining the priority of patients' treatments based on the severity of their condition (Wikipedia, 2019). The purpose of a triage system is to ensure that the patients with the most severe conditions are treated first. The word triage is originally French and means to sort.

Both the ED at Kalnes and the ambulance service use the RETTS triage system. RETTS triage is divided into five color-coded categories, based on the severity of the patient's condition. See Figure 2.1 for an overview. An evaluation of the triage is based on both vital parameter measurements, which are objective physiological measures, and algorithms for the valuation of different contact causes, called Emergency Symptoms and Signs (ESS). Based on these contact causes, health personnel can identify possible diseases. Finally, when both the vital parameters and ESS are scored in one of five priority levels, the final triage priority rating is determined as the highest one of these scores (Henning et al., 2016).

At the Kalnes ED, four triage levels are utilized, meaning the healthy blue level is disregarded. As seen in Figure 2.1, the triage levels range from the less acute green to the most acute level red. Within each triage level, there are standardized procedures and tasks for the staff constituted to assure that the



RED	ORANGE	YELLOW	GREEN	BLUE
Unstable patients			*Stable patients*	
Life threat Immediate assessment	Potentially lifethreatened Emergency care immediatley	Without ongoing life-threat In need of emergency care	No life-threat In need of care within reasonable time	Restricted needs Can be taken care of by another care level
Vital Signs Obstructed airways Regular pulse >130 or unregular >150 Uncoscousness Ongoing seizurs	***Vital Signs*** Pulse >120 or <40 Temp >41°, <35°	***Vital Signs*** Pulse >110 or <50 Temp >38,5°	***Vital Signs*** Pulse 50-110 Temp 35°-38,5°	

Figure 2.1: An overview of the different triage levels with main vital signs.

condition of the patient is taken care of in the ablest way.

Functions - A function is in this thesis, a small health service provider giving service to patients with the goal of meeting the patient's medical needs. Examples of functions include care room areas, where patients are examined and given basic treatment.

Locations - Locations are the different rooms in the ED, and every location in the ED is capable of hosting any function. All locations in the model representation are normal-sized care room size. The functions that require more space than one normal-sized care room are placed at several adjacent locations.

Configurations - When a function is placed in the ED, it is given a center-location, having a location close to the geographic center of the function. Based on a given center-location, the various functions have different configurations. A configuration is the alternative locations a function covers with a specific center-location. Functions with equal size have the same type of configurations, but there are variations between functions of unequal size. An example of configurations for an x-ray unit is as follows. The unit covers two locations, with the possibilities of covering locations vertical or horizontal. For further reading about configurations, the reader is referred to Section 5.1.

Flows - Flows are the number of patients and staff moving in between the different functions in the ED for a specified time period. The flows are divided into patients and staff. Besides, the patient and staff flow are separated based on the triage levels. The flows give the basis for how to locate different functions, where functions having a considerable amount of flow between them are supposed to be located close to each other.

2.2 Norwegian Health Care Organization

The Norwegian health care system is public and mainly financed by the state of Norway, rendering the patient's personal economy irrelevant to the treatment given. Further, the health care system is divided into *primary health services* and *special health services*. The primary health care services are organized within each municipality and include services like regular general practitioner doctors (RGP), home nurses, physiotherapists, occupational therapists, and speech therapists. In addition, it includes institutions like nursing homes and retirement homes. The special health care services are organized in four health regions, and the geographic areas of the regions are presented in Figure 2.2. Special health care services include somatic and psychiatric hospitals, ambulance services, drug treatment institutions, and other health care institutions. Somatic hospitals have their expertise within the treatment of physical illnesses, while psychiatric hospitals handle mental diseases. Many hospitals in Norway are a combination of a somatic and a psychiatric hospital and have an ED to take care of acute patients.

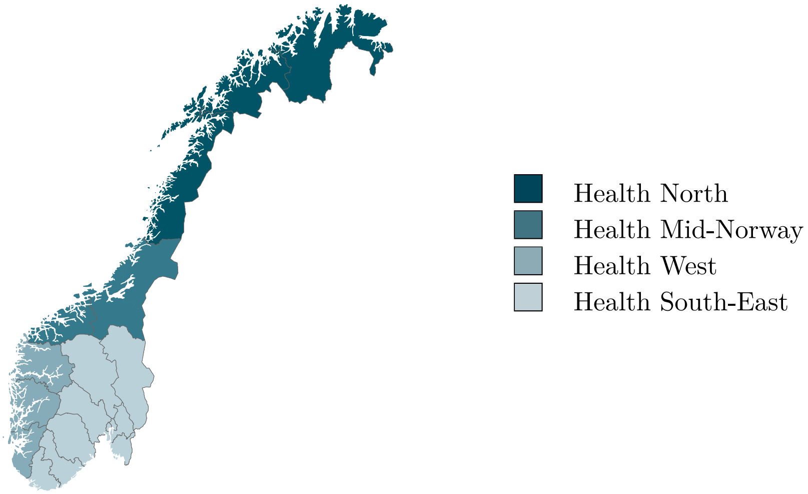


Figure 2.2: Map of Norway divided into the four health regions

2.2.1 The Emergency System

The emergency system in Norway consists of hospital EDs and RGP doctors. In Norway, each citizen has their own appointed RGP doctor. A standard process for an ill patient is to first seek help with their RGP doctor to get an assessment and necessary treatment. If the condition of the patient is acute, and the doctor is not able to give the required treatment, the patient is sent to an ED or admitted at a specific department at the hospital. Usually, the patients have to fix transportation by themselves, but in the most critical situations, the patient is transported by ambulance.

For the even more acute patients, there is no time to visit the RGP doctor, and the patient or their dependents call the emergency telephone directly. Emergency services consider the condition of the patient. If the situation is critical, emergency services requisition an ambulance car or a helicopter to transport the patient expeditiously to an ED.

Additionally, in some cases, patients show up at the ED by themselves, without being considered by an RGP doctor or emergency services. Also, a small proportion of the patients are transferred from wards within the hospital to the ED.

2.3 Sykehusbygg HF

Sykehusbygg Helseforetak, from here on referred to as Sykehusbygg, is a public enterprise owned by Norway's four health regions. Sykehusbygg is one of the industry partners in this report. Sykehusbygg was established in October 2014 and contributes to every major hospital construction- and rehabilitation project with a budget above 500 million NOK (Sykehusbygg, 2019). The primary purpose of Sykehusbygg is to be an internal provider of expertise for the regional health authorities and the country's health enterprises. This is achieved through the transfer of the success keys from the existing hospital by developing models, guidelines, methods, and tools to new hospital developments. The company shall facilitate and contribute to standardization, transfer of experience, proper resource utilization, and resource access within the design and construction of hospitals. Their methods are based on an extensive basis of experience and knowledge from earlier projects and discussions with involved stakeholders.

2.3.1 Evaluating EDs

Sykehusbygg evaluates the performance of the various EDs around the country. The use of standard evaluation criteria of EDs is written as one of Sykehusbygg's main purposes. However, the evaluation must also be conducted in the context of the goals of the specific ED. The standard evaluation criteria include the average time to triage (TTT), the average length of stay (LOS) in the ED and the number of and the severity of the deviation reports. TTT is the consumed time from a patient arrives at the ED until the first medical examination. The process of triage is different from other consultations and consists of a checklist to get a quick overview of the state patient. Since it can be crucial for urgent patients to be treated quickly, time to triage is widely used as a safety measure. LOS within the ED says something about the capacity of the various processes at the ED and is closely related to overcrowding. A deviation report is given if a standardized process is violated for a patient. For instance, a deviation report is written if a patient with a specific disease does not get the apparent treatment within a standardized time. The amount and severity of these reports give information about the quality of the processes at the ED. However, there are some variations in the culture of writing these deviation reports among the hospitals, making comparisons between different EDs a difficult task. All these metrics are common indicators to evaluate an ED and thoroughly reported in the literature and discussed further in Section 3.3.

2.4 Østfold Hospital - Kalnes

Kalnes is a Norwegian hospital located just outside Sarpsborg in Østfold county. In Figure 2.3, a map representing the geographic location of Kalnes hospital, is given. At this hospital, there are working 4 800 employees distributed on 85 500 square meters and 3 664 rooms. The hospital has both psychiatric and somatic departments. Kalnes hospital is relatively new and opened in 2015 at a price of more than 6 billion NOK. Together with Moss hospital, these two hospitals have the responsibility to give satisfactory treatment options to 300 000 people. Kalnes and Moss hospital is a result of a merger of 5 hospitals in Østfold and is owned by Health South-East. Østfold hospital's vision is to offer excellent and equitable health care services to all people who need health care, independent of age, residence, ethical background, sex, and economy. Kalnes hospital is at the forefront when it comes to digitization. Health Information and Management Systems rank Kalnes at level 6 on a scale from 0 to 7, which is the best ranking among the hospitals in Scandinavia (Svendsen, 2018). An example of this is the specialized IT systems for radiology and lab results, registration without staff, and a database for medical records.

2.4.1 ED at Kalnes

Kalnes has one of the largest EDs in Norway, with almost 1 200 square meters distributed on 97 rooms. In 2018 more than 39 000 patients passed through the ED, and the arrivals to the ED have risen annually with 8% since opening in 2015. A significant number of patients make high claims to a well working ED. The ED is open 24/7 and also serves the rest of the hospital in acute situations. In the next sections, the layout and rooms at the ED will be described. Following this, an evaluation of the current situation at the ED Kalnes is conducted.

Figure 2.3: Kalnes Hospital is located in the south-east part of Norway, near the towns of Fredrikstad and Moss

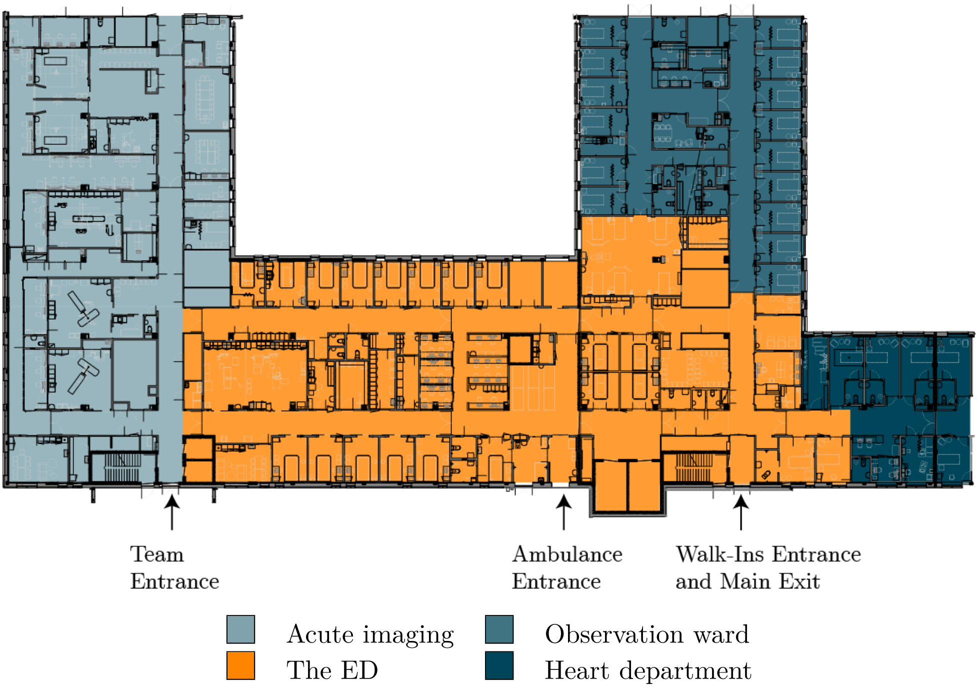


Figure 2.4: An overview of the Kalnes ED and close units

Layout and room descriptions

There are three entrances to the ED. One for *walk-in patients*, one for *team patients* and one for *ambulance patients*. The team patients are the most urgent, often arriving by an ambulance helicopter or an ambulance car. These patients are labeled team patients since they require an entire team consisting of different physicians and nurses in the treatment.

In contrast, less acute patients arriving by ambulance are directed to the regular ambulance entrance. For patients arriving at the walk-in entrance, the first stop is at the reception desk for arrival registration. Near the reception, there are two waiting rooms. Besides, extra chairs are placed outside the waiting room to tackle situations with high census and avoid overcrowding of the main waiting room. See Figure 2.4 for an overview of the ED and adjacent departments, and Figure 2.5 for a detailed overview of the different areas in the ED.

At the ED, patients undergo different procedures to examine and treat their condition. The staff tries to ensure these procedures are fast and in a satisfactory manner. Among other things, there are two triage rooms, where a nurse or physician examine the walk-in patients. For patients arriving by ambulance, a triage is conducted during transportation. As discussed in Section 2.1, the ED at Kalnes and the emergency service utilize the same triage system, making the ambulance triage transferable to the ED. There are two outpatient clinic rooms where a physician thoroughly examines the walk-in patients. In times with high census, a third outpatient clinic room is opened, lent to ED by the heart department.

Furthermore, there are two single treatment rooms for the team patients, which is equipped for more advanced treatment compared to the other treatment rooms. For urgent, but stable patients, area 4 contains a treatment area with a capacity of six people. This room is an open room with curtains separating the different beds. The purpose of this layout is to help the assigned health personnel to gain a valuable overview of all patients. There are 14 single care rooms equipped for basic treatments distributed in area 1 and area 2. If any additional equipment is needed, staff can find this at any of the depots. In the central part of the ED, a medicine room containing all medicament's necessary for the ED and a delivery station for lab samples is located. Lab samples are sent to the lab through the pneumatic tube system, which is fast and reliable. When the analyzes of the lab samples are finished, the results are sent back to the ED digitally. The only task the nurses have to do in this context is to deliver the test at the tube. Also, inside the ED, the staff has

Figure 2.5: A detailed overview of the ED

facilities like work stations, living rooms, offices, break rooms, and a small kitchen.

The acute imaging department is placed adjacent to the ED. Here, there are two x-rays, one ultrasound, two CTs, and one CT angiography. In the central hospital imaging department, located directly below the ED, there is some extra imaging resources and one MRI. Imaging is, for instance, used to detect cancer, broken bones, pregnancy, damage on organs, and internal bleeding. The heart department is placed in a short distance from the ED, where more advanced treatment and surgeries can be given.

When the treatment of a patient is completed, the patients are sent home, to an observation ward, or another department at the hospital. 37% of the patients are discharged after the examination, and treatments are finished. For the patients with special needs of medical supervision and observation, there are two observation wards with respectively 13 and 9 beds close to the ED.

Staff at the ED

There are several different types of staff working at the ED in order to handle a large number of patients with different needs. The most common staff types are nurses and physicians. Based on job position and continuing education on top of medical school, a physician can be categorized as *LIS1*, *LIS*, *Specialist* or *Physician*

Executive. LIS1 physicians are the ones with the least experience, LIS physicians have some more experience, while Specialists and Physician Executives are most experienced. Moreover, the physicians specialize within a particular field of the medical profession. Within an ED, the most common specializations are internal medicine, surgical, orthopedic, neurologically, and cancer specialist. In addition to physicians and nurses, the ED is also dependent on staff like health secretaries, conveyors, and cleaning personnel. Detailed staff schedules for the Kalnes ED is given in Appendix C.4.

Teams

The ED is divided into four different treatment areas, as shown in Figure 2.5. Both nurses and medical physicians are divided into teams, which take care of the patients in their specific area. Team 1 and 2 handle patients assigned to care room areas 1 and 2. Team 3 has the responsibility for the walk-in arrivals, and conduct triage and examination of the patients. Finally, team 4 takes care of the more urgent patients in area 4. Other categories of physicians serve the entire ED since there are fewer arrivals in their respective medical category.

In addition to the area based teams, there are also teams for the most critical patients; the emergency teams. The emergency teams are composed of various types of staff, mixed to have the necessary knowledge and experience to examine and treat patients with life-threatening conditions as fast as possible. Some of the team members regularly work at the ED, while others are recalled from other departments. At the Kalnes ED, there are, among others, emergency teams for medical patients, trauma patients, cardiac arrest, and thrombolysis. An example of a composition of an emergency team is one physician, two nurses, one emergency nurse, one bio-engineer, and one radiographer.

2.4.2 Today's situation at the ED Kalnes

Today there are some challenges at the ED Kalnes. Even though the staff are highly qualified and provide satisfactory service to the patients, the ED suffers in regards to overcrowding and long waiting times. When planned and built, the goal for the ED was to have an average LOS under 2 hours for all patients. Today, this metric is above 4.5 hours. Steps are taken to help with overcrowding problems. Extra chairs are installed in the waiting room area, and hallways are utilized for both patient treatment and to store patients beds. Still, conforming to the staff at the ED, no easy fix exists to bring down waiting times.

The cause of the overcrowding problems at the ED Kalnes are composed. According to the stakeholders, one of the main issues is related to lack of care, exam, and triage rooms. On weekdays, 80 patients are on average examined at the triage, while there are only two rooms allocated for this function, and only three rooms are available for the outpatient clinic. The lack of care rooms leads to situations where several patients regularly have to stay in mobile beds in corridors. Since there are no barriers between the waiting room area and the care room area, walk-in patients and dependents can walk into the care room area on their own. Here, walk-in patients and dependents can observe the examination and treatment of other patients, which is a situation that does not adhere to the patients' right to confidentiality.

The service for acute patients is, however, exemplary. There are multiple teams ready to examine and treat the team patients in a short time after arrival. Additionally, a six-person observational room is reserved for acute patients with orange and red triage. This room is constructed to make it easy for the staff to gain an overview of every patient quickly. Another successful part of the ED is the connection with the lab through the pneumatic tube system. In 2018 about 99% of all lab samples taken in the ED were answered within the deadline. The deadline varies between different test from 3 to 24 hours.

Conforming to the staff at the ED, the acute imaging department is a bottleneck of the patient flow. Since a majority of the patients need to take some images, the results are lack of capacity at the imaging department and thus queuing. Furthermore, multiple patients stay in the care rooms for a longer time than desired after their treatment at the ED is finished. The reason behind this is complex, but stakeholders claim overworked nurses and overcrowding at other departments are some of the reasons.

Chapter 3

Literature

This chapter contains an overview of relevant literature for this thesis. The problem studied in this thesis is a layout planning problem of an emergency department, which can be seen as a Facility Layout Problem (FLP). This problem is solved through a combination of optimization and simulation. The overall aim of layout planning problems is to arrange different functions inside a building such that the available area is optimally utilized, and distances between the highly interactive functions are minimized.

The framework of Hans et al. (2012) is exploited in Section 3.1 to position this work within a framework for health care planning and control. In Section 3.2 relevant literature on FLPs is discussed through a classification of different aspects of the problem. In Section 3.3 simulation literature is reviewed and compared, before literature on the combination of optimization and simulation is discussed in Section 3.4. Within every Section, the work in this thesis is classified and compared to existing literature.

3.1 Framework for Healthcare Planning and Control

The demand for research within health care services has received increasing attention during the last decades due to increasing longevity and population. Even though health care is a vital service in our community, health care planning, and control lag far behind traditional manufacturing planning and control (Hans et al., 2012). Furthermore, Hans et al. (2012) argue that current frameworks for health care operations management are too narrow, only focusing on a single managerial area, or ignoring the hierarchical levels. In their article, they propose a modern framework for health care planning and control that integrates all managerial areas in health care delivery operations and all hierarchical levels of control.

The framework of Hans et al. (2012) presents a two-dimensional framework for healthcare planning and control, which considers four management areas and four hierarchical levels. Table 3.1 show an example of the framework put into the context of a general hospital.

Table 3.1: Hans et al. (2012) present a two-dimensional framework for healthcare planning and control which considers four management areas and four hierarchical levels.

	Medical planning	**Resource capacity planning**	**Materials planning**	**Financial planning**	
Strategic	Research, development of medical protocols	Case mix planning, capacity dimensioning, workforce planning	Supply chain and warehouse design	Investment plans, contracting with insurance companies	**Hierarchical decomposition**
Tactical	Treatment selection, protocol selection	Block planning, staffing, admission planning	Supplier selection, tendering	Budget and cost allocation	
Offline operational	Diagnosis and planning of an individual treatment	Appointment scheduling, workforce scheduling	Materials purchasing, determining order sizes	Diagnostic related grouping billing, cash flow analysis	
Online operational	Triage, diagnosing emergencies and complications	Monitoring, emergency coordination	Rush ordering, inventory replenishing	Billing complications and changes	
	Managerial areas				

On the horizontal axis, the different managerial areas consisting of different planning areas for the management are positioned. These areas are medical planning, resource capacity planning, materials planning, and financial planning. Where earlier frameworks mostly focus on resource capacity planning, Hans et al. (2012) argue that their framework manages to encompass all areas when health care delivery processes are to be redesigned or optimized.

The vertical axis reflects the hierarchical nature of decision making, based on the classical decomposition often used in manufacturing planning and control first described by Anthony (1965). These levels are strongly related to the time horizon of the decisions. The four decision levels to consider are; strategic, tactical, offline operational, and online operational.

Strategic planning involves defining the organization's mission and the decision making to translate this into the design, dimension, and development of the health care delivery process (Hans et al., 2012). Inherently, strategic planning has a long planning horizon and is based on highly aggregated information and forecasts. The reconstruction or an extension of an emergency department is an example of strategic planning decision-making.

The tactical hierarchic level consists of more operational decisions than the strategic level, with a subsequent shorter time horizon. Tactical planning translates strategic planning decisions to guidelines that facilitate operational planning decisions. The capacities are set, and the decision-makers have to maximize their utility. The operational levels also undertake these problems but at an even short time horizon than the tactical level. At the operational levels, capacities are fixed, while temporary capacity expansions like overtime or hiring extra staff are still possible in tactical planning. Operational planning involves short-term decision making related to the execution of the health care delivery process.

The framework of Hans et al. (2012) applied to this thesis reveals that it positions itself within the strategic and tactical hierarchic levels, offering insights on alternate layouts for the ED. Problems on higher hierarchical levels increase the potential impact. However, required investments are usually also higher, and the effects of interventions are felt on a longer-term (Hans et al., 2012). An alternative layout will affect all managerial areas.

3.1.1 Hospitals

While the framework of Hans et al. (2012) is valid for the entire health care supply chain, this report looks specifically at a hospital, and even more specifically, an ED. A survey conducted by Rais and Viana (2011) gives an overview of the problems solved by OR in this domain. The survey reveals that deterministic OR methods show promising results within scheduling problems like surgery and ED scheduling, as well as staff and shift scheduling. Deterministic methods can solve capacity planning, resource/budget allocation, and show encouraging results with layout optimizing problems.

Simulation and related non-deterministic OR have their strengths when the environment of optimization is stochastic. Such problems can, for instance, be problems associated with hospital admission, hospital services, patient recovery, resource planning, facility utilization, logistics, supply chain coordination, and emergency response.

3.1.2 Emergency Department

Within hospital planning, EDs are particularly considered due to their complexity and impact on saving lives with high acuity. EDs are the main entry point for patients to a hospital. Therefore, the patient flow emanating from EDs determines the operating conditions of many units and wards in a hospital and, consequently, also its resources and service levels (Uriarte et al., 2017). One of the most reported and analyzed problems concerning EDs in literature is the problem of overcrowding. The consequences of ED overcrowding include delays in time-sensitive diagnostic and treatment decisions, poorer patient outcomes, patient and provider dissatisfaction, and the inability of staff to adhere to guideline-recommended treatment (Morley et al., 2018; Villa-Roel et al., 2012). Hence, over the last couple of decades, the allocation of resources and design to care delivery processes have become increasingly crucial for health care providers (Furian et al., 2018).

Standard solutions to avoid overcrowding are extra resources, redirecting patients, and increasing the efficiency of existing resources (Uriarte et al., 2017). None of these solutions offer an easy and quick fix. The traditional approach for decision-making in continuous improvement projects, like EDs, is based on the experience of the decision-maker and a trial and error procedure. However, this approach has many limitations, including the amount of time required, the cost, and the fact that it can never ensure an optimal result.

To solve the problems faced by EDs, Uriarte et al. (2017) suggest moving from the traditional approach towards knowledge-driven and evidence-based decision making. One can define evidence-based decision making as making decisions on policies, programs, and projects by utilizing the best available evidence and objective knowledge from research. In order to find the best objective solution, different OR techniques can be utilized. Within an ED, Brailsford et al. (2009) reports that a statistical approach, followed by simulation, qualitative techniques, and mathematical modeling, is the most reported ones in the literature. In their review of OR contributions to EDs, both Vanbrabant et al. (2019) and Saghafian et al. (2015) concluded that simulation is and will be a leading tool for analysis of patient flow optimization.

3.2 Facility Layout Problems

FLPs is a class of operation research problems that aims to determine the placement and the relative positions of facilities in a layout area, to minimize the traveling or handling costs (Drira et al., 2007). The specific placement of these facilities is known to impact the system performance significantly. However, the FLP is a complex combinatorial optimization problem of many dimensions with a high number of variables making it hard and time-consuming to solve.

In its most basic form, an FLP is often formulated according to the Quadratic Assignment Problem (QAP), a classical model in discrete optimization which works by enumerating different layout configurations until the best arrangement is obtained. Although mathematically elegant, QAP is an NP-hard problem (Sahni and Gonzalez, 1976), which implies that it is computationally impractical for problems over a certain size.

Due to the various applications of FLPs, different approaches for categorizing and describing FLPs have been proposed. In this literature review, the framework developed by Drira et al. (2007) is exploited to obtain a greater understanding of the FLP. Also, this framework is used to guide the choices for formulation and solution methods for the FLP in this thesis. This Section is divided into three main categories, following the framework of Drira et al. (2007). Section 3.2.1 highlights the characteristics of the environment of the application, before Section 3.2.2 investigates the formulation of the problem. Finally, Section 3.2.3 focuses on the different approaches used to solve the FLP.

3.2.1 Area of Application

FLPs are widely applicable in several sectors. Research on FLPs originated from typical industrial applications. In these problems, the focus is, for instance, on organizing manufacturing units to improve the performance of workers by reducing walking distances or by locating machines to streamline a production line. However, in the last two decades, research on layout problems has been extended to include the design of circuit boards, spaces in service sectors such as airports, retail stores, and healthcare facilities (Vahdat et al., 2019). The layout problems addressed are strongly dependent on the specific features of the environment applied to (Drira et al., 2007). Therefore, a problem solved in one industry is not easily transferable to another.

FLPs in the hospital environment constitute a specific type of problem called Hospital Facility Layout Problem (HFLP). Elshafei (1977) formulated the first FLP concerning layout planning in hospitals. In their paper, 19 equally-sized clinics are to be placed within the hospital, minimizing the total distance traveled by patients.

In general, layout design in healthcare has been characterized by the scale of the design problem. Arnolds and Nickel (2015) propose a categorization of either *macro level* or *micro level.* In *macro level* layout planning, all functional departments such as wards, emergency departments, and outpatient clinics are assigned to locations inside the hospital. In contrast, *micro level* hospital layout planning consists of planning the layout of a single functional department. The layout of an emergency department is an example of a *micro level* planning problem, in which units such as care rooms, treatment rooms, and radiology is to be located. This problem is a special case of HFLPs, named Emergency Department Facility Layout Problem (EDFLP). Patients in the ED typically suffer from serious or unexpected diseases and need immediate treatment. Thus, shorting their travel distance and time by optimizing the department layout is very meaningful (Zuo et al., 2019).

As noted in 3.1, the traditional approach within hospital planning is based on the experience of the decision-maker, and a trial and error procedure. Mathematical optimization in hospital planning is little explored. FLPs in the industrial context is well documented and can give direct economic and efficiency benefits when used frequently for improvement processes (Tompkins et al., 2010). Ahmadi et al. (2017) concludes that FLPs are well suited and could equally relevant for hospital planning problems as for other applications. However, HFLPs may, in many cases, require a higher degree of information processing than other FLPs, as hospitals provide additional complexity of flows compared to, for example, a production line (Kvillum and Vigerust, 2018). In this context, according to Burgess et al. (1993), simulation is the only methodology robust enough to systematically examine the role and impact of product complexity and other key variables on facility performance. This is especially true because simulation models can capture many of the requirements and attributes of real-life problems that are difficult to consider using analytical models for the layout optimization problem (Aleisa and Lin, 2005).

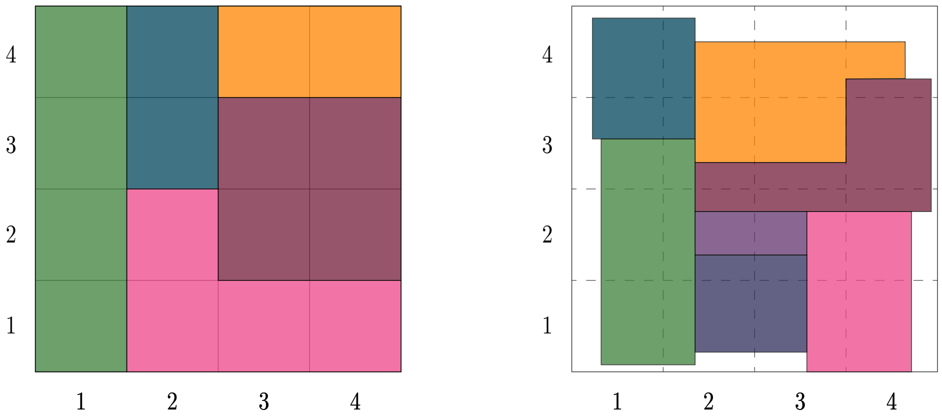
3.2.2 Formulation

The formulation of the FLP has consequences for the solution procedure of the problem. Insight into different formulation approaches in the literature provides a basis for the model formulation choices.

Static vs. Dynamic

A problem formulation of the layout problem can be categorized as *dynamic* or *static* by whether the problem incorporates changes over time or not. In a static problem, parameters such as flows between functions are stable over the planning horizon, while a dynamic problem must be flexible or at least take into account flows that may vary over time (Arnolds and Nickel, 2015). According to Drira et al. (2007), most FLPs are considered static. However, dynamic approaches have gained increasing attention within industrial applications due to their flexibility in the last decades. In these formulations, the objective can be to determine a layout for each period in the planning horizon, while minimizing the sum of material handling costs and the sum of rearrangement costs over all periods (Drira et al., 2007).

An HFLP has several dynamic aspects to its nature. Patient arrivals change over time, and seasonal variations in diseases and damages demand a wide variety of resources. Rebuilding is costly and sought avoided. Consequently, the solution of the



(a) Discrete **(b)** Continuous

Figure 3.1: Discrete and continual layout representations.

layout problem must retain as much flexibility in the layout as possible to keep the cost of future changes to a minimum. Despite the dynamic aspects of the planning, the solution of the HFLP itself, when executed, is static (Kvillum and Vigerust, 2018).

Solution space

Problems can according to Drira et al. (2007) be classified into two main formulation categories; *discrete* and *continuous* formulation. These two classifications are based on how the area of the planar site in the FLP is modeled, and how the functions to be placed is represented. An example can be seen in Figure 3.1.

The representation of the footprint by its size, shape, and areas available for the placement of functions is an essential part of the problem formulation. In a *discrete* formulation, the facility and the departments are usually represented in a grid structure. The dimension of the facility is usually fixed, and the departments are composed of an integer number of grids. Drira et al. (2007) found in their survey that an even division into grid elements are the most frequently used discrete formulation. This follows naturally as a consequence of the facility's often being rectangular. However, a discrete representation is not suited to represent the exact position in the planar site and can not model appropriately specific constraints as the orientation of facilities (Drira et al., 2007). In a discrete formulation, the functions areas are defined as a number of grid elements, and the functions' shapes are constituted by arranging the grid elements in different ways (Kvillum and Vigerust, 2017).

In a continuous representation of the FLP, the planar site is not divided into discrete locations, rather all units with unequal sizes and shapes can be located at any place in the planar site as long as they do not overlap (Das, 1993). A solution to this problem formulation was first proposed by Montreuil (1991) in which binary variables are exploited to avoid overlapping. In a continuous formulation, the functions can be divided into parts and span several grid elements or take shapes different than rectangular. Vahdat et al. (2019) formulate a continuous layout problem of an outpatient clinic where each function is defined by the coordinates of the centroid of the function. In this formulation, standard-sized functions can be placed either vertical or horizontal. Variable-sized units are optimized in the model to fit the planar area. A continuous approach can be argued to have abilities to capture cases closer to reality and being more flexible; however, they will usually require increased computational effort and are more complicated to formulate compared to the discrete approach (Kvillum and Vigerust, 2018).

Objective function

Discrete formulations of the FLP are mostly explored by QAP modeling (Vahdat et al., 2019). The QAP describes an assignment problem where the objective depends on the relation between the location of several elements. This gives the problem a second-degree objective function where the location of functions is interdependent, and the objective is dependent on products of pairs of binary variables. Koopmans and Beckmann (1957) was the first to formulate the FLP of locating functions based on flows between them. The works of Helber et al. (2016) and Elshafei (1977) are examples of formulations of HFLPs as QAPs.

In a survey conducted by Kusiak and Heragu (1987), different approaches for formulating the FLP were evaluated, including QAPs, Quadratic Set Covering Problems (QSP), Integer Linear Programming Problems (ILP) and Mixed Integer Linear Programming Problems (MILP). Despite differences in structure, a decision variable relating the placement of one function to another is common in all formulations. Kusiak and Heragu (1987) remark that the most natural formulation of an FLP is a QAP, but traits of the other approaches can be seen as supplements to improve or simplify the formulation. The QSP introduces the division of larger locations into smaller blocks of equal sizes, where each block is occupied by at most one facility. In contrast to the QAP, a function in this instance can cover several blocks. Utilizing this formulation, the QSP is able to handle functions of varying size, and define functions as configurations of a number of blocks. The ILP provides a linearization to the quadratic structure of the FLP. Through connecting the binary decision of placement for two functions, a new set of binary variables is introduced, describing the relationship of placement between two functions.

The relation parameter between functions is not discussed in the framework of Drira et al. (2007). However, most FLPs define the cost variable of the problem as transportation efforts, using registered data of transportation over time (Helber et al., 2016). Within a hospital environment, this cost variable translates to the flow of both patients and staff between different functions, where the cost is the distance traveled.

3.2.3 Solution Methods

The solution approaches can be divided into *exact* and *heuristic* methods. Solving a complex combinatorial problem like the FLP is a trade-off between obtaining an optimal solution, which requires a great amount of computational time for problems above a certain size, and obtaining a solution that creates a satisfactory layout in a shorter amount of time. Exact solution approaches should be considered if the solution space is sufficiently constrained. Heuristics and metaheuristics cannot guarantee the optimal solution but manage problems with higher complexity. In contrast to heuristics, metaheuristics include some smartness to avoid getting stuck in local optima. In the survey on FLPs conducted by Ahmadi et al. (2017), the majority of articles solved their problems by applying a heuristic. The wide use of heuristics results from the high complexity of the FLP.

Several articles simplify the solution method by solving the problem in multiple stages. In the first stage, large function groups are allocated to larger areas, and in the second stage, separate functions are allocated to their optimal location within the larger areas. This solution method simplifies the solution process, allowing for models with a high number of functions and locations, but can come at the expense of the quality of the solution.

3.2.4 Classification of the FLP in this Thesis

The FLP in this thesis is developed to generate layouts for an ED. Flows of patients and staff, generated from a simulation model, are used as input to the optimization model. The optimization model assigns functions to locations with the goal of minimizing distances between the functions, multiplied with the weighted flows between pairs of functions. The importance of the flows is weighted based on the triage level of the patient. Besides, the flow is weighted whether the associated flow is for a patient or staff. Due to the objective function, the problem has similarities with the QAP, where the center of each function is assigned to one location.

The problem is modeled in both one and multiple stages. In the one-stage model, both the footprint and functions have a discrete representation. All functions cover a set number of locations, but the functions covering several locations can take different configurations. The choice of configuration is incorporated in the formulation and implementation of the model as a part of the decision variables. All decision variables in this formulation are binary, rendering the model a QAP modified by linearization, as in the formulation of Helber et al. (2016).

In the multi-stage approach, some relaxation is introduced to help to solve larger instances of the problem. In each stage, there are three sets of importance, in fact, the set of functions included in the stage, the functions to be locked at the end of the stage, and the set of functions locked in an earlier stage. When a function is locked, this function is given a specific location and configuration in all the following stages. Except for the last stage, there are some functions to be locked in a later stage. These functions are of less importance and, therefore, relaxed to a continuous representation. The relaxed functions have the opportunity to split, and a location can be shared between different functions, each taking a proportion of the location. This produces a problem that is a Mixed Integer Linear Program (MILP), including both binary and continuous variables. The last stage of this multi-stage approach is the same as in the one-stage solution method since every function is to be locked after the stage, and no functions are relaxed. The solution framework uses exact techniques to solve every stage. However, by only including a subset of all functions to be placed in each stage, the method is no longer exact, but rather a good approximation of the optimal solution.

The discrete formulation with equal-sized locations in this problem may not be the optimal approach, but it works as a reasonable simplification of the EDLP. The stochasticity in the ED is not captured by the static approach in the optimization model. However, by combining optimization with simulation, the stochasticity in the problem is taken into account.

Compared to existing literature, see Table 3.2, the EDLP of this thesis has many of the same traits as the model of Kvillum and Vigerust (2018) and Helber et al. (2016). However, to the authors' knowledge, this thesis is the first to combine a simulation model of such detail and an optimization model in an iterative solution framework within an ED.

Table 3.2: Classification of the relevant literature discussed in the review in regards to FLP

References	Environment	State	Objective Function	Facility Layout	Function Shapes	Stages	Solution Method	Relation Parameter
This report	ED	Static	QAP	Discrete, equal size	Multiple locations with different configurations	Multiple-stage	Hybrid SO, Exact	Patient and staff flows
Kvillum and Vigerust (2018)	Hospital	Static	QAP	Discrete	Continuous	Two-stage	Two-stage Decomposition	Proximity values
Elshafei (1977)	Hospital	Static	QAP				Heuristics	Flows
Helber et al. (2016)	Hospital	Static	QAP	Discrete		Two-stage	Heuristics (Fix-and-optimize)	
Montreuil (1991)	General		MIP	Continuous	Continuous			
Acar et al. (2009)	General		MIP					
Vahdat et al. (2019)	Outpatient Clinic	Static	MIP	Continuous	Continuous	Two-stage	Hybrid SO, Heuristics (Particle Swarm)	Flows
Zuo et al. (2019)	ED		Multi-objective, MIP	Continuous	Continuous		Hybrid SO, Heuristics (Tabu search)	Flows and Proximity values
Queirolo et al. (2002)	Warehouse					Two-stage	Hybrid SO, Heuristic (Genetic algorithm)	
Arnolds, Nickel, et al. (2012)	Hospital		Robust optimization					

3.3 Simulation in Emergency Departments

Simulation refers to an extensive collection of methods and applications to imitate the behavior of real systems (Kelton et al., 2015). The main advantage of simulation is conforming to Vanbrabant et al. (2019), the high level of detail that can be taken into account, such as individual patient characteristics. This observation leads to less restrictive assumptions and the opportunity to model the case in a study close to the real world. In the explored Hybrid SO, the simulation part is generally poorly described. To get a thorough understanding of simulation of EDs, articles that only conduct simulation is included.

3.3.1 Simulation techniques

Different types of simulation techniques exist, and dependent on the environment of simulation an appropriate simulation technique is determined. In literature, the main techniques are *system dynamics* (SD), *agent-based simulation* (ABS), and *discrete-event simulation* (DES).

SD is a dynamic simulation technique where differential equations are discretized, used to model complex systems as it evolves. SD is made up of stocks, and the flows between them. Stocks represent the state of the different parts of the system, like the number of patients in the waiting room and triage in an ED. The flows connect the various stocks and represent the rate change of the stocks.

ABS is a dynamic, stochastic, and discrete simulation technique used to model the interactions among autonomous agents in complex systems over time. An agent is an individual entity in the model, like a single patient or a physician. The discrete agents make their own individual decisions according to given rules.

DES is a simulation method that models the system as a series of discrete events. In an ED, events can be the arrival of patients, move a patient to a new function, complete a process, or move a patient out of the ED. An event will cause a change in the systems state. A state, in this case, can be how many of the different patient types in the various functions in the ED. Furthermore, DES is a dynamic model where states change over time. There is no change in states between two events. More technical, DES is a simulation of multiples queues and stochastic service stations in a system.

ABS, DES, and SD are all well suited to simulate the behavior of a complex system. They are all dynamic simulation techniques, with the ability to reflect on how the system evolves. DES and ABS are stochastic models, which fit the variability in arrival rate and service time. Due to the lack of randomness and resource constraints, SD is a lousy choice for modeling resource-constrained queuing models, such as an ED (Mohiuddin et al., 2017). In ABS, the agents are independent entities with the ability to make their own decisions. Since patients follow given treatment routines determined by the staff, ABS utilizes the interactions between patients and staff to a lesser extent. In practice, an ED can be seen as a system with multiple queues at different service stations. DES can simulate those queue systems and is therefore well suited to simulate an ED. Table 3.3 shows the main differences between SD, ABS, and DES.

Table 3.3: Comparison of simulation methods

	SD	**ABS**	**DES**
Static/Dynamic	Dynamic	Dynamic	Dynamic
Deterministic/Stochastic	Deterministic	Stochastic	Stochastic
Discrete/Continuous	Continuous	Discrete	Discrete

3.3.2 Comparing earlier work

Today, no universal reporting guidelines for simulating EDs exist. Different health care systems around the world lead to different EDs. This fact has resulted in several different approaches by researchers and has complicated and delayed the work on a generic simulation model for any ED.

As mentioned above, DES is well suited to simulate an ED. In a recent literature review by Salmon et al. (2018), 254 articles simulating an ED are reviewed. 209 of these articles applied DES, 25 applied ABS, 18 applied SD, while 13 articles had a combination of DES and SD or DES and ABS. All the selected relevant articles to the problem in this report use DES. By taken these observations into account, DES is a natural choice for simulation an ED in this thesis.

There are significant differences in the complexity of the selected articles, both based on the assumptions and simplifications applied. An essential factor for model complexity is which entities the simulation model takes into account. Entities are items that flow through a network of queues and servers during a simulation. The entities found in the majority of the articles reviewed are patients and staff. This fact is not stated explicitly. However, based on the fact that these articles utilize a specific simulation program for health care, it is assumed that all articles simulate both the patient and staff as entities. By including both patients and staff as entities, the realistic behavior of the model is significantly increased. Even though Duguay and Chetouane (2007) include staff as an entity, the transfer time between different functions in the ED is disregarded. That is a considerable simplification, consequently decreasing computational time.

In several articles, laboratory test samples are included as an entity. In this case, there is an interaction among patients, staff, and lab samples. The patient has to wait until the lab sample completes the queue, and the analysis is finished. The reasoning behind including lab samples in the simulation model is to try to capture the real world. Uriarte et al. (2017) notes that lab samples often tend to delay ED processes and that including this as an entity is an important metric in order to capture the real dynamics of the ED. Eskandari et al. (2011) also includes lab tests in the model, but instead of modeling the lab samples as an entity, the waiting time for the test results is simulated as delays.

Key Performance Indicators

To be able to analyze and optimize the operations of an ED, performance indicators are required to evaluate the system. According to Vanbrabant et al. (2019), time-related KPIs are the most frequently used KPI. Several other KPIs exist, like proportion-, utilization- and budget KPIs. However, these KPIs will not be discussed further in this review due to their limited relevance in literature and the objective of this thesis.

LOS is the most reported KPI, found in six of seven published articles. This metric is important due to its tight correlation with the number of patients in the ED. Further, the patient safety metrics TTT and DTDT are somewhat less used than LOS, with respectively four and three articles. Besides, both Khadem et al. (2009) and Duguay and Chetouane (2007) look at the total wait time and activity time, while Oh et al. (2016) only look at the total time consumed waiting in the ED.

The simulation model in this Thesis

The simulation model developed in this thesis employs DES for decision making in an ED environment. By modeling in a graphical simulation software, the literature standard is followed. Patients and staff are modeled as entities. With inspiration from a considerable amount of articles, the lab samples are included as an entity to increase the real-world behavior of the model.

In accordance with the reviewed literature, LOS is utilized as a KPI. In line with the greater part of the articles, the patient safety metrics TTT and DTDT are included. Finally, this thesis stands out by using RTT as a KPI to consider the ability to transfer patients from the ED. In Table 3.4, the characteristics of the simulation model in this thesis are compared to existing literature.

Table 3.4: Classification of the relevant literature discussed in the review in regards to simulation and KPIs.

References	**Environment**	**Study**	**Simulation software**	**Simulation technique**	**Entities**			**Time KPIs**			
					Patient	*Staff*	*Lab*	*LOS*	*TTT*	*DTDT*	*RTT*
This thesis	ED, Norway	Hybrid SO	FlexSim	DES	✓	✓	✓	✓	✓	✓	✓
Uriarte et al. (2017)	ED, Sweden	Hybrid SO	FlexSim	DES	✓	✓	✓	✓	✓	✓	
Cocke et al. (2016)	ED, USA	Simulation	Arena	DES	✓		✓	✓	✓	✓	
Oh et al. (2016)	ED, USA	Simulation	Arena	DES	✓		✓	✓	✓	✓	
Eskandari et al. (2011)	ED, Iran	Simulation	Arena	DES	✓	✓		✓			
Khadem et al. (2009)	ED, Oman	Simulation	MedModel	DES	✓	✓		✓			
Duguay and Chetouane (2007)	ED, Canada	Simulation	Arena	DES	✓	✓	✓				
Ruohonen et al. (2006)	ED, Finland	Simulation	MedModel	DES	✓	✓	✓	✓	✓		
Acar et al. (2009)	General, Turkey	Hybrid SO		DES							
Vahdat et al. (2019)	Outpatient clinic, USA	Hybrid SO	Anylogic	DES	✓	✓					
Zuo et al. (2019)	ED, China	Hybrid SO	MedModel	DES	✓	✓					
Queirolo et al. (2002)	Warehouse, Italy	Hybrid SO	MANUALWARE	DES							
Azadivar and Wang (2000)	General, USA	Hybrid SO		DES							
Arnolds, Nickel, et al. (2012)	Hospital, USA and Germany	Hybrid SO		DES	✓	✓					

3.4 Combining Simulation and Optimization

Optimization and simulation are two relevant methods for any facility planning process, as outlined by Aleisa and Lin (2005). Simulation has the advantage of producing more accurate flow data for layout optimization than other comparable methods. By combining simulation and optimization, the proposed layouts take the stochastic behavior and complex interactions of the system into the solution.

Nolan and Sovereign (1972) first introduced solving problems through a combination of simulation and optimization. In their article, the disadvantages of modeling large systems with either optimization or simulation are outlined. Simulating a detailed model with multiple experimental designs may require high computational power. In comparison, optimization models with complete details may be difficult to solve in a reasonable time. By combining simulation and optimization, the simulation model captures the complex behavior of the system, while the optimization model is able to find promising solutions to large-scale combinatorial problems.

One of the main challenges hybrid simulation-optimization tries to answer is uncertainty. This aspect is addressed by a variety of more conventional approaches, such as stochastic programming, fuzzy programming, and stochastic dynamic programming. The accuracy and detail of these models are, however, much lower when compared to simulation approaches (Figueira and Almada-Lobo, 2014). In FLP, the objective is usually in conjunction with traveling distances for various stakeholders or closeness among functions. In contrast, with a simulation-optimization approach, the objective is to optimize performance measures (Azadivar and Wang, 2000).

3.4.1 Classification of Simulation-Optimization

Figueira and Almada-Lobo (2014) classifies simulation-optimization approaches based on several dimensions, most relevant for this thesis; simulation purpose, hierarchical structure, and search scheme. Simulation purpose and hierarchical structure focus on the interaction between simulation and optimization. While simulation purpose describes how simulation and optimization benefit from each other, the hierarchical structure focuses on the iterative process of the two techniques.

As presented in the simulation purpose, there are several different aspects of the simulation model to utilize in a simulation-optimization framework. First, simulation can be used as an Evaluation Function (EF). Other approaches are to utilize simulation to construct a surrogate model or parameter refinement, categorized as respectively Surrogate Model Construction (SMC) and Analytical Model Construction (AME). Finally, the solution may be generated by the simulation model, following the Solution Generation (SG) practice.

Sequential Simulation Optimization (SSO) is a hierarchical structure method where simulation and optimization are run in sequence. Other aspects in this dimension exist, in fact, Optimization with Simulation-based iterations (OSI), Alternate Simulation Optimization (ASO), and Simulation with Optimization-based Iterations (SOI). In OSI, at least one complete simulation is conducted for each optimization procedure. By applying SOI, one optimization method is run for each simulation. Alternate Simulation Optimization (ASO) is a combination of OSI and SOI, where both optimization and simulation is run entirely in each iteration.

In contrast to simulation purpose and hierarchical structure, search scheme concerns different realizations to handle stochastic in the simulation model. In this context, realizations are defined as a repeating run of the simulation experiment. The simulation model may be run with one realization for each solution (1R1S), different realizations for each solution (DR1S), common realizations for each solution (CR1S), or one realization for multiple solutions (1RMS).

3.4.2 Comparing earlier work

In this section, six articles with a simulation-optimization approach for solving FLP are reviewed. Three of these articles are in a hospital environment, while the other articles either study a general approach or within another field. In the context of simulation, all reviewed articles utilize DES to evaluate the performance of the layouts. However, Acar et al. (2009) and Vahdat et al. (2019) stand out by updating parameters in the optimization model as a result of a simulation run.

Simulation and optimization are according to the literature run in sequence. Nevertheless, there are some differences in the interaction between simulation and optimization in the articles. Vahdat et al. (2019) run the simulation model before and after the optimization, while Zuo et al. (2019) only do a simulation run after the final solution is found. In contrast, all other articles run simulation and optimization in a sequence multiple times until a convergence criterion is fulfilled.

To reduce the output variance of a simulation, multiple replications is the standard practice in the literature. Since conducting a simulation run with multiple replications may be computationally expensive, Azadivar and Wang (2000) uses a statistical approach to reduce the number of replications. On the other hand, Queirolo et al. (2002) applies a deterministic simulation model, making several simulations redundant.

Since FLP is an NP-hard problem, the majority of the articles utilize metaheuristics to generate solutions. Metaheuristics (MH) and regular heuristics (H) cannot guarantee to find optimal solutions. However, metaheuristics include techniques with some kind of smartness to avoid getting stuck in local optimums. The different metaheuristics used in the articles are genetic algorithms, tabu search, and particle swarm optimization. In contrast, Acar et al. (2009) uses an exact MIP method to generate layouts. Arnolds and Nickel (2015) solve their FLP using an exact method, however the exact method is only a processing step before an improvement heuristic search is applied for a local optimum.

3.4.3 Classification of Simulation-Optimization in this Thesis

In accordance with the reviewed literature, the model of this thesis simulates and optimizes in a sequence. Further, the common practice is followed by utilizing DES as the evaluation function of the layouts. Pursuant to the minority, the parameters of this optimization model are updated based on the simulation output. Nevertheless, this model stands out by updating the flows of patients and staff in between the functions for every simulation run. Table 3.5 presents a comparison between this thesis and the reviewed literature.

Multiple replications are used to reduce the variance of the simulation runs. Even though the problem is NP-hard, an exact solution method is applied. This solution method is possible because the solution space is sufficiently reduced in the layout representation, making this article unique compared to the existing literature.

To be more specific, this model fits the Recursive Optimization-Simulation Approach (ROSA) presented in Figueira and Almada-Lobo (2014). Like this thesis, the ROSA approach runs a deterministic analytical model and a simulation model alternately. The simulation outputs performance measures based on the solution from the analytical model. Then, the analytical model parameters are refined based on the simulation output, and this iterative process continues until a stopping criterion.

Table 3.5: Classification of the relevant literature discussed in the review in regards to combining simulation and optimization

References	**Environment**	**Simulation technique**	**Simulation purpose**				**Hierarchical structure**				**Search scheme**				**Solution approach**			**Stopping criteria**
			EF	SMC	AME	SG	OSI	ASO	SSO	SOI	1R1S	DR1S	CR1S	1RMS	E	H	MH	
This report	ED, Norway	DES	✓		✓				✓			✓			✓			Convergence
Acar et al. (2009)	General, Turkey	DES	✓		✓				✓			✓			✓			Convergence
Vahdat et al. (2019)	Outpatient clinic, US	DES	✓		✓				✓			✓					✓	1 iteration
Zuo et al. (2019)	ED, China	DES	✓						✓			✓					✓	1 iteration
Queirolo et al. (2002)	Warehouse, Italy	DES	✓						✓		✓						✓	Convergence
Azadivar and Wang (2000)	General, US	DES	✓						✓			✓					✓	Convergence
Arnolds, Nickel, et al. (2012)	Hospital, US and Germany	DES	✓						✓			✓			✓	✓		Convergence

Chapter 4

Problem Description

The problem studied in this thesis is an Emergency Department Layout Problem (EDLP), with the overall aim to improve Key Performance Indicators (KPIs) of the ED by producing better layouts. An ED consists of different *functions* with varying sizes and features. Patients and staff move between the different functions based on their condition and tasks, in an effort to diagnose and heal the patients. These movements can be seen as *flows*, creating dependencies between the functions. In the EDLP, the functions are to be placed at different *locations* within the ED, minimizing the distance between functions of high dependencies.

The specific case studied is within an existing ED, specifically the Kalnes ED. The total area and footprint of the ED are considered known. This includes the placement of hallways, as well as other static structures within the ED, such as stairs and elevators. All static structures are locked and cannot be moved. The feasible area where functions can be placed is discretized into blocks of equal size. This size is chosen to be the size of a standard-sized care room, which in turn is the smallest function to be placed.

A function covers a discrete set of locations. Every location within the ED is assumed to be able to host any function. However, there are requirements for certain areas within the ED, as well as other function-specific placement rules. Such rules are, for instance, requirements for proximity to the entry or a specific function, or access to facilities like hallway and window. A location can only be covered by one function, and consequently, no functions can overlap. Functions covering more than one location is given one center-location, often located close to its geographic center. Depending on the center-location, these functions can take on different configurations. Some functions have configurations that can span across hallways. The distance between two functions is calculated from the center-locations by finding the shortest path following the hallways, disregarding the configurations of the functions.

Arriving patients have different medical complications, needing examination, and necessary treatment by physicians and nurses. When these services are provided, patients and staff move between different functions in the ED, creating flows. The movements of patients follow *clinical pathways*, which are standardized, typically evidence-based health care processes. They define the sequence of procedures such as diagnostics, surgical, and therapy activities applied to patients. As patients use several functions and several functions take care of several different patients, dependencies between the functions and their placement are created, thus affecting efficiency and KPIs. If there are several functions providing a service that a patient needs, the patient is escorted or transported to the closest function. When this function is occupied, the patient will be escorted to the closest free function or sat in a queue. The triage level of a patient determines the prioritization within the ED, meaning that a patient of a high triage level will be prioritized before a lower triaged patient in a queue.

The objective of the optimization model is to minimize the weighted distances between functions, with an overall goal to improve the KPIs on which the ED is evaluated. As a consequence, a correlation between walking distances and the KPIs is one of the main assumptions. However, this connection is composed. Shorter walking distances for the patients enable lower walking times, with following better KPIs. In other cases, patients wait for staff to conduct an activity, with a potential of lower waiting times by reducing the walking-distances for the staff. But, in the case where both patients and staff are only waiting for available rooms, the KPIs will not be significantly impacted by lower walking distances. Some different prioritization parameters are introduced to make the model work as intended. Patients and staff can be assigned priorities by weighting the flows. Besides, prioritization can be assigned to different triage levels, making the model able to consider high acute patients.

Chapter 5

Mathematical Model

In this chapter, the mathematical model formulated to solve the Emergency Department Layout Problem (EDLP) is presented. The model is designed to solve an FLP, which incorporates a Quadratic Assignment Problem (QAP), a problem where multiple functions are assigned to a set of locations simultaneously while accounting for their interactions. However, the introduction of different configurations for some functions leads to differentiation from the standard QAP.

In Section 5.1, some decisive assumptions for the model formulation is presented. Further, the notation and objective function is described in respectively Section 5.2 and 5.3. The model constraints are explained in Section 5.4. In Section 5.5 a revised model is presented.

5.1 Model Assumptions

The overall aim of this model is to assign *functions* to *locations*, minimizing the distance between functions with dependencies, indicated by large flows of patients and staff between them. For instance, the triage rooms and the waiting rooms are two functions with a large flow in-between them. Patients walk back and forth to get their triage done, and staff walk between the two functions escorting patients. The model seeks to reduce the distance between these two functions, making the walking distance, and thereby the time consumed, as short as possible. Due to a large number of functions and locations, this problem becomes very complex. Therefore, some simplifications are introduced to develop a model capable of solving this problem. In this section, some basic information about model representation, configuration, distances, and flows are described. In order to solve a real-world case, more assumptions to reduce the model complexity are necessary. These assumptions are discussed in Section 8.1.

In addition to minimizing distances, the original QAP formulation includes a place-

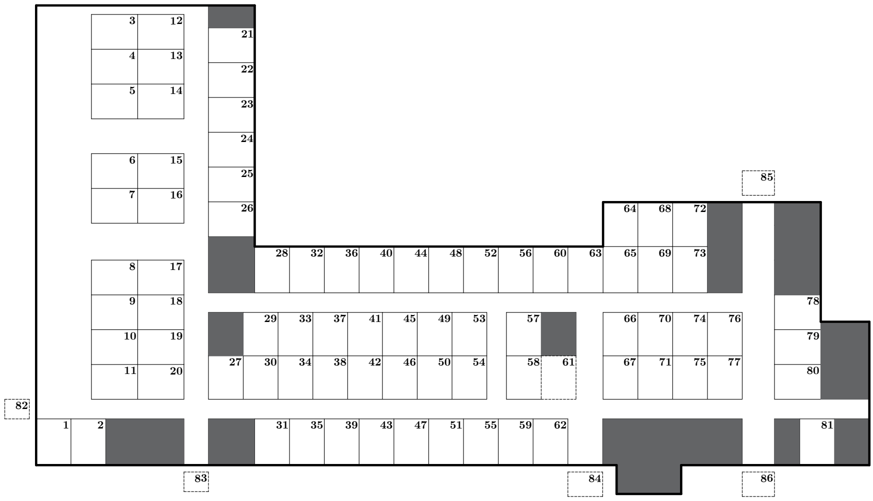


Figure 5.1: Discretized layout of the Kalnes ED

ment cost for locating functions to different locations as part of the objective. However, the information on placement cost for the different functions within the ED is limited or non-existent. Therefore, focus is directed towards minimizing distances with respect to flows, and the placement cost is assumed to be equal for all functions and locations and hence omitted from the model.

5.1.1 Model representation of the ED

To reduce the complexity of the formulation, the ED is represented as a grid with equal-sized rectangles, referred to as *locations*. The size of the rectangles is chosen to be the standard-sized care room, which, in turn, is approximately the smallest individual room to be placed. Figure 5.1 shows the discretized layout of the Kalnes ED. Available locations are marked as rectangles with their room number in the top right corner. Once allocated, each function cover one or more rectangles, where the total number of rectangles is approximately equal to the function size. The required number of locations for each function is known in advance. For instance, a CT requires approximately four times the area of a standard care room. Therefore, a CT is separated into four rectangles. The model makes sure the four CT rectangles are located adjacent, in order to assure that the shape of the CT is unchanged. Some functions are smaller than a standard-sized care room. These functions are typically storage rooms, bathrooms, and some other less essential functions. By aggregating small-sized functions into the size of the model rectangles, all functions in the model are at least the size of a standard-sized care room.

Fixed installments within the ED as hallways, lifts, and stairs are assumed locked.

Additionally, heating, ventilation, and air condition rooms are presumed fixed. These functionalities require a considerable amount of resources to locate differently and are therefore omitted as variables in the model. By excluding these installments, the model complexity is reduced. In Figure 5.1, the fixed and non-movable locations are marked in dark gray.

5.1.2 Configurations

Functions that cover more than one location can take on different configurations. Every configuration has a defined center-location. The center-location and the selected configuration defines which locations the function covers. A covered location cannot be covered by any other function, hence preventing overlapping functions.

A function with the size of five locations can, for instance, have ten different configurations, as shown in Figure 5.2. The center-location is indicated with $\ast$. Every configuration a function might take is not feasible in every location. The development of feasible configurations is made in cooperation with stakeholders, finding configurations where practical considerations are taken into account. The general assumptions guiding the generation of feasible configurations at a center-location can be found in Section 8.1.

The choice of one location to be the center-location of a configuration will, in some instances, make the center-location different from the true center of the function. This is a simplification of the problem. However, the center-locations of every configuration is chosen as the location closest to the true center. Appendix B.2 includes a full overview of every feasible configuration in this model. The distances between allocated functions are calculated as the shortest distance by following the hallways between the center-locations of the functions.

5.1.3 Flows

The simulation model outputs flow of both staff and patients between different functions within the ED. These flows are aggregated based on the triage level of the patient. For instance, if a nurse has to pick up some consumables at a depot, this flow is recorded with the triage level of the patient, the nurse is conduction the task for. The importance of each flow, dependent on the triage level, can be adjusted in the model. The greater the flow between two functions, the more these two functions relies on each other, and the higher the closeness between them is prioritized in the assignment process. In the objective function, flows are multiplied with the distance

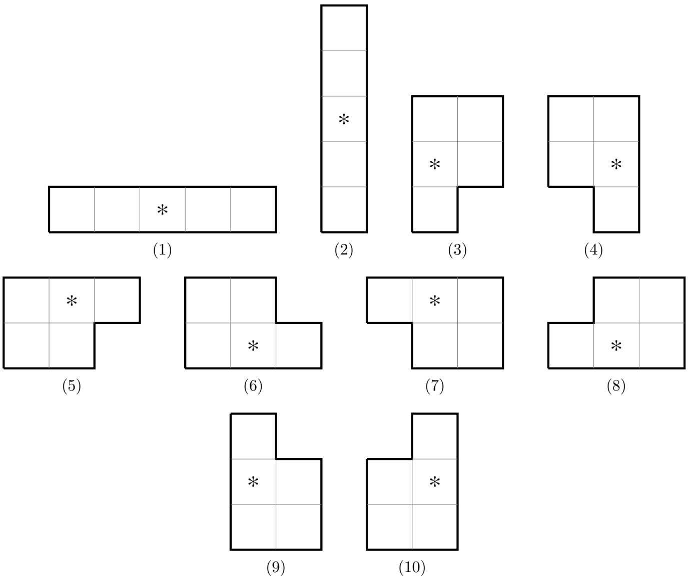


Figure 5.2: Five locations

between them, pushing highly dependent functions close.

In this thesis, the flows between two particular functions are assumed equal in both directions. In the real ED, the flow between two functions may be different for the two directions, however these differences are small. For example, the patient flows from the waiting room to triage may be higher than the opposite. This assumption is advantageous in regards to limiting the size of the model by breaking the symmetry and creating at most one connection between function pairs.

5.2 Notation

In this section, the indices, sets, parameters and variables used in the model are presented. Sets are named using uppercase calligraphic letters, variables using lowercase letters, and parameters using uppercase letters. Subscripts indicate indices, while superscripts of capital letters specify the meaning of some parameters and sets.

5.2.1 Indices

Table 5.1 summarizes all indices used in the model.

Table 5.1: Indices

Indices	Description
f, g	Functions
n, m	Locations
t	Triage level
k	Configuration

5.2.2 Sets

The sets of the model are shown in Table 5.2.

Table 5.2: Sets

Set	Description	
$\mathcal{F}$	Set of functions	
$\mathcal{L}$	Set of locations	
$\mathcal{T}$	Set of triage levels	
$\mathcal{E}$	Set of entrances	$\mathcal{E} \subset \mathcal{F}$
$\mathcal{F}_n$	Set of functions with ability to cover location n	$\mathcal{F}_n \subset \mathcal{F}$
$\mathcal{F}^F$	Set of function pairs (f, g) where $f \in \mathcal{F}$, $g \in \mathcal{F}$ and $f < g$, where a flow of either patients, staff or both exists	
$\mathcal{F}_f^R$	The associated reception to entrance $f \in \mathcal{E}$	$\mathcal{F}_f^R \subset \mathcal{F}$
$\mathcal{L}^E$	Set of entrance locations	$\mathcal{L}^E \subset \mathcal{L}$
$\mathcal{N}_f$	Set of legal center-locations for function $f \in \mathcal{F}$	$\mathcal{N}_f \subset \mathcal{L}$
$\mathcal{M}_f$	Set of legal locations function $f \in \mathcal{F}$ can cover	$\mathcal{M}_f \subset \mathcal{L}$
$\mathcal{N}_n^R$	Set of possible reception locations close to entrance location $n \in \mathcal{L}^E$	$\mathcal{N}_n^R \subset \mathcal{L}$
$\mathcal{N}_{fn}^I$	Set of locations function f with center location n cover with any configuration	$\mathcal{N}_{fn}^I \subset \mathcal{M}_f$
$\mathcal{L}_{fn}^C$	Set of all center-configuration pairs $(m, k) \in \mathcal{L}_{fn}^C$ for function $f \in \mathcal{F}_n$ covering location $n \in \mathcal{L}$.	
$\mathcal{K}_{fn}$	Set of possible configurations when function $f \in \mathcal{F}^F$ has its center location at $n \in \mathcal{N}_f$	

The set $\mathcal{F}$ represents all the functions that need to be placed within the ED. The locations $\mathcal{L}$ contain the areas in the ED where functions can be placed. Further, $\mathcal{T}$ is the set of triage levels, representing the patient's acuity. $\mathcal{E}$ is the set of different entrances, in fact, the walking-in, ambulance, and team entrance. For a given location n, $\mathcal{F}_n$ consists of all functions with ability to cover this location. The set $\mathcal{F}^F$ is created to have exactly one connection for a pair of functions, (f, g), with a flow in between them. Since the flow $(f - g)$ is the same as $(g - f)$, the set is only created for $f < g$, breaking the symmetry. $\mathcal{F}_f^R$ includes the reception for a given entrance f, while $\mathcal{L}^E$ contains the different entrance locations. The feasible placement sets $\mathcal{N}_f$ and $\mathcal{M}_f$ are two sets with high interaction, ensuring the functions placed at appropriate locations according to ED rules for room placement. The locations-set $\mathcal{N}_f$ contains all available center-locations for a function f, while $\mathcal{M}_f$ consists of the locations a function has the ability cover. $\mathcal{N}_n^R$ represents the possible reception-locations n within an acceptable distance from a specific entrance-location. $\mathcal{N}_{fn}^I$ includes all locations function f covers when assigned at n, independent of the configuration that f takes. This set is useful to reduce the number of center-function pairs $(f, n) - (g, m)$, by finding all locations any function cannot cover when function f has its center at location n. In the set $\mathcal{L}_{fn}^C$, all possible combinations of location m and configuration k resulting in the coverage of location n by function f are included. This set is generated based on the information about which locations a function cover for a given center-location. Every configuration for a function f is not feasible in every center-location n, due to both operational and practical reasons. The set $\mathcal{K}_{fn}$ keeps track of these restrictions, and includes all feasible configurations a function f may have if placed at center-location n.

5.2.3 Parameters

The parameters of the model are shown in Table 5.3. The parameter α is used to specify the prioritization between patients and staff. In D_{nm}, the distances between all pairs, (n, m), of locations are given. F_{fgt}^P and F_{fgt}^E represent the flows of respectively patients and employees. These flows are aggregated to be symmetric, meaning the flow from f to g is equal to the flow from g to f for a given triage level t. Finally, I_t^{PE} considers the prioritization between the different triage levels. By adjusting this parameter, for a triage level t, the flows of these patients and staff can be prioritized in a higher extent in the function allocation process.

Table 5.3: Parameters

Parameter	**Description**
α	Weighting parameter utilized to either give preference to patients or employees
D_{nm}	Distance between location n and location m
F_{fgt}^P	Flow of patients with triage level t between function f and function g
F_{fgt}^E	Flow of employees between function f and function g on behalf of a patient with triage level t
I_t^{PE}	Importance value for patients with triage level t, and staff providing service to patients with triage level t

5.2.4 Variables

The variables of the model are shown in Table 5.4. All variables are binary variables

Table 5.4: Variables

Variable	**Description**
x_{fnk}	= 1 if function f is centered at location n with configuration k
y_{fn}	= 1 if function f covers location n
z_{fngm}	= 1 if function f is centered at location n, function g is centered at location m, and there exist i flow between function f and function g.

that take the value 1 when true. The variables are highly intertwined and dependent on each other. The variable x_{fnk} describes the center placement n of function f with configuration k. The center-location is utilized in combination with the distance matrix D_{nm} to calculate the distance between function f and g. y_{fn} keeps track of which locations n function f covers. z_{fngm} is a helping variable used to linerize the objective function and connect two specific functions located at two particular locations together.

5.3 Objective Function

$$\min\ Z = \sum_{(f,g)\in\mathcal{F}^F} \sum_{n\in\mathcal{N}_f} \sum_{m\in\mathcal{N}_g\setminus\mathcal{N}^I_{fn}} D_{nm} G^{PE}_{fg} z_{fngm} \tag{5.1}$$

The objective function presented in (5.1) minimizes the weighted importance of distance traveled by patients and staff, by assigning functions f to locations represented by n and m. The parameter G^{PE}_{fg} is the flow of patients and staff multiplied by several prioritization parameters. G^{PE}_{fg} is derived in the equations (5.2), (5.3) and (5.4). In equations (5.2) and (5.3), the flow of patients and staff are summed over all triage levels t and each triage level is weighted with parameter I^{PE}_t. Finally, equation (5.4) adds the weighted patient flow with the weighted staff flow and utilize parameter α to weight the importance of the flow of patients versus staff. Since the flow parameter G^{PE}_{fg} is multiplied with the distance D_{nm} in the objective, allocating functions with lots of flow in between them close to each other would be preferable.

$$G^P_{fg} = \sum_{t\in\mathcal{T}} F^P_{fgt} I^{PE}_t \tag{5.2}$$

$$G^{E}_{fg} = \sum_{t \in \mathcal{T}} F^{E}_{fgt} I^{PE}_{t} \tag{5.3}$$

$$G^{PE}_{fg} = \alpha G^{P}_{fg} + (1 - \alpha) G^{E}_{fg} \tag{5.4}$$

5.4 Constraints

In the following sections the constraints of the mathematical model is presented. The constraints are divided into categories based on their role in the model.

5.4.1 Assignment Constraints

$$\sum_{n \in \mathcal{N}_f} \sum_{k \in \mathcal{K}_{fn}} x_{fnk} = 1, \qquad f \in \mathcal{F}, \tag{5.5}$$

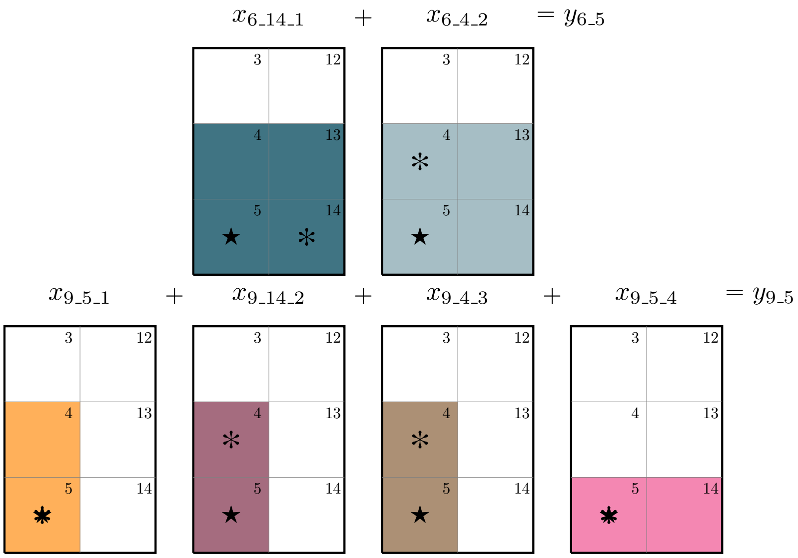
$$\sum_{f \in \mathcal{F}_n} y_{fn} \leqslant 1, \qquad n \in \mathcal{L} \tag{5.6}$$

$$\sum_{(m,k) \in \mathcal{L}^{C}_{fn}} x_{fmk} = y_{fn}, \qquad n \in \mathcal{L}, f \in \mathcal{F}_n \tag{5.7}$$

$$x_{fn1} = \sum_{m \in \mathcal{N}^{R}_{n}} x_{gm1}, \qquad f \in \mathcal{E}, n \in \mathcal{L}^{E}, g \in \mathcal{F}^{R}_{f} \tag{5.8}$$

$$\sum_{k \in \mathcal{K}_{fn}} x_{fnk} + \sum_{k \in \mathcal{K}_{gm}} x_{gmk} \leqslant 1 - z_{fngm}, \qquad (f,g) \in \mathcal{F}^{F},\ n \in \mathcal{N}_f, m \in \mathcal{N}_g \backslash \mathcal{N}^{I}_{fn} \tag{5.9}$$

Constraint (5.5) ensures that all functions are allocated, and have a feasible center-location with a feasible configuration, according to the set $\mathcal{N}_f$ and $\mathcal{K}_{fn}$. The constraints (5.6) and (5.7) are are highly connected. Firstly, the constraint (5.6) ensures that all locations are covered by at most one function, preventing functions from overlapping. Due to the binary restrictions on y_{fn}, a function either cover a location entirely or not at all. In cases where the total number of locations is greater than the required locations by the functions, some locations are not covered at all. Whereas, if these numbers are equal, all locations are covered by exactly one function. Then, Constraint (5.7) connects the covered locations with a specific center-configuration pair for every function. To elaborate this, when a function is centered with a specific configuration, this constraint makes sure the associated locations to this center-configuration pair are covered. An practical example of constraint (5.6) and (5.7) is given, considering location 5, and the functions CT1 and X-ray1, with function-numbers 6 and 9. The example is illustrated in Figure 5.3. In this figure, location 5 is marked with ★, while the center-location of the functions is marked with ✻. The area in this figure is a cut out from the northwest corner of the Kalnes ED, seen in Figure 5.1. In this example, location 5 is covered if the CT is centered at location 14 with configuration 1, or has its center at location 4 with configuration 2. For the x-ray, location 5 is covered if this function has its center at location 5 with configuration 1, location 14 with configuration 2, centered at 4 with configuration 3, or center at location 5 with configuration 4.



$$y_{6\_5} + y_{9\_5} \leqslant 1$$

Figure 5.3: Example of functions with center-configuration pairs covering location 5. Center-location is indicated with ✻ for every scenario.

These constraints only allow at most one of these center-configuration pairs to cover location 5. Since these two constraints are formulated for all locations $\mathcal{L}$, overlapping is prevented.

Constraint (5.8) makes sure a receptions is located close to its associated entrance. Lastly, constraint (5.9) ensures the variable z_{fngm} is equal to 1 when function f is placed at location n and function g is placed at location m. In all other cases, z_{fngm} is equal to 0.

5.4.2 Valid inequalities

$$\sum_{n \in \mathcal{N}_f} \sum_{m \in \mathcal{N}_g \backslash \mathcal{N}^I_{fn}} z_{fngm} = 1, \qquad (f,g) \in \mathcal{F}^F \tag{5.10}$$

$$\sum_{k \in \mathcal{K}_{fn}} x_{fnk} - \sum_{m \in \mathcal{N}_g \backslash \mathcal{N}^I_{fn}} z_{fngm} = 0, \qquad (f,g) \in \mathcal{F}^F,\ n \in \mathcal{N}_f \tag{5.11}$$

Valid inequalities are included in the model to strengthen the linearization, and thereby, reduce the complexity. Since the functions are placed at exactly one center-location each, there exists only one z_{fngm} when all possible center-locations for function f and g are summed over, as presented in (5.10). Constraint (5.11) utilizes the fact that there only exists a relation between two functions (f, g) at location n if function f is centered at n.

5.4.3 Variable definitions

$$x_{fnk} \in \{0,1\}, \qquad f \in \mathcal{F},\ n \in \mathcal{N}_f, k \in \mathcal{K}_{fn}, \tag{5.12}$$

$$y_{fn} \in \{0,1\}, \qquad f \in \mathcal{F},\ n \in \mathcal{M}_f \tag{5.13}$$

$$z_{fngm} \in \{0,1\}, \qquad (f,g) \in \mathcal{F}^F,\ n \in \mathcal{N}_f,\ m \in \mathcal{N}_g \backslash \mathcal{N}^I_{fn} \tag{5.14}$$

Constraints (5.12)-(5.14) are binary constraints. In an effort to minimize the number of variables, x_{fnk} is only created for feasible locations n, and configurations k for a function f. The same goes for z_{fngm}, which is only created between to feasible locations (n, m) for two functions (f, g). Since the set $\mathcal{F}^F$ only includes pairs of (f, g) where $f < g$, there is only one variable z_{fngm} connecting the placement of two functions at two separate locations together. y_{fn} is equal to 1 when the function f covers location at n, keeping track of which locations are covered and not.

5.5 Revised Model

There is a potential to make the formulation of the mathematical model more efficient. In this revised model, the variables keeping control of which locations a function cover, y_{fn}, are excluded. Still, the model remains mainly the same. However, the set $\mathcal{M}_f$ is redundant, since this set is only used in the creation of the y_{fn} variables. In addition, two constraints are combined into one. The entire revised model can be found in Appendix A.

5.5.1 Constraints

In the revised model Constraint (5.6) and (5.7) of original model are combined to one new constraint, namely (5.15). The new constraint replaces the constraints presented in the mathematical model.

Assignment Constraints

$$\sum_{f\in\mathcal{F}_n}\ \sum_{(m,k)\in\mathcal{L}^C_{fn}} x_{fmk} \leqslant 1, \qquad\qquad n \in \mathcal{L} \qquad\qquad (5.15)$$

Constraint (5.15) is an important constraint with several different functionalities, handling different aspects of the layout problem. Firstly, the constraint ensures that all locations are covered by at most one function, preventing functions from overlapping. Due to the binary restrictions on x_{fnk}, a function either covers a location entirely or not at all. The locations covered are connected to a specific function with a given pair of center-location and configuration. To elaborate this, when a function is centered with a specific configuration, this constraint makes sure the associated locations to this center-configuration pair are covered. An example of constraint (5.15) is given, the same as utilized in Section 5.4, considering location 5, and the functions CT1 and X-ray1, with function-numbers 6 and 9. The example is illustrated in Figure 5.4. In this example, location 5 is covered if the CT is centered at location 14 with configuration 1, or has its center at location 4 with configuration 2. For the X-ray, location 5 is covered if this function has its center at location 5 with configuration 1, location 14 with configuration 2, centered at 4 with configuration 3, or center at location 5 with configuration 4. The constraint only allows at most one of these center-configuration pairs to cover location 5. Since this constraint is formulated for all locations $\mathcal{L}$, the constraint prevents overlapping.

$$x_{6\_14\_1} + x_{6\_4\_2} + x_{9\_5\_1} + x_{9\_14\_2} + x_{9\_4\_3} + x_{9\_5\_4} \leqslant 1$$

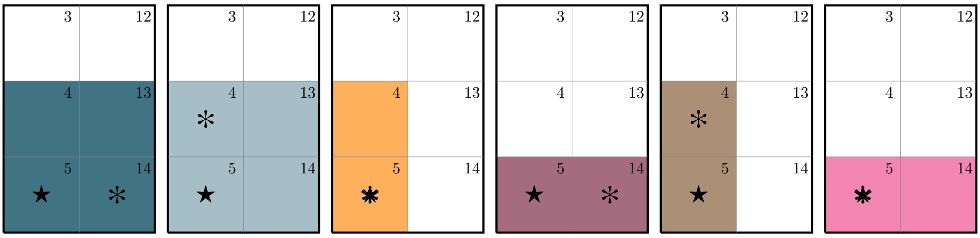


Figure 5.4: Example of functions with center-configuration pairs covering location 5. Center-location is indicated with ✻ for every scenario.

Chapter 6

Simulation Model

A data-driven Discrete Event Simulation (DES) model of the Kalnes ED is built to produce accurate flows of patients and staff, and to evaluate the layouts produced by the optimization model. By including the simulation model, the stochastic and dynamic behavior of the real-life ED, accounting for high levels of uncertainty, is considered in the framework to produce better layouts.

The simulation model used in this thesis builds upon the model developed in the preceding specialization project (Berdal and Nydal, 2019). The model is, however, extensively further developed to work in the solution framework of this thesis.

The focus of this chapter is to give an overview of how the simulation model works. The model tries to capture the real-world, which in turn makes the model complex. Key elements of the model will be described, and where found natural, additional information about the model can be found in Appendix C. Section 6.1 describes the processes as they are modeled in the simulation model, and some hints about the model implementation are also indicated where found natural. In Section 6.2 key aspects of the simulation model development and validation is presented.

6.1 System Description

To create the simulation model, a clear understanding of how the Kalnes ED works is essential. To acquire this knowledge, several interviews, visits, and conversations with stakeholders and experts were conducted. Sykehusbygg gave an overall overview of a typical ED with its functionality and staff. As the process progressed, more details were required about the specifics within the ED at Kalnes. In this context, the Kalnes ED was visited twice. Table 6.1 give an overview of some key data for the Kalnes ED.

Historical data serve as input and validation basis to the model. However, the avail-

Table 6.1: Key data for the Kalnes ED

Specification	**Data**
Arrivals, daily average	115
Area	1 200 sqm
Rooms	*97*
Care rooms	*21*
Mobile Beds	*20*
Staff	
Phys. Execs	*8-10*
LIS	*6-10*
Nurses	*8-15*
Other	*4*
Imaging resources	6
CT	*2*
CT Angiography	*1*
X-ray	*2*
Ultrasound	*1*

able data material is scarce. Due to this fact, several time estimations on different activities are made in cooperation with relevant stakeholders. The accuracy of these estimations is hard to validate without conducting time studies at the ED. Time studies were never conducted in this thesis. The lack of data was one of the main issues in the development of this model.

A conceptual model of the ED was developed in the form of several flowcharts. Figure 6.1 show the typical clinical pathways through an ED for a patient, with all processes marked as squares. Depending on the patient's condition, decisions are made, and different activities start. Diamond rectangles indicate where decisions are made. The staff at the ED makes these decisions. The numbers within each square and diamond rectangles indicate the process number within the simulation model. A complete list of all events can be found in Appendix C.1. The pathways are described as close to the real-world behavior of the ED as possible. However, an ED is complex to model, and therefore, simplifications and assumptions are inevitable. It is essential that these assumptions do not compromise the results in any case. Consequently, one of the main discussion topics with stakeholders was which assumptions could be deemed valid. In this section, the main focus is to explain how the simulation model works. More information regarding simulation theory and model assumptions can be found in Appendix C.1.

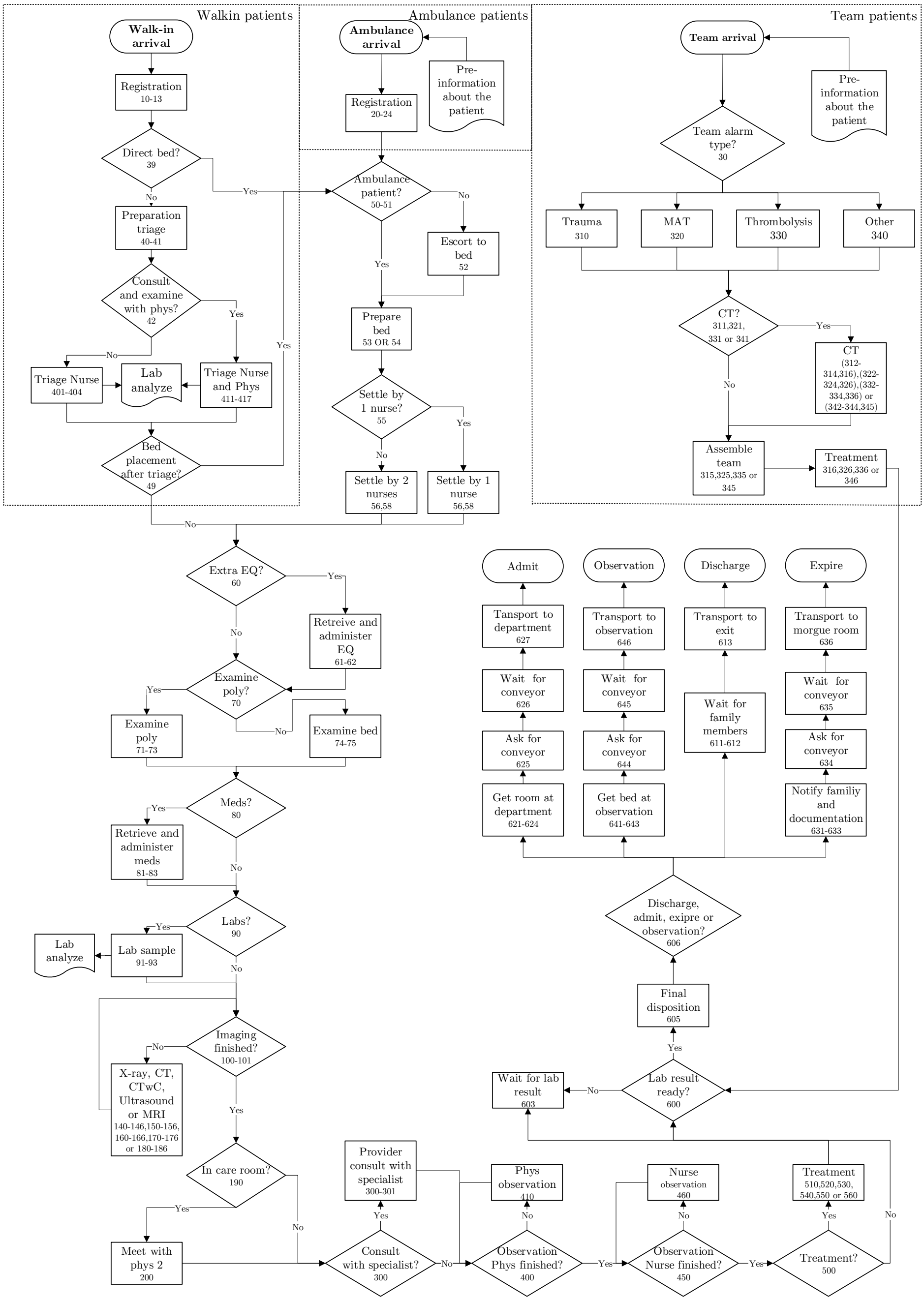


Figure 6.1: Flowchart presenting the clinical pathways of the patients at the Kalnes ED. Numbers indicated within the boxes correlates to the ID's on the simulation model processes found in Appendix C.1.

In the following simulation model description, the flow through the ED is seen from the perspective of a patient. However, the flow of other entities, such as staff and lab samples, is described where natural. Depending on the medical problem of the patient, specific staff groups are required to conduct processes and make decisions on behalf of the patient. The decisions lead to different activities, and thereby different paths for each patient.

The patient process begins when a patient enters the ED. There are three ways to enter the ED, the walk-in entrance, the ambulance entrance, and the team entrance. In the following sections, the process for the walk-in patients, the ambulance patients, and finally, the team patients is described. Each patient group can visit several locations during their stay at the ED. In Section 6.1.4, a thorough description of the possible patient locations are given and how the location is affected by decisions. Lastly, the possible locations for the staff are described in section 6.1.5.

6.1.1 Walk-in patients

With the purpose of giving a better overview of the clinical pathways of walk-patients in the simulation model, the process is divided into three phases. These phases are pre-triage, pre-physician, and closing procedure. Pre-triage is the period from the arrival to the triage, pre-physician is the phase between the triage and the initial meet with a physician, while the closing procedure is the time period after initial meet with a physician.

Pre-triage processes

Most patients in the model come through the walk-in entrance. Once they arrive at the ED, every walk-in patient has to register at the check-in area. Hereafter, the patients are directed to the waiting room area until a triage room is ready for them. In cases of high acuity, receptionists at the check-in area, send patients directly to a care room. Walk-in patients have no triage before arriving at the ED. Triage nurses primarily conduct the triage procedure. However, if the situation is urgent, a physician is called in to help. The triage is the first exam of the patients, and relevant samples are taken and sent to the lab for analyzing. See Section 2.1 for more information about triage.

Following this, the patient is sent back to the waiting room area. The triage nurses then complete the post triage and lab documentation. The triage is now set, and the care priority is established. Even though less acute patients arrive through the walk-in entrance, all triage levels can arrive here. If the patient's condition is urgent, the patient is sent to a care room, while all the others are directed to a waiting room. The probability of being directed to a care room increases with a more severe triage color. In other words, there is a higher probability that a patient with a red triage color is sent to a care room than a patient with an orange triage color.

Pre-physician processes

If a patient is directed to a care room before or after triage, a nurse prepares the bed and escorts the patient to the assigned room. Further, the patient can be settled in the room by either one or two nurses, dependent on the medical condition of the patient. Independent of the patient location, extra equipment, like food or medical equipment, is retrieved and administered. After triage or bed placement, a physician makes an examination of the patient at the outpatient clinic or a care room. Which physician conducting this assessment is dependent on what kind of disease the patient is suffering. If the examination is conducted by a LIS1 or LIS physician, a physician executive might be contacted for consultation and advice.

Closing procedures

If the physician deems that no further examination is needed, a final disposition is made. On the other hand, if found necessary in the examination, a nurse can retrieve and give some medication to the patients, more lab tests can be ordered, or the patient can be sent to imaging. A patient can conduct different types of imaging during the stay at the ED. When imaging results are ready, the physician might need to examine the patient one more time. In addition, a specialist is regularly contacted to consult on the matter, and this introduces a further delay. To keep an overview of the patient's health, and based on the acuity, a nurse and physician will look after the patient up to a few times. How many times a patient needs to be looked after, depends on the severity of the patient, and thereby the triage color. Between these tasks, the majority of the walk-in patient waits in the main waiting room. However, patients in the waiting room area with some special needs are allowed to use the waiting room with extra comfortable chairs.

If necessary, simple treatment is conducted at the outpatient clinic or care room. The type of treatment and the composition of staff can be different for the various patient types. When the processes at the ED is completed, the result of the lab sample needs to be ready in order to continue the patient process. Because of the limited capacity for analyzing at the lab, lab samples are queued waiting to be analyzed. The patient can be delayed in the ED due to these lab samples. When the lab sample is ready and based on the patient's condition, a physician admits the further process. The usual alternatives are to send the patient to an observation ward, another department, or home. In the worst case, the physician needs to inform the family and dependents of the passing of the patient.

When a patient is to be admitted to a ward or another department, a nurse asks the receiving department if they have the capacity to accept the patient. If there is an available spot, the ED receives an answer, and the patient can be transferred. At this point, a conveyor from outside the ED is ordered by a nurse. Before transfer, the nurse has to finalize and prepare the patient for transfer. Once this process is finished, the patient is transported to a specific department or ward.

6.1.2 Ambulance patients

The process for a patient arriving with an ambulance is mostly similar to the one of a walk-in patient. The main differences are in regards to triage. When arriving with an ambulance, the patient already has a triage, and thereby a priority upon arrival to the ED. This triage is done in the ambulance by the ambulance personnel. Since the ambulance service and the Kalnes ED both utilize the same triage system, this triage is usable in the ED. Before arriving at the ED, ambulance personnel notifies the ED with essential information about the patient. In cases of high acuity, different pre-arrival tasks are completed to speed up patient treatment. Patients arriving with ambulance are transported into the ED with gurneys by the ambulance personnel. A health care secretary gives the ambulance personnel a room number, or in cases with overcrowding, a bed number. Following this, the ambulance personnel transfers the patient to the assigned location where a nurse at the ED takes over the responsibility, and the ambulance personnel is relieved of theirs. After bed placement, the patient follows the same clinical pathways as described for a walk-in patient.

6.1.3 Team patients

The last group entering the ED is team patients. These cases are of high acuity, and time is at the essence. Once the ED is notified about team arrivals, a team is assembled based on the patient's injuries. In this model, there are unique teams for trauma, medical acuity (MAT), thrombolysis, and all other emergency alarms. The patient is transported directly to the CT if imaging is needed. If not, the patient is transported to one of the two trauma bays in the ED. Here, the team treats the patient and later decides whether to admit, discharge, or send the patient to observation.

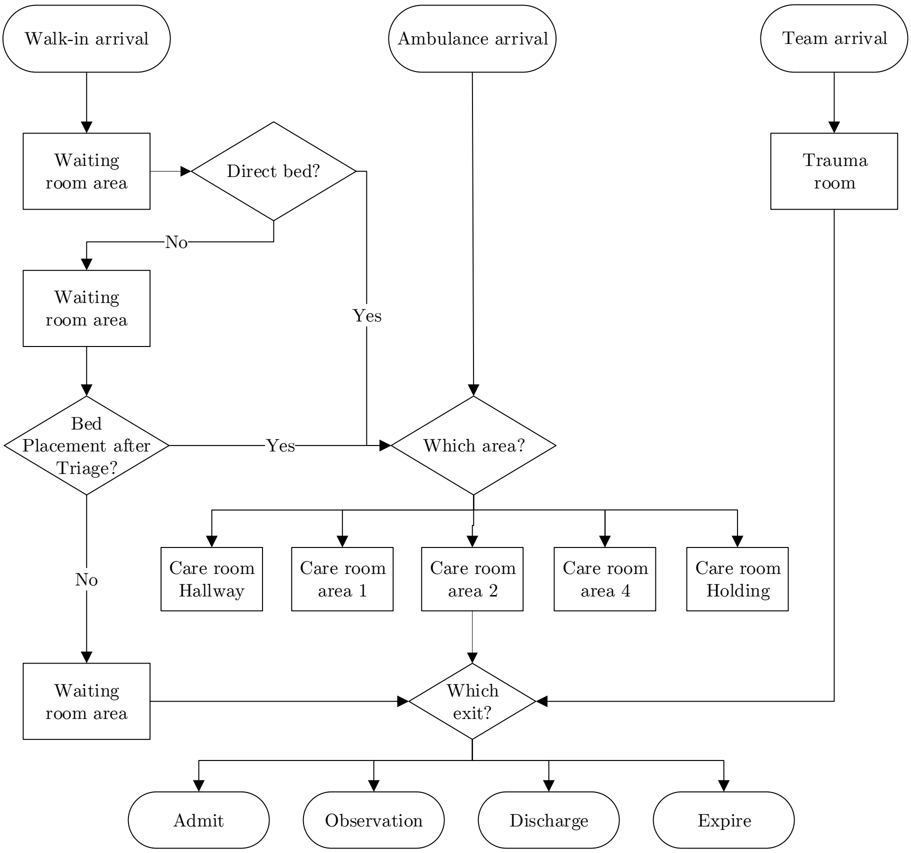


Figure 6.2: Flowchart displaying patient location for the various flows

6.1.4 Patient location

The patient location is in addition to the decisions during the stay, also dependent on the arrival at the ED. Figure 6.2 shows where the patient stays in between the different activities, dependent on the kind of arrival. The walk-in patients stay in the waiting room until the patient optionally is sent to a care room. A patient can be sent to a care room before or after triage. A more urgent triage color increases the probability of being directed to a care room. However, the ambulance patients are, as mentioned, sent to a care room right after arrival. Which care room area the patients are transferred to, depends on room availability and the patient's acuity. In contrast, the trauma patients stay at one of the trauma rooms, and therefore, do not interact directly with the other patients.

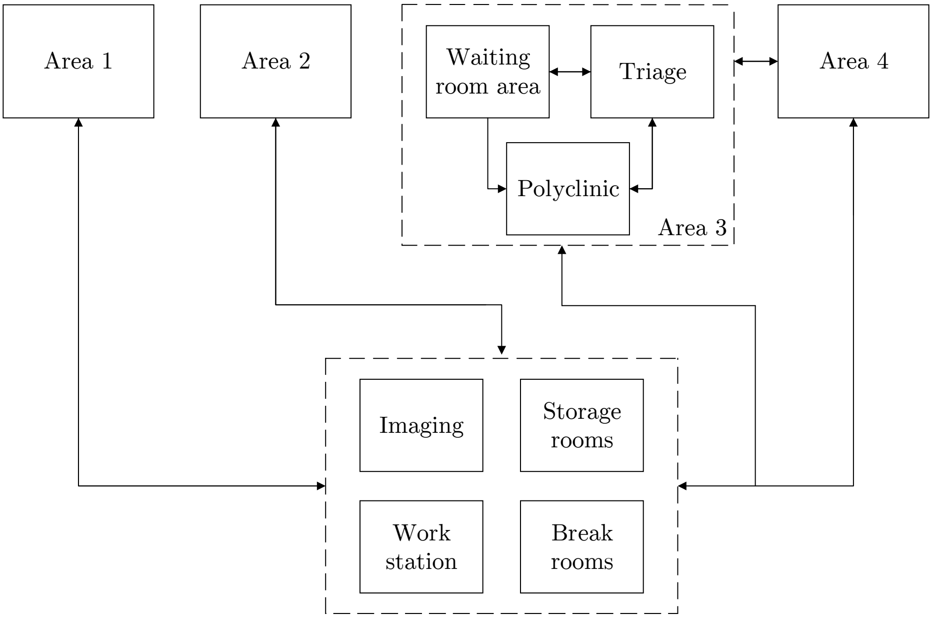


Figure 6.3: Flowchart displaying the possible flows of staff

6.1.5 Staff location

The staff flows in between various functions are based on the demanded service by the patients. The nurses and medical physicians are assigned to and have the responsibility for one of four areas. Figure 6.3 presents how the nurses and medical physicians are allowed to move in the model based on a given responsibility area. An example of this is the staff with area 2 as their responsibility area. The staff can move within area 2, in addition to back and forth to imaging, storage rooms, work stations, and break rooms. In contrast, surgeons, conveyors, and neurologists have no area assignment and therefore have the entire ED as their responsibility. Following, these staff groups move between all functions to provide service to the patients. A special case exists in co-juncture with team patients, where nurses from all areas may be given responsibilities within the treatment teams.

6.2 Model Development

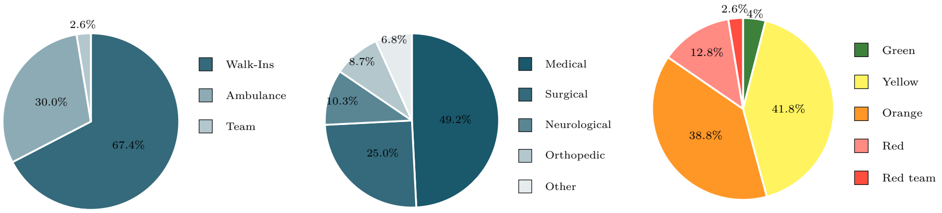
This section provides insight into the choices of how the model is developed and validated. In addition, the evaluation criteria for the simulation model are discussed.

6.2.1 Key Data

The simulation model heavily depends on the input data given to the model. An overview of the time estimates is given in Appendix C.6. Further, a complete overview of the staff working schedules can be found in Appendix C.4.

6.2.2 Arrivals

The arrival of patients is modeled as a non-stationary Poisson process that varies based on the hour of the day. It is commonly accepted that the arrival process to an ED can be modeled as a Poisson process because the arrivals typically come from the independent medical incidents of many different people, each of whom uses the ED infrequently (Whitt and Zhang, 2017). Other distributions are used for other processes within the ED. Statistical tools are utilized to find fitting distributions where data is available. In cases are stakeholders estimated time consumption, triangular distributions are utilized. Figure 6.4 shows the distributions of arrivals to the ED, separated on the entrance, medical problem, and triage level.



(a) Arrival at entrances **(b)** Medical problem **(c)** Triage color

Figure 6.4: Arrivals to the ED, in different entrances, with different medical complications and triage levels

6.2.3 System Components

Entities in a simulation model is elements flowing and queuing in the system. In the simulation model of this thesis, *patients*, *staff* and *lab samples* are modeled as entities.

In total, there are approximately 180 events and 150 states, rendering the simulation model a complex system. Typical events are examination and treatment of patients. Additionally, documentation, escorting patients, and conducting different kinds of imaging are some other examples. Due to the high number of events, the events are not presented further here. However, a detailed event list from the simulation model is given in Appendix C.1. The different state variables keep track of, among other things, the number of patients of different triage levels in the queues for different activities, the queued tasks for the different staff types, as well as, whether resources in the ED are busy or idle.

6.2.4 Simulation Time

With the purpose of reducing bias, sufficient simulation time, and the number of replications needs to be determined. There is a trade-off between doing only a few replications of a long simulation compared to multiple replications of a shorter simulation. The number of patients at the ED is close to zero at several nights during a week. As a consequence, the output for two days of the simulation model with a few days apart is approximately independent given random numbers. Therefore, a relatively short simulation length, four weeks, is chosen. In contrast, 20 replications are simulated in order to get a more substantial degree of independent random numbers across the replications. Adequate warm-up time is established. For this model, the warm-up time is chosen to be one week since the arrival rate varies among different days during the week. The variance between two different weeks is negligible.

6.2.5 Evaluation Criteria

The focus of this thesis is to improve the layout of the Kalnes ED by reducing overall walking distances for both patients and staff. Based on the problem at hand, relevant Key Performance Indicators (KPIs) are identified in order to capture the characteristics o the ED. A description of these KPIs are found in Table 6.2. Today, the ED is measured and evaluated on KPIs related to waiting times for the patients. These metrics are LOS, TTT, RTT, and DTDT. Thus, these KPIs are selected as an evaluation criterion of the simulation model. In the context of overcrowding, the selected KPIs are also the most reported ones in the literature. In addition to the time-related KPIs, it is of high interest to investigate the actual walking distances of both patients and staff in the model. The impact of walking distances on LOS is highly dependent on the walking speed of the patient. Previous studies show that a comfortable walking speed for healthy adults is between 1.26 and 1.46 meters per second (m/s) (Bohannon, 1997). However, in-hospital walking speeds for older adults can be as low as 0.43 m/s (Graham et al., 2010). To the author's knowledge, there are no published studies on walking speed of patients in an ED, especially with crutches or other walking aids. When escorting patients, the staff has the same speed as the patients, and when traveling alone, the speed is higher. An assumption in the simulation model is that patients and staff travel at 1 m/s.

Table 6.2: Description of the different KPIs the ED is evaluated upon.

Name	Abbreviation	Description
Length of Stay	LOS	Total time a patient spends at the ED
Time To Triage	TTT	Time spent from the arrival of a patient until the triage process starts
Door To Doctor Time	DTDT	Time spent from the arrival of a patient until the first meet with a physician
Ready To Transfer	RTT	The time from a patient is ready to transfer to another department until the patient is actually transferred

6.2.6 Validation

The conceptual model is validated through a thorough process with the ED stakeholders. Patient and staff flow are conceptualized and described both written and through flowcharts. This process is essential to ensure the right model behavior. With a well working conceptual model, capturing all essential activities at ED, the simulation model is able to output the desired results. However, as discussed earlier, the data input to this model is scarce. Consequently, the model, as it stands today, serves as a proof of concept. All essential processes are included, but better data is needed to ensure objective correct results.

The outputs of the simulation model are compared to real-world KPIs. With different random numbers as seeds for the simulation model, the output of two particular simulations gives different results. As a consequence, analyzing methods for taking the variation into account is required. More specifically, the real-world average is compared to the average, max, min, and 95% confidence interval from the model. Outliers can also be crucial when comparing the various scenarios. Consequently, the average of the worst 5% of the different KPIs is therefore included. Again, due to the little input data, the model is only validated with the average of the KPIs. For the validation of the model, a simulation run of 35 days with seven days of warm-up and 20 replications is chosen. Table 6.3 presents a comparison between the real world ED and the model outputs. The error column is the percentage difference between the real world and the model outputs. It can be observed that every KPI except DTDT is close to the real world. However, stakeholders note that the logging routine for the initial physician meet is very poor, and the data should not be trusted. Stakeholders also note that the model outputs in regards to DTDT seemed reasonable. A key factor in this stage of the process is the involvement of stakeholders. Several outputs from the model are discussed, and parameters are adjusted as a result of these conversations.

Table 6.3: Model validation results of the adjusted simulation model used in this thesis.

	Real ED	**Difference**	**Model**							
	Mean	Error	Mean	Median	CI95		Min	Max	Average worst 5%	CV
					Low	High				
TTT	39.8	2.7 %	40.9	19.9	40.0	41.8	4.9	561.4	219.9	1.2
TTT_orignal	*39.8*	*2.1 %*	*40.7*	*18.4*	*40.1*	*41.3*	*4.8*	*614.4*	*226.5*	*1.3*
DTDT	132.0	-55.2 %	85.1	68.9	84.3	85.8	1.7	550.5	249.9	0.6
DTDT_orignal	*132.0*	*-58.1 %*	*83.5*	*69.1*	*83.1*	*83.9*	*0.0*	*655.3*	*248.6*	*0.6*
RTT	59.8	2.0 %	61.0	59.6	60.3	61.8	14.5	1222.0	71.5	0.8
RTT_orignal	*59.8*	*1.0 %*	*60.4*	*59.6*	*60.0*	*60.8*	*14.2*	*1356.9*	*208.6*	*0.8*
LOS	268.0	0.3 %	268.9	250.9	267.4	270.3	74.6	1394.8	549.4	0.4
LOS_orignal	*268.0*	*0.1 %*	*268.3*	*249.5*	*267.5*	*269.1*	*55.8*	*1538.4*	*516.8*	*0.4*

Table 6.3 and the stakeholder's statements indicate that the model, marked with _original, built in this report represents the real ED at Kalnes in a reasonably accurate manner.

6.2.7 Further developments

As mentioned at the start of this chapter, the simulation model used in this thesis builds upon the model developed in the preceding specialization project. The model is, however, extensively further developed to work in the solution framework of this thesis. The original simulation model is made true to scale, with placements of beds and other installations at their real location. However, in this thesis, a grid with the grid-size of a care room is utilized to discretize the problem. Due to this fact, the locations available for objects to be placed at, do not correlate exactly with the real world. The adjustments made to the locations of the key objects within the ED is, however, small. As observed in Table 6.3, the adjusted simulation model is still within a reasonable range of the real-world ED, and it is therefore concluded that the model used to evaluate new layouts also represents the real ED at Kalnes in a reasonably accurate manner.

The simulation model outputs the flows of both staff and patients between different functions within the ED. These flows are aggregated based on the triage level of the patient. For instance, if a nurse has to pick up some consumables at a depot, this flow is recorded with the triage level of the patient, the nurse is conducting the task on behalf of. Further, the simulation model is programmed to automatically change the layout based on the input from the optimization model. These developments of the simulation model enable the solution framework of this thesis to work, allowing a consistent interaction between the two models of this thesis. ,

Chapter 7

Solution Framework

An Emergency Department Layout Problem (EDLP) has several dynamic aspects to its nature. Patient arrivals change over time, and seasonal variations in diseases and damages demand a wide variety of resources. Besides, there is, to a large extent, variation in the working efficiency of the staff, treatment procedure, and the staffing level. To capture all these details of the EDLP in one model, simulation and optimization are combined to solve the problem.

Traditionally, simulation and optimization are used as independent approaches for solving complex problems. However, the rise in computational power promoted the possibility of combining these methods to simultaneously explore the details of a system by simulation and identify optimal solutions using optimization methods (Figueira and Almada-Lobo, 2014). In this chapter, the solution method of this thesis is presented. First, in Section 7.1, the simulation-optimization procedure in this thesis is given. Then, Section 7.2 describes a simplified solution method of the mathematical model.

7.1 Simulation-Optimization Framework

This section briefly describes how the mathematical model and the simulation model presented in the previous chapters are combined. To generate high-quality layouts, the simulation model and the optimization model are arranged in a loop. According to the framework of Figueira and Almada-Lobo (2014), the interactions between the simulation and optimization modules in this thesis fits within Sequential Simulation-Optimization and Analytical Model Enhancement, rendering the entire solution method a Recursive Optimization-Simulation Approach (ROSA). The simulation model outputs flow based on the solution from the optimization model, and the optimization model parameters are refined based on the simulation output. This iterative process continues until a stopping criterion is reached.

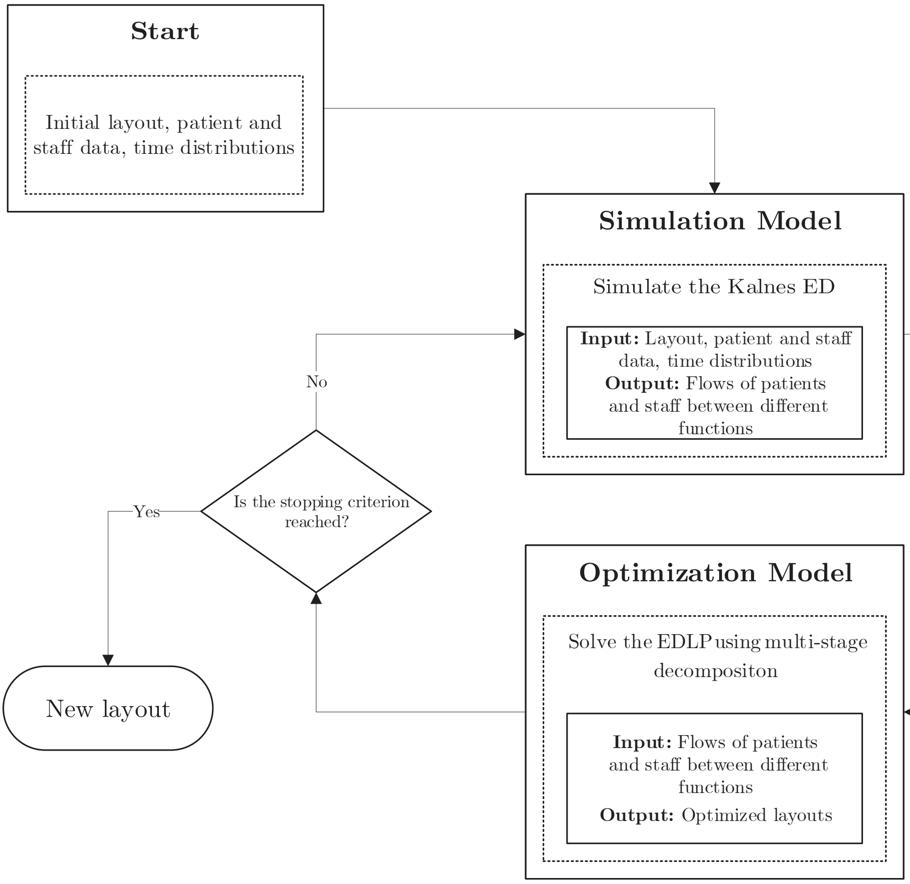


Figure 7.1: Flowchart presenting the solution framework of this thesis.

Figure 7.1 give an overview of the solution framework in this thesis.

7.1.1 Simulation

The solution approach starts with a simulation of the Kalnes ED. One of the key considerations in designing an efficient ED layout is to understand the flows of both patients and staff between each pair of units. These flows are hard to estimate, and the simulation model is an effective tool to identify these. At the start of the solution cycle, the simulation model is initiated with today's layout of the ED and historical data as input. The simulation model is run for 20 replications of one week, with one additional week as a warm-up. Based on these simulations, flows of patients and staff are generated. The flows are fed into the optimization model as parameters, more specifically, the parameters F^P_{fgt} and F^E_{fgt}. As seen by the indices, the flows are organized between pairs of functions, and the triage level of the patient.

7.1.2 Optimization

The optimization model solves the EDLP formulated as a QAP model with modifications. The model minimizes the weighted sum of the travel distances between each pair of function f and g in the ED by allocating functions to locations. The weights are the prioritization of different triage levels, or between patients or staff. Due to the high complexity of the EDLP, the problem is decomposed into stages. In every stage exact methods solve a part of the problem, however by decomposing the problem the entire solution procedure becomes a construction heuristic. A comprehensive solution procedure of the optimization model is given in Section 7.2. After solving the EDLP, the optimization model outputs a new layout which is imported and simulated into the simulation model.

The objective function is calculated from the center-locations of each function. These center-locations may not correspond to the realistic center of the functions, which can lead to instances where a lower objective value not necessarily means a better solution. However, in the simulation model, the different resources within a function are distributed at their correct location. When an activity occurs in the simulation model, the patient or staff will choose the closest available resource, thus minimizing the distance traveled. In turn, by running the two models recursively, the flow of patients and staff will mirror the choices made by both groups, producing improved layouts.

7.1.3 Stopping Criterion

The recursive process where the deterministic analytical model and the simulation model is run alternately is repeated until the solution in an iteration reaches a *stopping criterion*. The stopping criterion is two-fold. The recursive process stops if the optimization model outputs a layout which is equal to any of the previous found layouts. However, this is a stringent criterion. In many cases, the solutions converge towards a layout where there are only small, indifferent changes between two iterations. Therefore, the recursive process is also stopped if the total number of changes in the layout is less than 3 compared with the previous iteration. In Algorithm 1, a pseudocode of the simulation-optimization framework is given.

7.1.4 Evaluation

In the last run of the simulation model, the evaluation criteria are recorded for comparison, as well as the objective value of the optimization model. Even if the

Algorithm 1 Pseudo code for the Solution Framework

```
Require: a feasible layout $\sigma$//$\hat{\sigma}$ is the incumbent layout; $\bar{\sigma}$ is the last layout ; parameters ; sets
$\eta \leftarrow 0$; $\hat{\sigma} \leftarrow \sigma$; $\bar{\sigma} \leftarrow \varnothing$; objective$\leftarrow \infty$
while $\hat{\sigma} \neq \bar{\sigma}$ do
    flows, KPIs $\leftarrow$ Simulate(input= $\hat{\sigma}$) //Create new flows
    $\sigma$, objective $\leftarrow$ Optimize(input=flows, parameters, and sets) //Optimizes a new layout
    $\eta \leftarrow \eta + 1$ //Increment iteration counter
    $\bar{\sigma} \leftarrow \hat{\sigma}$ //Update the last layout
    $\hat{\sigma} \leftarrow \sigma$ //Update the incumbent layout
flows, KPIs $\leftarrow$ Simulate(input= $\hat{\sigma}$) //Evaluates the final layout
return $\hat{\sigma}$, KPIs, objective, $\eta$
```

objective value of the two solutions is the same, the performance of the layouts can differ. The optimization model only minimizes the weighted pair-wise cost of flows between functions. However, only the simulation model can capture the system effects of a new layout. System effects can be seen as improvements to the ED that come as an additional bonus due to better layouts. The layouts found in the solution framework produce layouts that have greater time savings than just the reduced walking times for the patients. With shorter walking distances for the staff, the queue accumulation for the patients may be reduced. However, reduced walking distances for staff with low utilization will not necessarily make a huge impact on the patients KPIs. To summarize, these system effects are composed, and difficult to predict in an optimization model. Consequently, the simulation model has to be run in order to capture the system effects of a new layout.

7.2 Solving the Mathematical Model

The quadratic nature of the EDLP makes solving it a challenging task. Therefore, introducing some form of decomposition seems both logical and inevitable in trying to obtain a good solution in a reasonable time. With unlimited computational power, the optimization model used to solve the problem would be equal to the mathematical model presented in Chapter 5. However, the computational time by solving the full problem is way too long.

As a consequence, the problem is divided into s stages. The basis of the multi-stage model is the revised model described in Section 5.5. In each stage, only a subset of all functions in $\mathcal{F}$ is included, narrowing the scope of the stage. Even though only a subset of functions is included in some stages, all locations are included in every stage. In a stage, some functions are to be locked. A function is locked to a location by determining a center-location and a specific configuration of the function. If a function is locked in a stage, the function will remain locked until the end of the iteration. At the start of every stage, previously locked functions, and the functions to be locked at the end of the stage are known. In addition, there are some functions included in the stage that are neither locked in previous stages nor the current stage. These remaining functions help guide the functions to be locked in the stage to more reasonable locations. Since these functions are only included to place the functions of interest, the binary constraints on their respective variables are relaxed. By doing this, these functions can be centered on fractions of several locations. A function can, for instance, have half their center in on location with configuration 2, and then the other half in another location with configuration 1.

In between stages, the sets are updated before the start of a new stage. Based on the locked functions in the previous stage, possible *center* locations are omitted in the input sets for the next stage, restricting the problem by creating fewer variables.

In the last stage, the model becomes the same as the one described in Chapter 5, with the exception of some of the input sets. A good proportion of the functions are already locked, and the last ones are set to be locked in the last stage, rendering all variables binary again.

The objective is to optimize the weighted walking distance of patients and staff in each stage. By optimizing and locking the function placement of a subset of $\mathcal{F}$, the functions can be given non-optimal placement compared to optimizing the whole problem in one stage. Therefore, including thoughtful functions in each stage is advantageous to minimize the negative effects of splitting the model into s stages. Some specific functions are required for a satisfactory placement of other functions. For example, locating the receptions without optimizing the entrances in this or an earlier stage, does not make sense. A thorough study of the different locking strategies is given in Section 9.2.

In Section 7.2.1, the notation of the multi-stage model is presented. Since the objective function in each stage is equal to the objective presented in the generalized model, the objective is not presented. Nevertheless, only the objective value in the last stage model is relevant to evaluate the layout, since all functions are placed in that stage. Finally, the constraints are given in Section 7.2.2.

7.2.1 Notation

In this section, the notation of the multi-stage model is presented. The notation is mainly equal to the revised model. Therefore only the differences are described in this section.

Figure 7.2 gives an overview of the interaction between sets, variables, and parameters in the multi-stage model. For each stage, three sets determine the model behavior. The set $\mathcal{F}_s^L$ includes the functions that are going to be locked to their location after the stage. Their associated x_{sfnk} variables retain their binary constraints from the revised model. In addition, the set $\mathcal{F}_s^{EL}$ includes all functions locked to a specific location in an earlier stage. The locking of these functions works through using the parameter $\hat{x}_{(s-1)fnk}$, including all information about the center-location and configuration for a given function. Lastly, the functions which are not in $\mathcal{F}_s^L$ or $\mathcal{F}_s^{EL}$ but in $\mathcal{F}_s^S$, are set to be continuous.

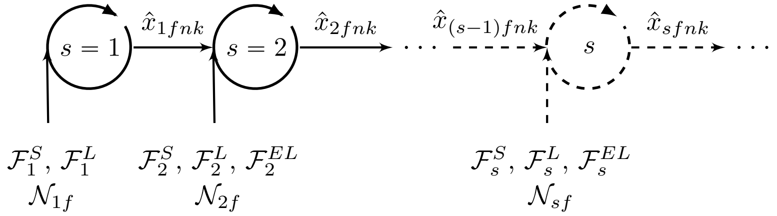


Figure 7.2: Overview of sets and variables in the multi-stage model

In stage s, the mentioned sets in the paragraph above determine which variables to relax. After solving the model, the output $\hat{x}_{sfnk}$ serves as input for locking functions in the next stage. The locations that a locked function f covers, controlled by $\hat{x}_{sfnk}$, and the locations in the given configuration, is omitted from the sets $\mathcal{N}_{sf}$ for all functions.

This section is divided into indices, parameters, and sets. The presentation of the variables is skipped since the same variables are used in the general model. However, there is a unique set of variables in each stage, and there are some changes from binary to continuous variables. These variable changes are described further in Section 7.2.2

Indices

The additional indices of the multi-stage model are shown in Table 7.1.

Table 7.1: Additional indices to the mathematical model

Indices	Description
s	Stage

The indices s is introduced to separate the different stages.

Parameters

The additional parameters of the multi-stage model are shown in Table 7.2. The parameter $\hat{x}_{(s-1)fnk}$ is the last stage solution $s-1$, representing if a function f had center location n and configuration k. These parameters are only created for the functions f locked in the previous stage.

Table 7.2: Additonal parameters to the mathematical model

Parameters	Description
$\hat{x}_{(s-1)fnk}$	The previous stage solution of the center-location variable x

Sets

The additional sets of the multi-stage model are shown in Table 7.3.

Table 7.3: Additional sets to the mathematical model

Set	Description	
$\mathcal{S}$	Set of stages	
$\mathcal{F}_s^S$	Set of functions included in stage s	$\mathcal{F}_s^S \subset \mathcal{F}$
$\mathcal{F}_s^L$	Set of functions to be locked at the end of stage s	$\mathcal{F}_s^L \subset \mathcal{F}_s^S$
$\mathcal{F}_s^{EL}$	Set of functions locked in an earlier stage	$\mathcal{F}_s^{EL} \subset \mathcal{F}_s^S$
$\mathcal{N}_{sf}$	Set of feasible center locations for function $f \in \mathcal{F}_s^S$	$\mathcal{N}_{sf} \subset \mathcal{L}$

The set $\mathcal{S}$ is new, representing the different stages, indexed by s. $\mathcal{F}_s^S$ is the set of functions included in the stage. $\mathcal{F}_s^L$ contains the different functions to lock at the end of each stage. Except for the first stage, all other stages take advantage of the functions locked in an earlier stage, $\mathcal{F}_s^{EL}$, to reduce the solution space. As mentioned earlier, the binary restrictions on the variables connected to the functions of the variables in $\mathcal{F}_s^S \backslash (\mathcal{F}_s^{EL} \cup \mathcal{F}_s^L)$ are relaxed. The set $\mathcal{N}_{sf}$ is updated before the start of a new stage with remaining available locations based on the solutions of the previous stages.

7.2.2 Constraints

The majority of the constraints of the multi-stage solution approach are generally the same as in the revised model. However, the indices s is added to all variables, making a unique set of variables, and following, a unique set of constraints in all stages.

Assignment Constraints

$$\sum_{(m,k)\in\mathcal{L}^{C}_{snf}} x_{sfmk} \leqslant 1, \qquad s \in \mathcal{S}, n \in \mathcal{L}, f \in (\mathcal{F}_{sn} \cap F^{L}_{s}) \tag{7.1}$$

The only constraint added, is constraint (7.1). In this constraint, a location n is covered by a binary function f if the combination of center-location n and configuration k covering location n. This is not a strengthening of the formulation in principle, but is proved to reduce the computational time in Section 8.7.

Variable definitions

$$x_{sfnk} \in \{0,1\}, \qquad s \in \mathcal{S}, f \in (\mathcal{F}^{EL}_{s} \cup \mathcal{F}^{L}_{s}), n \in \mathcal{N}_{sf}, k \in \mathcal{K}_{sfn} \tag{7.2}$$

$$0 \leqslant x_{sfnk} \leqslant 1, \qquad s \in \mathcal{S}, f \in \mathcal{F}^{S}_{s}\backslash(\mathcal{F}^{EL}_{s} \cup \mathcal{F}^{L}_{s}), n \in \mathcal{N}_{sf}, k \in \mathcal{K}_{sfn} \tag{7.3}$$

$$0 \leqslant z_{sfngm} \leqslant 1, \qquad s \in \mathcal{S}, (f,g) \in (\mathcal{F}^{F} \cap \mathcal{F}^{S}_{s}), n \in \mathcal{N}_{sf}, m \in \mathcal{N}_{sg}\backslash\mathcal{N}^{I}_{sfn} \tag{7.4}$$

To reduce the running time of the model, several variables are relaxed from binary to continuous. For the functions to be locked at the end of a stage, x_{sfnk} remains binary. In contrast, for the functions included in $\mathcal{F}^{L}_{s}$, x_{sfnk} is relaxed to continuous variables. Finally, all z_{sfngm} variables are relaxed. However, if f and g are locked at the end of the stage, z_{sfngm} is pushed to 0 or 1.

Locking Constraints

$$\hat{x}_{(s-1)fnk} = x_{sfnk}, \qquad s \in \mathcal{S}|s > 1, f \in \mathcal{F}^{EL}_{s}, n \in \mathcal{N}_{sf}, k \in \mathcal{K}_{sfn} \tag{7.5}$$

The locking constraint makes sure the correct variables are locked in stage s based on the previous solution $s - 1$. Constraint (7.5) fixes the center variables for the functions locked in a previous stage, with the information about center-location and configuration included.

Chapter 8

Testing the Optimization Model

The optimization model is implemented in Python 3.7.4 with the FICO® Xpress Optimizer Python interface version 8.5.13 with the Xpress optimizer version 34.01.06. All instances in the technical study are solved on a computer with 8 core Intel® Core™ i7-8700 CPU (3.20GHz) and 32GB RAM. The computer runs Windows 10 Education 64-bit Operating System.

Starting this chapter, assumptions, problem-specific constraints, and distance calculation, which are required for a satisfactory implementation of the problem, are presented in Section 8.1, Section 8.2, and Section 8.3. The main part of this chapter is testing different aspects of the optimization model. The model can be adjusted in several ways during the implementation, knowing the impact of these adjustments is thereby highly relevant. In Section 8.4 and 8.5, the sensitivity of the model complexity is examined by considering a subset of the functions and locking functions. Then, additional implementations of the model, with the purpose of reducing the computational time, are tested in Section 8.6 and Section 8.7. Section 8.8 focuses on the effects by different prioritizations of the triage levels. In Section 8.9, the consequences of splitting the model into multiple stages are found. Finally, the characteristics and features of the optimization model observed in the tests are discussed in Section 8.10.

8.1 Assumptions

In this section, the assumptions for the implementation of the model are presented. Due to the fact that EDLPs are NP-hard, assumptions are crucial to make the problems solvable. All rules mentioned in the following subsections are enforced in every solution to the problem. These assumptions are carefully considered in cooperation with the stakeholders to make reasonable simplifications of the model.

(a) The locations in the model are shaped like rectangles with the size equal to the

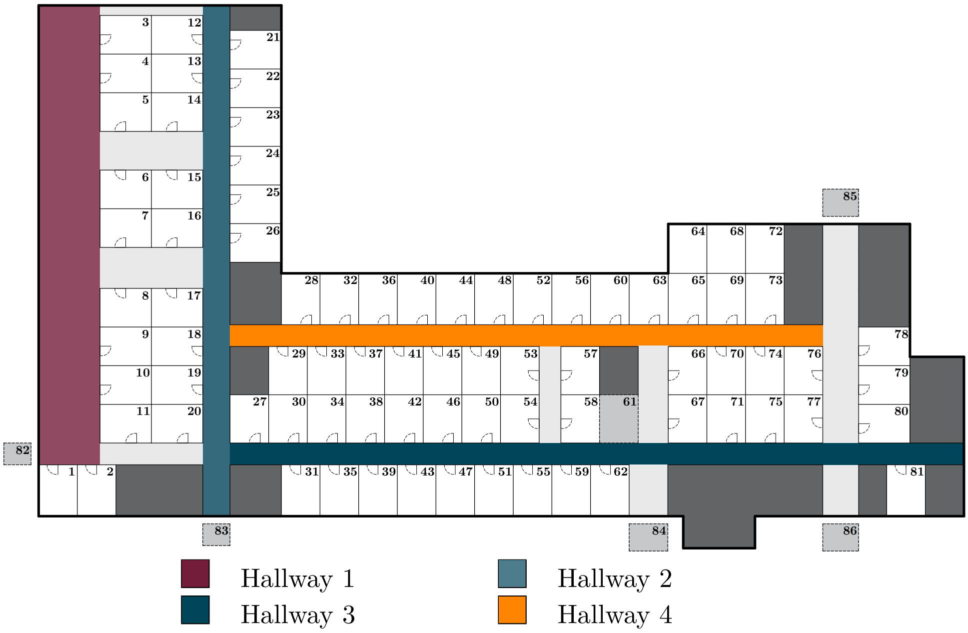


Figure 8.1: Layout highlighting the three main hallways

area of a standard-sized care room.

(b) Small-sized functions are aggregating into the size of the standard-sized location in the model. For example, a single bathroom does not take up the same area as a standard-sized care room. In total, there are 9 toilets at the Kalnes ED, which in the model representation are aggregated to 3 individual bathrooms.

(c) The area of each function is defined as an integer multiplied to the standard-sized locations.

(d) Lifts and stairs are omitted from the model, and their locations are not available for the functions in the model. This is due to the high costs of moving the lifts and stairs.

(e) The various entrances into one specific function, cannot be from more than one main hallway. For example, a 3 unit function is not allowed to have entrances into two locations from hallway 1 and one location from hallway 2. See Figure 8.1 for an overview of the four main hallways and the entrances into all the locations.

(f) The functions are divided into seven different categories based on how many units the function covers. These categories are 1, 2, 3, 4, 5, 6, and 8 units functions.

8.1.1 Configurations

Functions that cover more than one location can take on different configurations. A configuration is specified with a center-location, and a set of other locations covered. In this section, the assumptions for allocating feasible configurations for a function with a particular center-location is given. A figure representing the possible configurations for the functions covering a specific number of units is given in section B.2.

(a) All functions that cover the same amount of locations have the same possible configurations.
(b) Only 3, 5, or 8 unit functions are allowed to be located across hallways.
(c) Every configuration must fit the layout according to overall assumptions.

8.2 Implemented Constraints

Each function needs to be located based on individual requirements. For instance, some functions need to be placed at some specific locations to fulfill patient safety, while others need to be placed near an entrance. The majority of the constraints presented in Section 5.4 may not show all the problem-specific constraints taken into consideration. A large number of problem-specific constraints are developed in cooperation with stakeholders from Sykehusbygg and staff at the Kalnes ED. Most of the constraints not presented so far are based on the sets $\mathcal{N}_f$ and $\mathcal{L}^C_{fn}$. $\mathcal{N}_f$ contains the feasible center-locations, while $\mathcal{L}^C_{fn}$ connects the center-locations to the locations the function covers. The combination of these two sets determines which locations the functions can cover. The feasible cover-locations for the functions with the ability to be placed in a limited part of the ED are presented in several figures in Appendix D. All other functions can cover any location in the ED, which is not already covered by a predefined function. The feasible location constraints can be summarized in the following list.

(a) All functions need access to a hallway.
(b) Bathrooms are distributed to be easily accessible for all patients and staff from any location in the ED.
(c) Storage rooms are located in different parts of the ED to have medical equipment easily accessible from any location.
(d) 1 unit functions without flow to any other functions are distributed in different parts of the ED to avoid symmetry. These functions are bathrooms, storage rooms, and employee room.

(e) Some functions are locked based on the current layout and the importance of the function. For instance, the MRI is locked due to the current layout and the abnormally high cost of moving it. Due to practical reasons for the staff at ED Kalnes, the meeting rooms are locked to the locations in today's layout. Table B.1 show all functions, and indicate which functions are predefined and not.

(f) The washroom is positioned against the outer wall since this room needs to be accessed directly from outside.

(g) The Trauma entrance is locked at today's location due to its required closeness to the helicopter platform.

(h) The 1 unit employee room is placed close to the meeting rooms. However, the 2 unit employee room has feasible locations in another part of the ED. This distribution is decided in order to have an employee room in an acceptable distance for the staff working in different parts of the ED.

(i) The Trauma needs to be located close to the trauma entrance, with the purpose of fulfilling satisfactory patient safety.

8.3 Distance Calculation

The locations are connected through the network of hallways, as presented in Figure 8.1. The distance between two particular locations is calculated based on the shortest path between the center-locations of the functions. In this thesis, the shortest path is found automatically in the simulation software FlexSim HC. The applied technique in this software is a variant of Dijkstra's algorithm, finding the shortest path between one node to all other nodes in a graph. Here, the path network is modeled with nodes representing locations and intersections, with edges connecting the nodes with straight lines. With this layout representation, in combination with positive distances between the nodes, Dijkstra's algorithm is well suited to calculate the distances. All paths are two-directional, meaning that the distances is calculated only for location $n < m$.

8.4 Varying Size of Footprint an Number of Functions

The footprint of an ED varies between different hospitals. Changing the total footprint and the number of functions brings valuable insight into how the model handle problems of different sizes. Due to the quadratic nature of the model, the difficulty of the problem increases significantly as more functions are added. This observation is especially true when adding functions covering more than one unit and with several

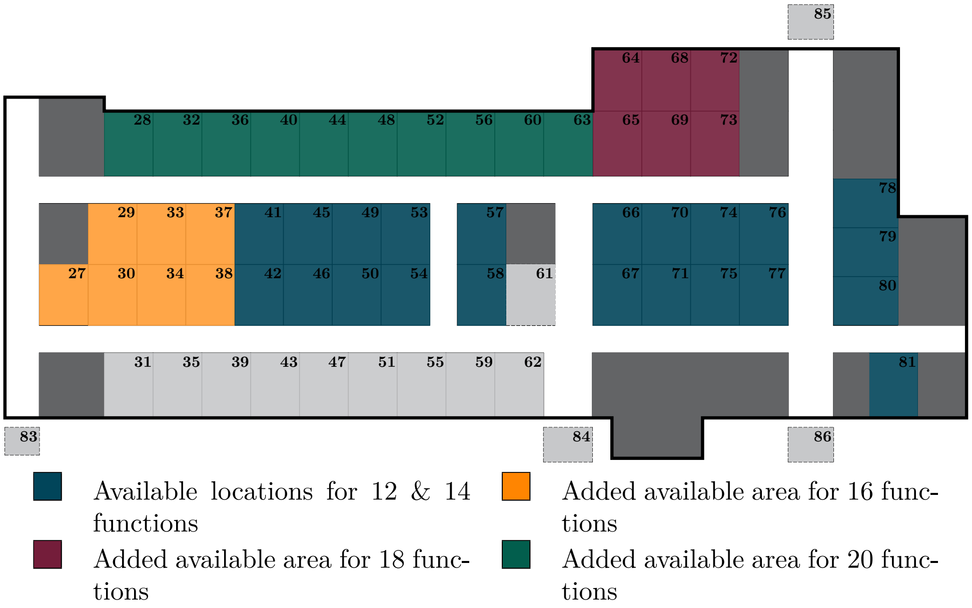


Figure 8.2: Available area for the different test instances with different number of functions.

possible configurations. The different test instances described in Table 8.1 include a variety of functions, both single and multiple location functions. The test instances with added functions include all functions of those with less.

Table 8.1: Results of test instances with varying footprint and number of functions

Instance	**Functions**	**Required number of locations**	**Available locations**	**Objective Value**	**Elapsed time [sec]**	**Rows/ Presolve**	**Columns/ Presolve**
12F22L	12	19	22	60 152.9	1	5 496 / 3 032	5 268 / 2 940
14F22L	14	22	22	85 342.6	4	9 032 / 5 568	8 654 / 5 410
16F29L	16	24	29	105 194.5	49	26 668 / 18 769	25 675 / 18 285
18F35L	18	31	35	115 445.1	1 030	48 764 / 37 345	47 333 / 36 536
20F45L	20	37	45	104 312.5	6 391	88 801 / 56 928	86 621 / 56 266

Table 8.1 shows the results from the test instances. It can be observed that the computational time increases significantly, even though the increase in functions is small. As the available footprint is changed, the optimal solution changes due to the changed number of functions and more possibilities for placing functions on different locations and with different configurations. Figure 8.2 presents the feasible locations for the functions in the various instances. A general observation is that the objective value increase as more functions are added. However, the objective value of 20 functions is lower than the test instance with both 16 and 18 functions. This result comes as a consequence of the larger available area for 20 functions, rendering a layout with a lower objective value than the one in the test with 16 and 18 functions.

However, it also allows the configurations to be positioned in a manner that causes the center-locations to a cluster. As the objective function is calculated from the defined center-location of functions, which may not correspond to the realistic center, this is not necessarily a better solution in the real-world.

8.5 Locking Functions To Locations

As observed in Section 8.4, the model complexity, as in computational time, increasing rapidly when more functions are included. When the size of the EDLP reaches a certain limit, the problem may be challenging to solve in a reasonable time. One way to make this problem solvable is by locking functions to specific locations. In the test instances described in this section, the functions are locked to a center-location with a specified configuration.

Four instances are tested based on the instance 16F29L. These four instances lock one particular function each, in fact, CT1, laboratory, reception walk-in, and waiting room main. Table 8.2 presents the results of the chosen instances. The first main finding is reduced model complexity and computational time when locking functions. The locking of the lab or waiting room has the most significant impact on the running time. These two functions have the highest flow of patients and staff among the different functions tried locked. Even though the CT covers four functions, the time reduction is more significant when locking the lab, covering only one single location.

Table 8.2: Results of test instances with locking of functions.

Instance	**Objective Value**	**Elapsed time [sec]**	**Rows/ Presolve**	**Columns/ Presolve**
16F29L	105 194.5	49	26 668 / 18 769	25 675 / 18 285
LockingCT	116 402.5	10	26 668 / 10 971	25 675 / 11 285
LockingLab	110 342.5	5	26 668 / 11 365	25 675 / 11 574
LockingReception	105 329.5	26	26 668 / 16 743	25 675 / 16 800
LockingWaitingRoom	112 863.9	6	26 668 / 10 406	25 675 / 10 590

Another main characteristic is the increased objective value when locking functions. This observation means that the functions are not locked at their optimal locations. As a consequence of locking functions to non-optimal locations, other functions are placed non-optimal as well, causing an additional increase in the objective value. The best final solution among the locking-instances is found when locking the walk-in reception. This finding has a logical explanation since the feasible locations for this function are neighboring, and the number of feasible locations is limited as well. Therefore, all non-optimal placements of the reception have a short distance to its optimal location.

8.6 Valid Inequalities

Valid inequalities are included in the mathematical model formulation to strengthen the linearization, and as a consequence, the computational time is assumed to reduce. However, the impact on computational time may be difficult to predict. Therefore, the effects concerning computational time by including valid inequalities are tested in this thesis.

In Section 8.4, several instances are analyzed concerning model complexity and computational time. The same instances are optimized in this section, but the valid inequalities are removed to observe the changes. The valid inequalities included in the model formulation is Constraint (5.10) and (5.11). When solving the EDLP without valid inequalities, the final solution remains the same. As a result, the running time is the only aspect of interest.

In Table 8.3, the results of including the valid inequalities are given. It is observable that the improvements in running time are non-existent in the two smallest instances. However, the effects in computational times seem to improve rapidly when the size of the cases increase.

Table 8.3: Results of test instances including and excluding the valid inequalities of the mathematical model.

Instance	**Elapsed time**	
	Standard formulation	Without valid inequalities
12F22L	1	1
14F22L	4	3
16F29L	49	99
18F35L	1 030	3 045
20F45L	6 391	NaN

The instances analyzed are only a smaller part of the whole ED. By taking into account the increasing difference between the instances having standard formulation and the valid inequalities excluded, it is assumable that valid inequalities may have a considerable effect concerning the entire ED.

8.7 Revised Model

In Section 5.5, a revised model excluding the y_{fn} variables are introduced. The revised model finds the same layout as the original model, rendering computational time the only aspect of interest when comparing the two models. The revised formulation includes fewer variables than the original, and the running time is expected reduced. However, the expected computational time improvements need to be verified. The revised model is tested on the same 5 instances as the original model in Section 8.4, and the results are given in Table 8.4. Additionally, the same 5 test instances are run with the extra constraint proposed in Section 7.2.2. These test instances are named ...w7.1, which is a reference to the specific constraint in Section 7.2.2.

Table 8.4: Comparing computational time of the revised model and the original formulation.

Instance	**Elapsed time** [sec]	**Rows/ Presolve**	**Columns/ Presolve**
12F22L	1	5 496 / 3 032	5 268 / 2 940
14F22L	4	9 032 / 5 568	8 654 / 5 410
16F29L	49	26 668 / 18 769	25 675 / 18 285
18F35L	1 030	48 764 / 37 345	47 333 / 36 536
20F45L	6 391	88 801 / 56 928	86 621 / 56 266
Revised12F22L	1	5 260 / 2 478	4 897 / 2 654
Revised14F22L	3	8 752 / 4 702	8 239 / 4 821
Revised16F29L	32	26 271 / 17 706	25 174 / 17 700
Revised18F35L	1 042	49 163 / 35 189	46 659 / 35 637
Revised20F45L	5 130	88 152 / 52 804	86 621 / 52 804
Revised12F22Lw7.1	1	5 314 / 2 534	4 962 / 2 714
Revised14F22Lw7.1	3	8 836 / 4 786	8 304 / 4 896
Revised16F29Lw7.1	27	26 403 / 17 832	25 304 / 17 832
Revised18F35Lw7.1	1 018	49 281 / 35 302	46 772 / 35 751
Revised20F45Lw7.1	4 730	88 263 / 52 912	86 734 / 52 916

The instances run with the revised model has fewer rows and columns, both pre- and post presolve. The computation times are much better in all the small instances for the revised model. However, some variations exist, and the improvements are almost negligible for the more complex instance Revised18F35L. Finally, when the most complex instance is considered, there is a significant improvement with the revised model. The test instances with the added constraint from Section 7.2.2 preform even better. The formulation is not strengthened by adding the constraint, so the time savings in computational time is linked to how the Xpress Solver solves the problem. To summarize, the computational times when using the revised model are better in most instances, and at worst, about the same as the original model.

8.8 Prioritization Triage

In this section, the prioritization of patients with different triage levels is considered. In the optimization model, this prioritization is controlled by the parameter I_t^{PE}. The footprint and the functions in the instance 16F29L are used to test different prioritization strategies.

In the instance 16F29L, each triage level is weighted equally. In this case, the total distances for all patients and staff are minimized. However, this does not take into account the time-sensitivity of the patients of a high triage level. In high acuity cases, only a few seconds can be the difference between life and death. By increasing the weights of high acuity patients, the resulting layouts will meet this challenge. This triage weighting strategy may come at the expense of the overall performance of the ED. However, saving lives is the overall goal of the ED, and this is something the optimization model can not incorporate. By weighting the different triage levels different, the model can find solutions where the KPIs are improved, and at the same time, the most urgent patient's safety is satisfactory.

Table 8.5: Weights given to the different triage levels in the test instances.

Instance	Staff	Triage 1	Triage 2	Triage 3	Triage 4	Triage 5	Elapsed time [sec]
16F29L	1	1	1	1	1	1	95
0T	1	0	0	0	0	0	10
1T	0	1	0	0	0	0	25
2T	0	0	1	0	0	0	34
3T	0	0	0	1	0	0	53
4T	0	0	0	0	1	0	39
5T	0	0	0	0	0	1	4
345T	0	0	0	1	5	10	46
2345T	0	0	1	4	7	10	92
12345T	0	1	3	5	7	10	65
012345T1	1	2	4	6	8	10	100
012345T2	1	2	3	4	5	10	113
012345T3	1	2	3	4	5	100	127

Ten instances with various weighting of the triage levels are optimized and presented in Table 8.5. Because of the different weighting of triage levels, the objective value is not a valid performance measure to compare the instances, and therefore not included in the table. However, the elapsed time is interesting since this metric is varying with the changing weights. Common for all instances is an increased running time if a triage level with a high number of patients is included. In contrast, when only triage level 5 is taken into account, as in instance 5T, the running time is at its smallest. This observation follows the same argumentation since there is only a small proportion of patients in this triage level.

In Table 8.6, the average walking distance for staff and patients are given, considering the various triage levels. By only prioritizing one specific triage level, the walking distance is heavily reduced for these patients and staff. However, a consequence of this strategy is increased walking distances for the other triage levels. By gradually increasing the priority for the more acute patients, all triage levels are considered, but the safety of the acute patients is given an extra focus. Compared to 16F29L, where every triage level is weighted equally, the instance 01234T3 has shorter walking distances for the high acuity patients and the staff helping these patients. Besides, the walking distances for the lower triage levels are only somewhat increased. Consequently, the safety of the acute patients is increased while, at the same time, taking less acute patients and the staff helping these patients into consideration.

Table 8.6: The average walking distances for all patients having a specific triage level and staff providing service to a patient with a particular triage level.

Instance	**Average walking distances**						**Average**
	Staff	Triage 1	Triage 2	Triage 3	Triage 4	Triage 5	
16F29L	774.2	103.6	292.7	139.3	188.3	52.1	155.2
0T	441.4	141	348.2	167	192.2	47.9	179.3
1T	772.3	103.5	297.3	151	196.6	51.1	159.9
2T	776	103.6	292.5	146.7	190.5	51.5	156.9
3T	1 088.50	139.50	333.40	125.10	177.80	51.50	165.50
4T	1 808.40	145.80	339.90	134.10	167.90	62.40	170.00
5T	2 893.00	200.10	452.50	235.50	210.90	43.00	228.40
345T	1 409.00	160.50	377.20	131.00	170.90	47.30	177.40
2345T	1 676.70	139.70	328.70	129.20	171.50	51.20	164.10
12345T	777.4	117.9	303.3	135.9	180.1	52.1	157.9
012345T1	774.2	103.6	292.7	139.3	188.3	52.1	155.2
012345T2	774.3	103.6	293	139.4	188.7	51.8	155.3
012345T3	652	113.2	300.8	146.5	181.6	47.8	158

8.9 Testing the Multi-Stage Model

The preceding sections clearly show that the computation time increases significantly when only a few functions are added. By including even more functions, the problem may be too challenging to solve in a reasonable time. Therefore, a decomposition into two stages is tested in this section, following the proposed solution method presented in Section 7.2.

In the first stage, a set of functions is to be locked, while the rest of the functions are only included to help guide the functions to be locked to their optimal location. Several different strategies to determine which functions to lock in the first stage are tested. In Table 8.7 the functions, with associated key features, included in instance 18F35L is presented. Total patient flow, total staff flow, and total flow contain the flow for a particular function to and from all the other functions in this instance. Connected functions are the number of functions with any flow to or from a specific function. Finally, patient steps are the minimum number of steps a patient may use to reach this function. Every patient enters the ED in one of the arrivals, requiring zero steps to reach these functions. In the next step, the patients walk or are transported to reception to get information about further processes. As a result, the receptions are reached in step one.

Table 8.7: Key feature values for the functions included in instance 18F35L.

Function	**Size**	**Total patient flow**	**Total staff flow**	**Total flow**	**Connected functions**	**Patient steps**
Care room area 1	**5**	409	2 007	**2 416**	**15**	**2**
Triage	2	**806**	**2 715**	**3 521**	11	3
Outpatient clinic	**3**	**860**	822	1 682	9	3
CT	**4**	30	57	87	9	3
X-ray	2	296	316	612	10	3
Ultrasound	2	84	79	163	8	3
Lab	1	0	1 739	1 739	**12**	-
Medicine room	1	0	711	711	**11**	-
WorkS. Nurses A1 & rcpt. EMS	1	208	1 601	1 809	8	**1**
Workstation Med.Phys Exec	1	0	**2 336**	**2 336**	10	-
Workstation medical LIS	1	0	1 681	1 681	5	-
Workstation nurses A3	1	0	**2 246**	2 246	9	-
Waiting room main	**3**	**2 868**	**2 552**	**5 420**	**14**	**2**
Reception walk-in	1	**1 204**	0	1 204	2	1
Walk-in arrival and main exit	1	754	0	754	3	**0**
Ambulance arrival	1	167	347	514	2	**0**
Trauma arrival	1	2	24	26	2	**0**
Observation and admit exit	1	232	123	355	8	4

Table 8.8 show every two-stage model solved for the same problem as instance 18F35L. The different locking strategies follow the different key features highlighted in Table 8.7. These strategies lock functions dependent on the size of the functions, highest flow, most connected functions, and the minimum number of steps required for a patient to reach the function. The name of the instances give hints of the locking strategy and how the instance is solved. For instance, *2S4Size* means that the instance is solved in two stages, where the functions determined in the first stage are the four largest in size. The same logic is followed in other instances. *2S3TotalFlow* means the problem is solved in two stages, where the three functions with the highest total flow are decided in the first stage. An exception of this logic is for *2SPatient1Step* and *2SPatient2Steps*. Here, the instances are still solved in two stages, but all the functions possible to reach in one or zero steps is determined in stage 1 for *2SPatient1Step*. Similarly, all functions with the possibility to reach in at most two steps are determined in stage 1 for *2SPatient2Step*.

Common for all the two-stage instances is the reduced solution time compared to

Table 8.8: Testing of different multistage models compared to the instance 18F35L.

Instance	Elapsed time [sec]	Objective value
18F35L	1 045	115 445.1
2S4Size	102 (98/4)	120 574.7
2S4PatientFlow	63 (57/6)	115 445.1
2S4StaffFlow	209 (206/3)	115 445.1
2S4TotalFlow	211 (205/6)	115 889.3
2S4ConnFunc	236 (234/2)	118 324.8
2SPatient2Steps	51 (45/6)	115 445.1
2SPatient1Step	198 (2/196)	116 543.1
2S3Size	51 (44/7)	124 610.9
2S3PatientFlow	44 (28/16)	119 415.6
2S3StaffFlow	68 (64/5)	118 243.2
2S3TotalFlow	83 (80/4)	115 889.2
2S3ConnFunc	92 (88/4)	115 889.3

solving the problem in one stage. This time reduction is even more significant when determining three functions in the first stage compared to four. However, there is no apparent connection between deciding three or four functions in the first stage for the objective value. The strategies concerning the patient flow, staff flow, and patient steps have all one optimal solution, which is equal to the solution found in the one-stage model 18F35L. By calculating the average, the strategies utilizing the total flows give the best objective value. In contrast, the worst objective values among these instances are found when determining the largest-sized functions in the first stage.

8.10 Discussion

Several aspects of the implementation of the optimization model are tested, where different model features result in different impacts on both objective value and computational time. In this chapter, only a small part of the ED is considered. The test instances show that despite the relatively small size, the problem has a high level of complexity. Increasing the size of the footprint or the number of included functions increases the complexity of the problem. Interestingly, only a small increase in the number of functions and the available area may result in an instance which is impossible to solve within a reasonable time. Therefore, a simplification of the problem is required to be able to solve it.

Locking functions to some specific locations is proven to reduce the model complexity, and thus, reduce the computational time. However, locking functions to non-optimal locations increases the objective value, and result in non-optimal locations of other functions as well. To summarize this, there is a trade-off between improved objective value and reduced computational time. A decomposition of the problem into multiple stages, locking a subset of functions in each stage, is shown to produce satisfactory results in a reasonable time.

Even though the binary restrictions on functions to be placed in a later stage is linearized, the multi-stage model finds, in several cases, the same solutions as the one-stage model. As expected, the two-stage models reduced the running-time compared to the one-stage model. The time-variations among the two-stage models are notable. An interesting observation is a reduced total computation time when three functions are determined in the first stage compared to four. The reasoning behind this is a close context with the nature of this problem. The computation time seems to increase exponentially, making the model highly sensitive to changes over a certain limit. When the first stage is more complicated than the last stage, the total running-time decreases by making the first-stage smaller, and the last stage bigger. Valid inequalities turned out to reduce the computational time significantly, making the model able to solve larger scaled problems. With valid inequalities included, additional simplifications are avoided, resulting in a better final layout.

The different locking strategies result in variations in both computation time and objective value. The main characteristic is that including functions with the largest flows in stage 1, give the highest running times, but at the same time, the lowest objective values on average. An exception to this observation is the strategies where the first-stage functions are chosen based on the patient steps feature. This strategy gives promising results, with objective values equal to or close to the optimal solution. Due to the variations in the computation time and objective value among the various strategies, thoughtful strategic choices are of high impact when dividing the model into multiple stages. In this chapter, the problem size is limited, making it possible to test multiple strategies. However, when the problem size is equal to a real-world problem, the complexity is heavily increased, making it time-consuming to test all locking strategies.

Finding a reasonable weighting strategy of the different triage levels leads to a challenging trade-off between overall system performance and the safety of acute patients. By weighting the triage levels equal, the average walking distance of staff and personal is at the shortest, which is advantageous for the overall performance. This strategy may have negative consequences for the high acute patients. Since the primary goal of an ED is to save lives, a somewhat higher prioritization of the most acute patients seems reasonable. However, the prioritization of the most acute patients needs to be contextualized with the overall performance of the system.

Chapter 9

Case Study

The aim of this thesis is to show how operational research methods can be used to help find better layouts for an ED. The case study exemplifies how the model can be used to solve a real-world Emergency Department Layout Problem (EDLP). Until now, the model is tested on significantly smaller instances significantly smaller than a real-world case. An important aspect of this case study is testing the model's ability to solve larger instances using the solution framework proposed in Chapter 7. The case study is performed on the Kalnes ED, and the modeling choices are made based on the discussions of the preceding testing of the optimization model.

In Section 9.1, further details about today's layout at the Kalnes ED is presented. Then, different strategies for solving the multi-stage model are tested in Section 9.2. The prioritization of patients and staff are considered in Section 9.3. After this, the model is prepared for solving, and three alternative layouts are developed in Section 9.4. Following this, the optimized layouts are compared with today layout when adding extra staff to get a sense of the value of the proposed new layouts. Finally, several different aspects of the final layouts and the various solution procedures are discussed in Section 9.5.

9.1 Case Description

The case of this thesis is the ED at Kalnes Hospital. This ED is thoroughly described in the preceding chapters, and especially in Section 2.4.1. Within this ED, there are 44 functions, which are to be located at possible 86 locations. In reality, some additional functions exist, but these functions are omitted from the model since relocation is very costly. All functions to be allocated are given in Table 9.1. This table gives an overview of the function number, the number of locations each function cover in addition to specifying whether a function has a predefined location or not. Through correspondence with stakeholders, both at the Kalnes ED and Sykehusbygg, some particular functions are prelocated. Additionally, individual requirements such as the need to have windows, to be located close to the outer walls, or close to an entrance are revealed for the different functions. As a result, some functions are considered locked, while other functions are given a limited number of feasible locations for placement. In Section 8.2, descriptions of the feasible locations for the different functions are given in detail.

Table 9.1: Functions list showcasing the function number, locations covered and if a function has a predefined location or not.

Function	Number	Locations	Predef.	Function	Number	Locations	Predef.
Care rooms area 1	1	5	No	Waiting room chair	23	1	No
Care rooms area 2	2	8	No	Waiting room main	24	3	No
Care rooms area 4	3	6	No	Reception walk-in	25	1	No
Triage rooms	4	2	No	Mors	26	1	Yes
Outpatient clinic	5	3	No	Bed area hallway	27	1	Yes
CT1	6	4	No	MRI	28	1	Yes
CT2	7	4	No	Walk-in arrival and exit	29	1	No
CT Angiography	8	4	No	Amb. arrival	30	1	No
X-ray1	9	2	No	Trauma arrival	31	1	Yes
X-ray2	10	2	No	Observation exit	32	1	Yes
Ultrasound	11	2	No	Wash room	33	2	No
Trauma	12	4	No	Employee room 1	34	1	No
Lab	13	1	No	Employee room 2	35	2	No
Consumable	14	1	No	Meeting rooms	36	5	Yes
Medicine room	15	1	No	Storage room 1	37	1	No
WorkS. Sur. Phys.	16	1	No	Storage room 2	38	1	No
WorkS. Neu. Phys.	17	1	No	Storage room 3	39	1	No
WorkS. nurses A1 & recp. EMS	18	1	No	Storage room 4	40	1	No
WorkS. nurses A2	19	1	No	Storage room 5	41	1	No
WorkS. Med. Phys. Exec.	20	1	No	Bathroom 1	42	1	No
WorkS. Med. Phys. LIS	21	1	No	Bathroom 2	43	1	No
WorkS. nurses A3	22	1	No	Bathroom 3	44	1	No

The EDLP is a problem with high complexity, rendering several assumptions necessary to make it solvable. One of these simplifications is the representation of the ED as a grid with equal-sized rectangles. In Figure 9.1, the Kalnes ED is presented as given in the model formulation. In this figure, the functions are more or less placed at the same locations as today.

Today, the acute imaging department is separated from the rest of the ED. A majority of the patients need some sort of imaging, rendering the total distance walked by patients and staff to this resource considerably long. Considering today's layout, the walk-in patients mostly stay close to the walk-in entrance, while regular ambulance patients stay in the care room areas distributed in different parts of the ED. Additionally, the trauma patients stay close to the trauma entrance, with the trauma room as the main base.

The walk-in patients are most dependent on the following functions; triage, outpatient clinic, waiting rooms, and imaging. Only focusing on the patients, the current layout seems reasonable. The waiting-rooms, triage, and outpatient clinic are all located close to the walk-in entrance. The imaging functions are the only ones requiring long walking distances for the patients. However, the situation is less optimal for the

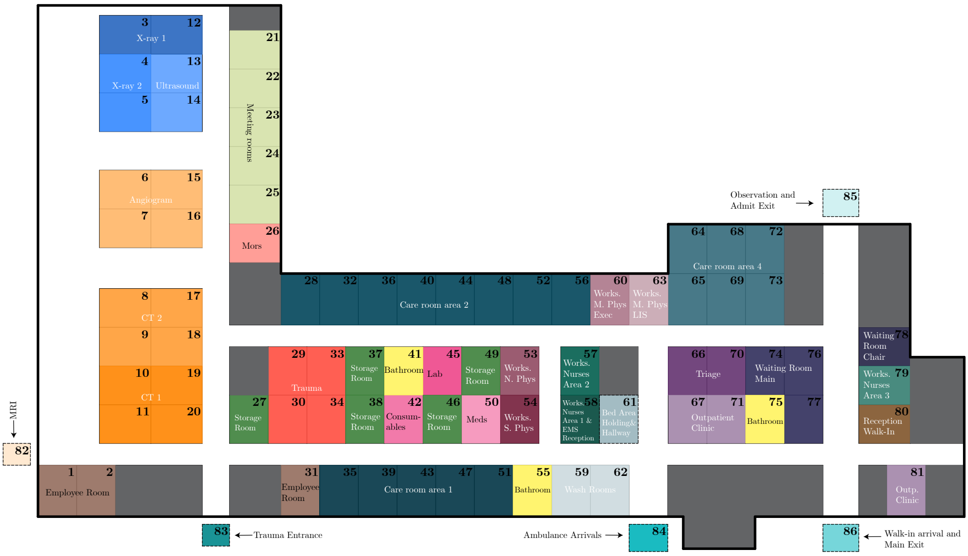


Figure 9.1: Today's layout of the Kalnes ED, presented in the gird used in the optimization model.

associated staff, utilizing some additional functions like the lab, medicine room, and consumables. Consequently, the staff consumes a significant amount of time to walk between these functions.

Considering the regular ambulance patients and their associated staff, the majority of the dependent functions are located relatively close. However, the distance to some specific imaging functions is longer than preferable. Besides, the more acute patients staying in bed area 4 are placed in a less central location, resulting in long walking-distances for the staff.

The situation is significantly better for team patients. These patients are transported from the trauma entrance to the trauma room, located just by the entrance. The only additional function these patients need is the CT, located adjacent to the trauma room. However, the staff provides service to other patients when not taking care of the team patients, resulting in some walking from other parts of the ED to the trauma room when these patients arrive.

9.2 Locking Strategies

The computational study revealed that different locking strategies have a strong impact on the final layout. Even though the instances are only tested on smaller cases than a real-world ED, the main characteristics are nevertheless relevant. In this section, the locking strategies with the best potential are tested on the Kalnes ED. As outlined in Section 8.10, including functions with the largest flows in an early stage, give the best objective values. Therefore, strategies based on the total flow is developed when optimizing the entire ED. Since the staff has higher flows than the patients, the staff flow strategies have significant similarities to the total flow strategies. Consequently, patient flow strategies are included in favor of staff flow. Besides, the promising results when considering the first steps for the patients in the clinical pathways, makes this feature a natural choice for developing strategies.

In Table 9.2, the quantities patient flow, total flow, and minimum patient steps, are presented with its associated feature values for all the functions in the ED. Combining the features with the varied number of model stages, different strategies are developed. The strategies are divided into three, four, and five stages, with a negatively correlated computational time when increasing the number of stages. By solving this layout problem in three stages, the running time is expected to be longer compared to a five-stage model. In Table 9.3, the instances tested in this case are presented. For each stage, the functions to be locked and the functions included are given. The functions are provided with its function number, and the connection between the function number and the function name is given in Table 9.1. When *Flow functions* is provided, all functions with any flow to any other function are referred to. These functions have a function number from 1 to 32.

On the upper part of the Table 9.3, the patient-flow strategies are presented, followed by total flow, and patient steps. The various feature-strategies are separated with a solid line, while the number of stages within each feature is separated with dotted lines. There is a logic in the given instance names, where *4SPatientFlow2* means that the problem is solved in four stages based on the patient flow feature.

In every instance, the entrances are locked in the first step. Even though the entrances has a small flow emanating from them, their impact on the internals of the ED is significant. In the following steps, functions are chosen to be locked following the locking strategy. In every stage, as many functions as possible are included, limited by an aim to solve the stages in a reasonable time. The functions included in all instances rigidly follow the locking strategy, varying only by the size of each stage.

The results of the tested instances, with associated computational time and performance measures, are presented in Table 9.4. There is a clear trend where the better objective value from the optimization model results in better simulation KPIs. However, the trend is not monotonous. In general, LOS is the KPI that follows the

Table 9.2: Overview of patient flow, total flow and the minimum number of steps a patient must take before it reaches a function.

Function	**Patient flow**	**Total flow**	**Minimum patient steps**
Care rooms area 1	559	3 354	2
Care rooms area 2	631	3 399	2
Care rooms area 4	1 075	3 876	2
Triage rooms	1 260	3 933	3
Outpatient clinic	760	1 711	3
CT1	76	139	2
CT2	149	274	2
CT Angiography	196	362	3
X-ray1	678	1 360	3
X-ray2	534	1 086	3
Ultrasound	188	350	3
Trauma	51	267	1
Lab	0	2 278	-
Consumable	0	707	-
Medicine room	0	1 138	-
Workstation surgery physicians	0	1 391	-
Workstation neurological physicians	0	422	-
Workstation nurses area 1 and reception EMS	335	2 575	1
Workstation nurses care room area 2	0	1 394	-
Workstation medical physician executives	0	2 831	-
Workstation medical physician LIS	0	2 651	-
Workstation nurses area 3	0	2 260	-
Waiting room chair	836	1 548	2
Waiting room main	2 933	5 639	2
Reception walkin	1 116	1 116	1
Mors	0	0	3
Bed area holding and hallway	157	970	2
MRI	150	273	3
Walkin arrival and main exit	810	810	0
Ambulance arrival	169	727	0
Trauma arrival	16	53	0
Observation and admit exit	461	630	3
Wash room	0	0	-
Employee room 1	0	0	-
Employee room 2	0	0	-
Meeting rooms	0	0	-
Storage room 1	0	0	-
Storage room 2	0	0	-
Storage room 3	0	0	-
Storage room 4	0	0	-
Storage room 5	0	0	-
Bathroom1	0	0	-
Bathroom2	0	0	-
Bathroom3	0	0	-

Table 9.3: Instances in locking strategy testing

Instance	**Stage 1**		**Stage 2**		**Stage 3**		**Stage 4**		**Stage 5**	
	Functions to be locked	Functions included	Functions to be locked	Functions included	Functions to be locked	Functions included	Functions to be locked	Functions included	Functions to be locked	Functions included
3SPatientFlow1	4,24,25,29,30	Flow functions	3,4,23,24,25,29,30	All functions	All functions	All functions				
3SPatientFlow2	4,24,25,29,30	Flow functions	3,4,5,23,24,25,29,30	All functions	All functions	All functions				
3SPatientFlow3	4,24,25,29,30	Flow functions	3,4,5,9,23,24,25,29,30	All functions	All functions	All functions				
4SPatientFlow1	29,30	Flow functions	4,24,25,29,30	Flow functions	3,4,23,24,25,29,30	All functions	All functions	All functions		
4SPatientFlow2	29,30	Flow functions	4,24,25,29,30	Flow functions	3,4,5,23,24,25,29,30	All functions	All functions	All functions		
4SPatientFlow3	29,30	Flow functions	4,24,25,29,30	Flow functions	3,4,5,9,23,24,25,29,30	All functions	All functions	All functions		
5SPatientFlow1	29,30	Flow functions	4,24,25,29,30	Flow functions	3,4,23,24,25,29,30	All functions	Flow functions	All functions	All functions	All functions
5SPatientFlow2	29,30	Flow functions	4,24,25,29,30	Flow functions	3,4,5,23,24,25,29,30	All functions	Flow functions	All functions	All functions	All functions
5SPatientFlow3	29,30	Flow functions	4,24,25,29,30	Flow functions	3,4,5,9,23,24,25,29,30	All functions	Flow functions	All functions	All functions	All functions
3STotalFlow1	3,4,24,29,30	Flow functions	1,2,3,4,18,20,21,24,29,30	All functions	All functions	All functions				
3STotalFlow2	3,4,24,29,30	Flow functions	1,2,3,4,20,24,29,30	All functions	All functions	All functions				
3STotalFlow3	3,4,24,29,30	Flow functions	2,3,4,24,29,30	All functions	All functions	All functions				
4STotalFlow1	29,30	Flow functions	3,4,24,29,30	Flow functions	1,2,3,4,18,20,21,24,29,30	All functions	All functions	All functions		
4STotalFlow2	29,30	Flow functions	3,4,24,29,30	Flow functions	1,2,3,4,20,24,29,30	All functions	All functions	All functions		
4STotalFlow3	29,30	Flow functions	3,4,24,29,30	Flow functions	2,3,4,24,29,30	All functions	All functions	All functions		
3SPatientSteps1	12,18,25,29,30	Flow functions	1,2,3,6,7,12,18,23,24,25,29,30	Flow functions	All functions	All functions				
4SPatientSteps1	29,30	Flow functions	12,18,25,29,30	Flow functions	1,2,3,6,7,12,18,23,24,25,29,30	All functions	All functions	All functions		

objective value of the closest. The link between the other KPIs and the objective value seems weaker.

The locking strategies based on total flow perform the best, both in terms of objective value and KPIs. This might not come as a big surprise since these functions have the largest impact on the ED, given their high flows. The strategies following the patient's steps perform the worst when simulated. Even though this strategy might sound reasonable in theory, the strategy only focuses on the patient, which in turn has smaller flows than the staff. A general finding is that the locking strategies which place functions with high flows in early stages seem to perform the best. The resulting layouts from the two instances having the best objective value are fundamentally different. Whereas *4STotalFlow2* places care room area 4 at the same location as in today's layout, *4SPatientFlow1* places the function in the middle section of the ED. This leaves room for the triage and outpatient clinic where care room area 4 is located today.

In the following sections, the instance *4STotalFlow2* is investigated in detail. This instance shows promising simulation KPIs while at the same time, having the best objective value. In addition, the instance *4SPatientFlow1* is explored. Both instances are examined using the solution framework described in Section 9.4.

Table 9.4: Results in objective value and simulation KPIs for different locking strategies. The table is sorted on the objective value column, from best to worst. W. 5% represents the average of the worst 5%.

Instance	**Elapsed time [sec]**		**Objective value**	**Simulation KPIs**							
				LOS		TTT		DTDT		RTT	
	Total	Stages		Avg.	W. 5%	Avg.	W. 5%	Avg.	W. 5%	Avg.	W. 5%
4STotalFlow1	4 521	(34/2 692/1 682/113)	272 414.4	255.3	500.1	34.3	173.7	79.2	204.3	58.6	123.1
4STotalFlow2	3 172	(34/2 773/271/94)	272 414.4	255.3	500.1	34.3	173.7	79.2	204.3	58.6	123.1
4SPatientFlow1	3 315	(52/1 792/167/1 304)	275 658.9	255.1	490.5	35.1	184.8	80.7	211.7	59.2	178.6
5SPatientFlow1	3 602	(47/1 787/167/1 579/22)	275 658.9	255.1	490.5	35.1	184.8	80.7	211.7	59.2	178.6
3STotalFlow1	13 451	(12 221/1 085/145)	277 286.5	255.4	498.9	34.0	178.9	79.3	211.6	58.8	172.8
3STotalFlow2	12 216	(11 785/176/255)	277 286.5	255.4	498.9	34.0	178.9	79.3	211.6	58.8	172.8
3STotalFlow3	13 554	(12 165/41/1 348)	277 286.5	255.4	498.9	34.0	178.9	79.3	211.6	58.8	172.8
4STotalFlow3	6 229	(48/2 673/80/3 428)	277 784.4	255.8	506.4	36.6	195.8	81.2	221.0	58.6	166.8
4SPatientFlow2	2 424	(47/1 707/160/510)	277 926.3	259.5	544.4	34.2	179.9	82.0	246.3	59.4	176.7
5SPatientFlow2	2 321	(51/1 724/174/350/22)	277 926.3	259.5	544.4	34.2	179.9	82.0	246.3	59.4	176.7
3SPatientFlow1	15 145	(9 518/59/5 568)	284 087.8	257.2	504.8	36.1	194.0	80.9	219.0	59.4	181.6
3SPatientSteps1	23 304	(168/23 037/99)	284 190.0	260.8	517.5	40.8	215.4	83.5	236.3	61.0	146.9
4SPatientSteps1	23 107	(49/77/22 893/88)	284 190.0	260.8	517.5	40.8	215.4	83.5	236.3	61.0	146.9
4SPatientFlow3	2 699	(48/1 743/422/486)	286 134.2	256.9	510.2	34.0	180.5	79.5	209.8	59.7	179.0
5SPatientFlow3	2 179	(51/1 746/168/23/191)	286 134.2	256.9	510.2	34.0	180.5	79.5	209.8	59.7	179.0
3SPatientFlow2	10 087	(9 342/206/539)	288 597.9	257.2	529.9	35.9	184.6	80.5	225.3	60.4	184.2
3SPatientFlow3	10 822	(9 357/422/1 043)	292 526.5	258.4	534.6	36.1	186.1	80.9	222.5	59.9	173.4

9.3 Prioritization of Patient and Staff

In this section, prioritizing patient and staff is tested by varying the parameter α. This parameter is introduced in Table 5.3, and an increased value of α means prioritizing the patients to a greater extent. Instance *4STotalFlow2* is used in these tests. By finding the best-suited parameter α, additional improvements in the KPIs are achievable. With α equal to 1.0, the optimized layout only considers the patient flows, while having α equal to 0.0 only regards the staff flows. When prioritizing the patients, the functions connected with a high patient flow are drawn closer together. By considering the staff, the same logic is followed, resulting in reduced distances between the functions with high staff flow. This effect can be observed for the patients in Figure 9.2, and for the staff in Figure 9.3. When staff and patients are prioritized equally, the distances between the functions with high staff flow are reduced to a greater extent than the functions with high patient flow. This observation can be seen in connection with the size of the flows, where the staff flows are significantly larger than the patient flows.

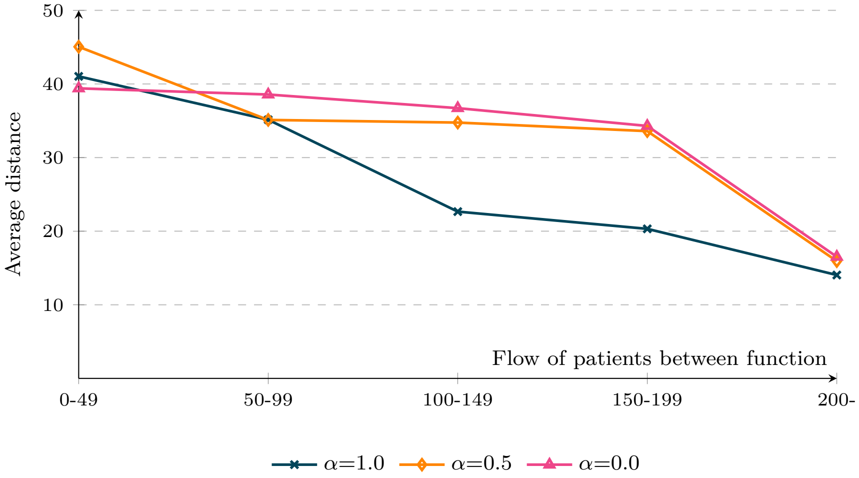


Figure 9.2: Average distance between the functions having a specific amount of patient flow in between them for three different values of the parameter α.

The results of the patient and staff prioritization are given in Table 9.5. As observed when looking at these results, there is a slight tendency with improved LOS for patients when prioritizing staff. This connection might seem like a logical flaw. However, patients spend a large amount of their time within the ED waiting for staff to help them. One of the key findings by analyzing the simulation model is that patients wait for rooms in peak arrival hours while they wait for staff members during the night. Especially at nights during the weekends, there are difficulties regarding high queues and waiting times.

Similar to LOS, the same trends exist for the other KPIs TTT and DTDT. However, these tendencies are less clear than LOS. This observation can be seen in context with

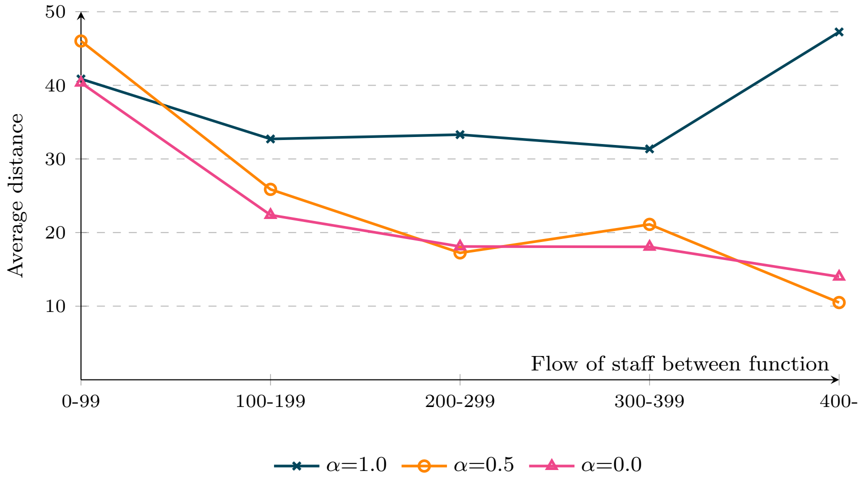


Figure 9.3: Average distance between the functions having a specific amount of staff flow in between them for three different values of the parameter α.

the high flow of patients in between functions affecting TTT and DTDT. In contrast to the mentioned KPIs, it is more challenging to see any connection for RTT when changing the parameter α. Several aspects of the simulation model are difficult to predict. The staff clarifying the patients to be transported to other departments are more available than the staff examines patients at the outpatient clinic and triage. A result of this is a lower variance for the RTT than the other KPIs.

Table 9.5: Results in KPIs when prioritizing either patients or staff.

Instance	LOS		TTT		DTDT		RTT	
	Avg.	Worst 5%	Avg.	Worst 5%	Avg.	Worst 5%	Avg.	Worst 5%
1.0α	265.4	540.7	47.7	246.6	87.9	266.6	59.1	186.1
0.8α	257.0	519.0	34.8	197.4	79.7	225.1	58.0	172.8
0.6α	256.6	508.4	35.6	193.9	80.2	221.8	58.4	176.4
0.5α	255.3	500.1	34.3	173.7	79.2	204.3	58.6	123.1
0.4α	255.7	511.6	33.7	184.3	79.7	212.0	58.8	183.9
0.2α	256.5	512.1	34.7	168.9	79.3	206.5	58.6	173.9
0.0α	258.7	520.7	34.1	186.7	79.2	215.2	59.1	132.0

Despite the tendency between prioritizing staff and improved KPIs, the most promising solutions are found when considering both patient and staff flow. There is a point when the effects of additionally reduced walking distances for staff is limited. Instead of additional prioritizing the staff, the patients should be more considered. By also prioritizing the patients, the walking distances for the patients are reduced. Following this, decreased queue accumulation may exist because of positive system effects. To summarize, there is a trade-off by prioritizing staff and patients. Prioritizing the staff causes the most significant improvements, but the patients should be prioritized as well.

9.4 Solving the Case

The difference in objective value and KPIs, as observed in Section 9.2, between the different solution approaches are minimal. However, some variations in the performance measures still exist. The two locking strategies *4STotalFlow2* and *4SPatientFlow1*, are chosen to be investigated based on their performance measures and computational times. Three cases are developed based on these two locking strategies.

In Case 1 and 2, the locking strategy *4STotalFlow2* is utilized. There is a difference between these two cases when it comes to the prioritization of patients with a particular triage level and its associated staff. This difference is described in detail later in this section. The instance *4STotalFlow2* is based on locking the functions with the highest total flow first. All entrances and receptions are locked in the first stage. Included in the stage, but not to be locked, are all functions with a flow. In stage 2, care room area 4, triage, and the main waiting room are to be locked, while the same functions as in the first stage are included to help guide the placement of the functions to be locked. At stage 3, all care room areas and the workstation for medical physician executives are to be locked. All functions at the ED are included in this stage. Finally, in the last stage, all functions are to be allocated to a location, producing the final layout.

In Case 3, the locking strategy *4SPatientFlow1* is optimized using the solution framework in this thesis. The overall strategy, in this instance, is to lock functions with the highest patient flow first. However, in the first stage, entrances are locked. To help guide the entrances to their optimal placement, all functions with a flow are included in the stage. At stage 2, triage, waiting room main, and reception walk-in are to be locked. The same functions as in stage 1 are included in the stage. In stage 3, care room area 4 and waiting room chair is locked as well. At this stage, all functions are included in the stage to help guide the functions to be locked. In the last stage, all functions are included, and all functions are to be allocated to a location.

In Section 8.8, optimizing layouts with several different triage prioritization strategies are tested. The main finding is that prioritizing the most acute patients caused somewhat reduced overall performance. However, seconds can distinguish life from death for the most acute patients. Analyzing the medical implications of the layouts is beside the scope of this thesis. Consequently, to give decision support on the matter to stakeholders, two different cases are developed to highlight the issue. Case 2 makes a high prioritizing of acute patients, while Case 1 considers the different triage levels equally. The triage prioritization strategies for the cases are given in Table 9.6. Case 3 has the same triage priorities as Case 1.

Table 9.6: Prioritization of the different triage levels in the three cases.

Instance	Staff	Triage 1	Triage 2	Triage 3	Triage 4	Triage 5
Case 1	1	1	1	1	1	1
Case 2	1	2	3	4	5	100
Case 3	1	1	1	1	1	1

The initial flows of patients and staff between the different functions are developed simulating today's layout at ED Kalnes. All data, except for the flows, are kept constant throughout the case instances. Based on these flows, new layouts are optimized for the three cases. The flows within the simulation model are dynamic, meaning patients or staff will choose the nearest of two equal functions. An example of this might be if a patient needs an x-ray examination. There are two x-rays at the Kalnes ED, and the patient is escorted to the nearest available x-ray. In the case where all x-rays are occupied, the patient is sat in a common queue. Due to these dynamics, the flows of patients and staff may change with a new layout. In every iteration of the solution framework, the optimized layout is simulated, resulting in new patient and staff flows. The simulation-optimization procedure is continued for these instances until the stopping criterion is reached.

9.4.1 Results

Table 9.7 summarizes the KPIs and the objective value of the cases. By looking at today's layout, two objectives are given. These objective values are calculated based on the triage prioritization values in the proposed cases. Consequently, the objectives for Case1 and Case 3 are comparable with 392 566.0, while the objective values in Case 2 are comparable with 2 141 615.0. One of the main characteristics is the substantial improvements in LOS in the first iteration. In the following iterations, the time-reductions are gradually diminishing. The trend is, however, not monotonous. There are iterations where the simulation KPIs perform worse than in the previous iterations. Among the other KPIs, the trend is less clear than with LOS. The KPIs are improved, but the trend on how these KPIs perform is hard to distinguish. However, the correlation with lower LOS seems tight. Case 1 performs the best when purely looking at the KPIs. Case 3 performs well in terms of TTT but has slightly higher LOS.

Table 9.7: Results in objective value and simulation KPIs for the different rounds in Case 1, Case 2, and Case 3.

Instance	**Iteration**	**Objective value**	**LOS**		**TTT**		**DTDT**		**RTT**	
			Avg.	W. 5 %	Avg.	W. 5 %	Avg.	W. 5 %	Avg.	W. 5 %
Today's layout	0	392 566.0	268.9	549.4	40.9	219.9	85.1	249.9	61.0	216.6
Triage pri. as Case 2	0	2 141 615.0								
Case 1	1	272 414.4	255.3	500.1	34.3	173.7	79.2	204.3	58.6	123.1
Case 1	2	285 188.0	254.8	502.9	32.3	173.4	78.1	207.1	57.8	166.5
Case 1	3	284 611.3	252.7	487.3	32.3	168.2	77.5	204.0	58.3	175.6
Case 1	4	293 281.5	253.2	503.4	33.1	183.8	78.8	221.0	57.4	166.8
Case 1	5	287 883.6	252.7	487.3	32.3	168.2	77.5	204.0	58.3	175.6
Case 2	1	1 540 567.2	256.1	509.4	35.2	196.4	80.0	223.1	58.5	178.1
Case 2	2	1 583 726.8	255.8	510.1	34.2	187.8	79.4	217.8	58.6	180.3
Case 2	3	1 591 702.5	255.8	510.1	34.2	187.8	79.4	217.8	58.6	180.3
Case 3	1	275 658.9	255.1	490.5	35.1	184.8	80.7	211.7	59.2	178.6
Case 3	2	283 363.4	253.6	503.2	31.7	167.4	77.1	205.5	58.0	165.5
Case 3	3	275 394.9	253.6	503.2	31.7	167.4	77.1	205.5	58.0	165.5

Considering the objective value, the most significant improvements for the instances are in the first iteration. Then, the objective fluctuates, and in several cases, increases, making it difficult to see the connection between a higher iteration number and the objective value. One explanation of this observation is non-optimal placements of functions in the first stages because of the changed flows. Besides, the increased objective may be due to the fact that a better layout will cause the patients to leave the ED faster. When stopping the simulation at a specific time, more patients have left the ED in a better layout, with following higher patient and staff flows. Therefore, the objective may increase when the layout remains the same in two following iterations.

There are several differences between the three cases, both in terms of layout and performance. Case 1 converges in five iterations, while both Case 2 and 3 reach the convergence criterion in only three iterations. It is, however, partly expected that Case 2 converges fast since prioritizing the acute patients make a high impact on the placement of several functions, and apparently, a bigger impact than the flow changes. The overall performance in the ED is considerable better when weighting all the triage-levels equal, as in Case 1 and 3. Since there is a relatively low number of highly acute patients, having the high acute functions in central locations would cause non-optimal placements of functions with higher flows. Comparing and ranking these layouts is a difficult task and besides the scope of this thesis. Case 2 optimizes the layout towards serving the most acute patients. Medical expertise is required to make reasonable conclusions about these prioritizations.

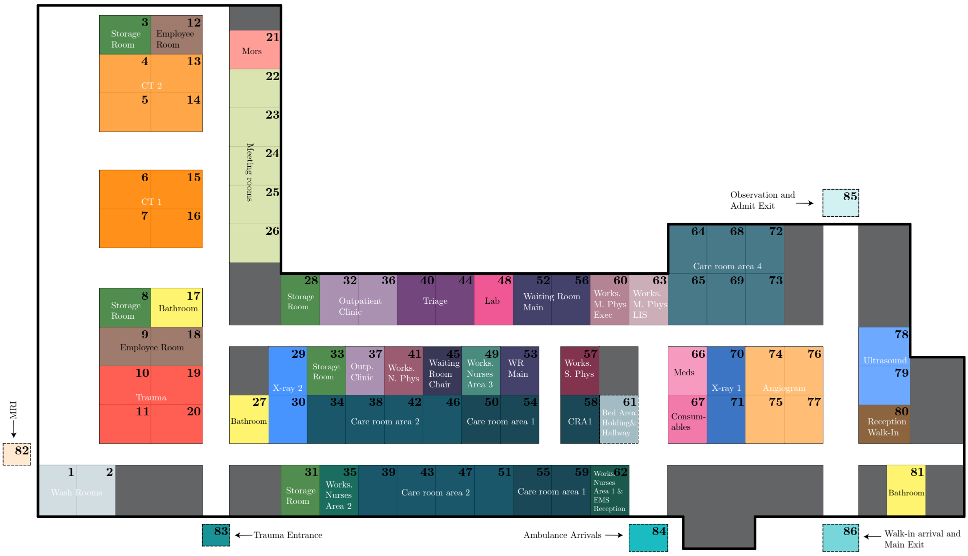


Figure 9.4: Final layout from Case 1

Final Layouts

The Figures 9.4, 9.5 and 9.6 show the final layouts from the solution framework. There are several similarities and differences between the layouts. Firstly, Case 1 and 2, which are optimized using locking strategy *4STotalFlow2* has the same general layout. The triage, outpatient clinic, and waiting rooms are placed closely together in the center of the ED. The same goes for the care room areas, which are located near the ambulance entrance. In Case 1, the imaging resources are spread out across the ED, while Case 2 has some clustering of these functions. In Case 2, the trauma and CT1 are located adjacent to each other. The most acute patients with triage level 5 are highly dependent on CT1, allocating this function to locations close to the trauma area. By moving the trauma area into the central area of the ED, some of the support functions for patients with lower acuity are pushed to less optimal locations.

Case 3 is optimized using *4SPatientFlow1*, producing a completely different layout than in Case 1 and 2. In this layout, the areas within the ED are more secluded. Walk-in patients have nearly all their necessary functions in the right part of the ED, while ambulance arrivals and trauma arrivals are located in the central and left part. Imaging resources are distributed around in the ED, and workstations for the staff are centralized.

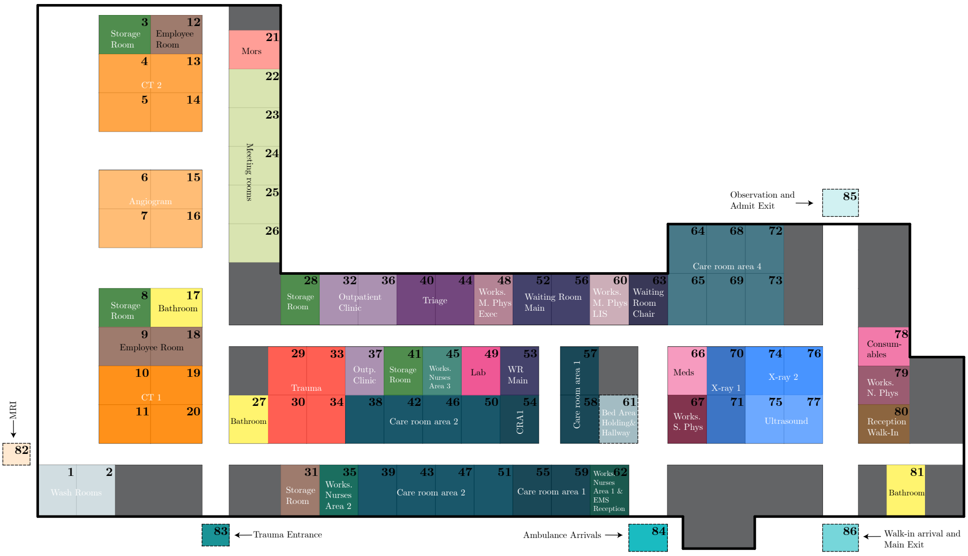


Figure 9.5: Final layout from Case 2

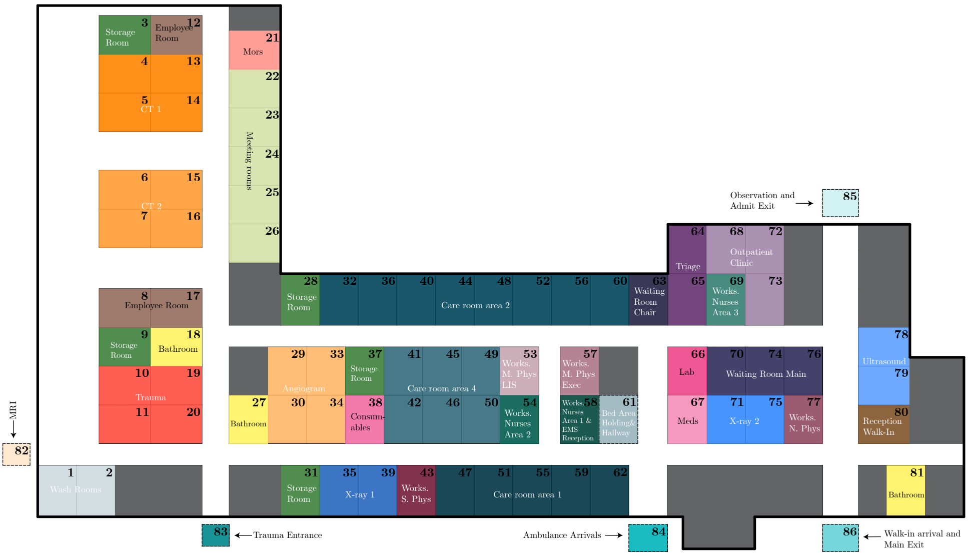


Figure 9.6: Final layout from Case 3

Walking Distances

Walking distances are minimized in the solution framework. Table 9.8 shows that there are significant reductions in the average walking distances for the three cases compared to today's layout. The average walking distances are divided based on the triage levels. Within a triage level, walking distances for both patients and staff are included. Today's layout performs well in terms of walking distances for the most acute patients and its associated staff. Considering Case1 and Case2, the differences in walking-distances are closely connected to the triage prioritization. When prioritizing the most acute patients, the walking distances for these patients and staff are significantly lower. However, when prioritizing the triage levels equally as in Case 1, the walking distances for all other triage levels are lower, and thereby also the overall average distances. Case 3 performs very well in terms of low staff walking distances when staff is performing tasks without being on behalf of patients.

Table 9.8: The average walking distances for all patients having a specific triage level and staff providing service to a patient with a particular triage level.

Instance	**Average walking distances**						**Average**
	Staff	Triage 1	Triage 2	Triage 3	Triage 4	Triage 5	
Today	1423.3	381.5	828.1	924.7	865.6	303.1	986.9
Case1	963.1	222.2	516.4	712.3	627.6	363.6	697.6
Case2	1170.7	238.2	546.3	721.9	654.4	290.6	723.5
Case3	790.6	241.7	546.8	714.9	651.3	367.0	711.2

9.4.2 Analyzing the Performance of the best performing Case

Case 1 has the best overall performance, both in terms of KPIs and walking distances. In the following section, Case 1 is compared to today's layout of the Kalnes ED. Key bottlenecks of this ED are identified both through analysis of the simulation model and in discussions with stakeholders.

The triage is identified as one of the main bottlenecks of this ED by stakeholders, and walk-in patients wait a considerable time for triage. The Time To Triage (TTT) is one of the most important KPIs in any ED, closely linked to patient safety. Figure 9.7 plots the utilization of both triage rooms and nurses for both layouts. It is observable that the utilization of triage rooms increasing in peak arrival hours. Consequently, triage rooms are assumed to be a limiting factor in the peak arrival hours. In contrast, the staff is the limiting factor at night. While Case 1 has higher utilization of the triage rooms than today's layout, the utilization of triage nurses are more or less the same. Figure 9.8 plots the average and max queue lengths on weekdays and weekends for the two layouts. The queues are lower in the layout of Case 1. The proposed layout seems to tackle situations with long queues better, having lower max queues and reducing the queue length earlier in the afternoon. When combining the findings in these two layouts, it is observed that the utilization is higher, and the queues are shorter. This observation means that less time is wasted in the triage process on tasks irrelevant to treating patients.

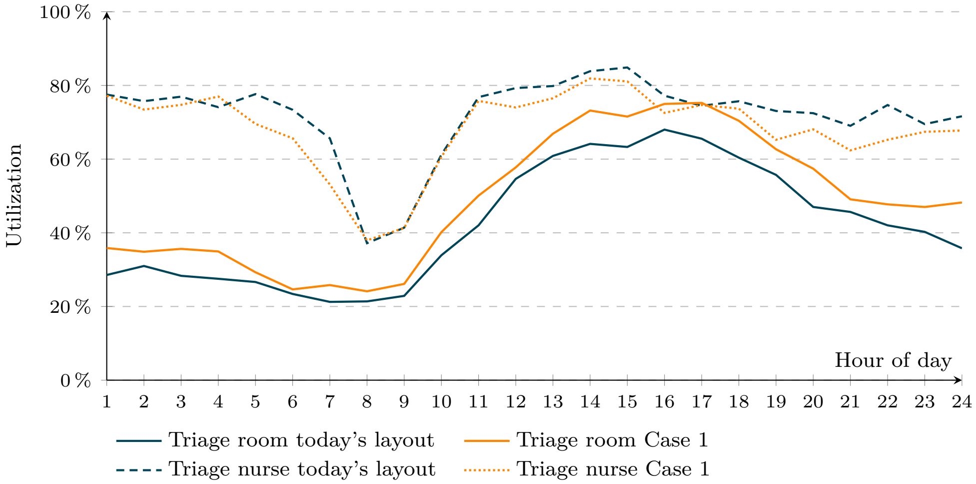


Figure 9.7: Utilization of both triage rooms and triage nurses at different hours of the day.

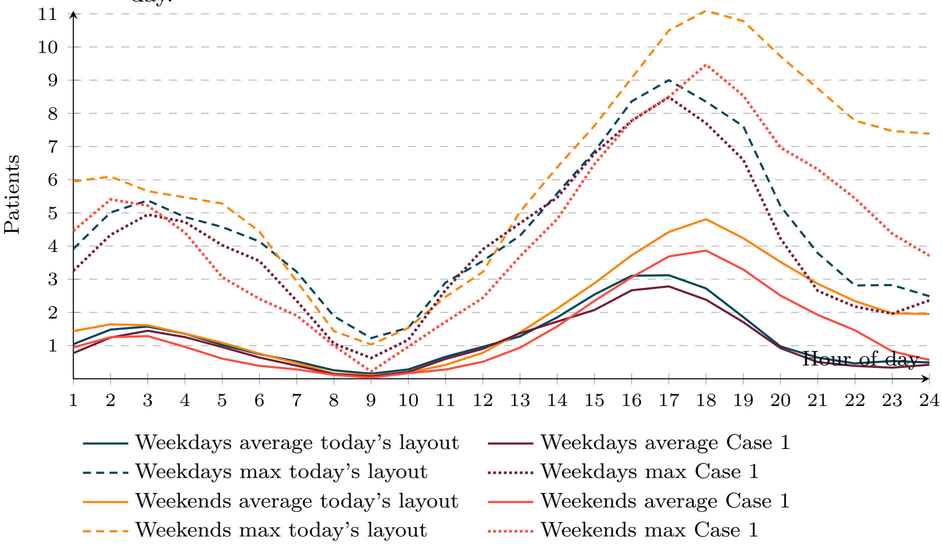


Figure 9.8: Number of patients in queue for triage at different hours of the day.

The same story is observed in Figure 9.9, which plots the average waiting time for patients to conduct an x-ray. Case 1 performs significantly better than today's layout, having 3-5 minutes shorter waiting time on average. The time savings are higher than the pure time consumed walking back and forth between the patient areas and the x-ray area. Consequently, there are some more significant system effects by relocating the x-rays to more central placements.

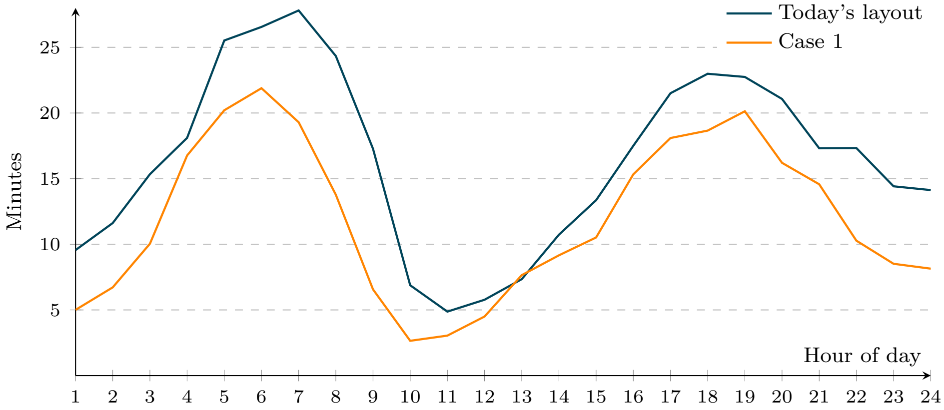


Figure 9.9: Average waiting time for X-ray compared between today's layout at the Kalnes ED and the final layout from Case 1 at different hours of the day.

9.4.3 The value of the proposed layout

The value of the proposed solution is difficult to estimate. Even though the KPIs show improvements, these numbers might be difficult to grasp. In discussions with stakeholders, a question arose whether extra resources need to be added to today's layout before it is equally good as the proposed layouts.

Several factors affect the performance of the ED. In this thesis, the focus is directed to layout optimization. However, other improvements may have a high impact on the ED, such as increased area, more staff, or more specific medical resources. Since increased area requires costly investments and new medical resources need space or is challenging to measure the effect of, the scenarios in this section are generated by adding more staff.

In this simulation study, different staff types are added to the existing staff group. The extra staff is added to improve the performance measure to the greatest extent by adding a minimum number of extra staff. Four different scenarios are generated, where extra nurses are added to the triage or the different bed areas. These scenarios are given in Table 9.9. While only one extra triage nurse is added in scenario 1 and 2, one additional nurse is added in both Area 1 and Area2 for scenario 3 and 4. In scenario 1 and 4, the added nurses are on a schedule, only working from 12:00 to 20:00 every day.

Table 9.10 shows the results of the tested scenarios. It can be observed that scenario

Table 9.9: All extra staff scenarios to be tested in this section.

Scenario	Changes to the ED operation
1	One extra triage nurse on a shift schedule.
2	One extra triage nurse on all shifts.
3	One extra nurse in Area 1, and one extra triage nurse on all shifts.
4	One extra nurse in Area 1, one extra nurse in Area 2, and one extra triage nurse on shift schedules.

3, where nurses are added on all shifts, perform the best. Scenario 4 performs closest to Case 1, considering the KPIs. In scenario 4, an extra nurse is added in area 1, area 2, and to the triage process. All added nurses are on shift schedules from 12:00 to 20:00 every day. Compared to Case 1, all KPIs in scenario 4 are better. However, the extra resources added in this scenario are substantial. This goes to show that a good layout can give as good improvements as adding more resources.

Table 9.10: KPIs for Case 1 and the improvement instances of today's layout.

Instance	LOS		TTT		DTDT		RTT	
	Avg.	Worst 5%	Avg.	Worst 5%	Avg.	Worst 5%	Avg.	Worst 5%
Case 1	252.7	487.3	32.3	168.2	77.5	204	58.3	175.6
1	261.7	497.5	25.3	157.8	78.6	196.2	58.6	204.6
2	256.9	505.7	21.0	122.6	72.6	218.9	59.5	200.3
3	246.3	464.8	20.3	114.7	70.1	156.4	55.2	135.7
4	250.4	463.8	27.9	150.2	74.3	183.8	55.8	142.8

9.5 Discussion

In this thesis, the layout at ED Kalnes is optimized with the goal of improving the KPIs. Because of the stochasticity in the ED, it is challenging to include all details in an optimization model. Therefore, an optimization model finds new layouts, while KPIs and flows are found through simulation of the layouts. By running the optimization and simulation model in an iterative sequence, the flows are adapted to the new layout, making possibilities for additional improvements. A general assumption in this solution framework, and a prerequisite for the iterative process to work as intended, is a correlation between lower objective value in the optimization model and better KPIs in the simulation model. In this thesis, layouts are developed by optimizing the objective, which is, minimizing the walking distances for patients and staff. As result of minimized walking distances, the KPIs are expected to be improved.

However, the connection between walking distances and KPIs are not straight forward. There are several different factors affecting the queues and waiting times in the different parts of the ED, among others, staff, rooms, or other medical resources. Even though the patients save approximately 2 minutes in walking times with the optimized layout for Case 1, the reduced LOS is, because of various system effects and following reduced queue accumulation, as much as 16 minutes. However, the system effects may have some variations in different parts of the ED. If the capacity of staff at a specific function is satisfactory, reduced walking distances for these staff may not affect the KPIs significantly. The optimization model has no information about which flows are critical to the system performance. Identifying critical flows is a very difficult task, which implies some guesswork. The flow of one group can be critical in one layout, while at the same time be of less importance to another layout. Based on this, the formulation does not included any extra formulation about critical flows. To sum up, an improved objective is not directly transferred to better KPIs. If the optimization model mainly reduces the walking-distances for less busy staff, the KPIs can increase an iteration. However, the results show a clear tendency between the optimization and simulation model, and consequently, the layout is normally improved in an iteration.

Even though the KPIs of a layout are worse than in the previous iteration, the iteration procedure may still continue. In the search for better layouts, the solution framework can in some iterations find local optimums. This requires the framework to be able to continue, finding less promising solutions before finding a better one. When developing a reasonable stopping criterion, several aspects must be taken into consideration. Instead of focusing on the KPIs, comparing the function placements of the new layout with previous iterations is a more reasonable strategy. By doing this, the framework has the ability get out of local optimums.

The optimization model solves the EDLP and creates new layouts. Because of the quadratic nature of this problem, solving it until optimality is a challenging task. Therefore, a decomposition approach is introduced, solving a smaller part of the problem in each stage. Exact solution approaches are utilized in each stage. However, some functions are locked to locations on a smaller information basis in the first stages, resulting in non-optimal placements of functions in several cases. As a consequence, the final layout is not guaranteed to be optimal. In every iteration the resulting layout is developed from scratch, meaning that only the input flows and the constraints of the EDLP determine the layout. This renders the optimization model to be categorized as a construction heuristic.

Several perspectives of the optimization model should be considered to reduce the negative effects of solving the problem in multiple stages. A thorough strategy is proven to have an impact on the objective value, and thus, the KPIs. Locking functions with a high total flow or patient flow in the earlier stages may be advantageous techniques for finding promising solutions. Another aspect is finding well-suited prioritization parameters. Prioritizing patients versus staff is utilized to improve the KPIs. In contrast, determining the priority of the triage levels requires medical expertise. A layout is chosen to maximize the ability to save lives, not necessarily minimizing the KPIs. Prioritizing the most acute patients can be advantageous for saving lives, but increased KPIs may be the disadvantage.

Today at the Kalnes ED, functions with similarities are located close, while functions with more differences are placed farther apart. The acute imaging department is placed in one part, the functions related to trauma and walk-in patients are located on each side of the ED, while the regular ambulance patients stay mostly in the middle. However, several functions are common for a large proportion of patients and staff. For example, different kinds of imaging functions are highly utilized by trauma, walk-in, and regular ambulance patients. Except for the team patients, there is a considerable walking distance for patients and its associated staff when taking some sort of imaging.

Conforming to the ED stakeholders, there is a common practice within ED planning to locate similar functions close. This practice does not seem to be the best approach in the process of optimizing KPIs in an ED. In this thesis, highly interactive functions are located close, and less interactive functions are placed farther apart. A consequence of this approach is having imaging functions distributed all over the ED, while common functions, like the lab, workstations, medicine, and consumable, are centralized. The final layouts show a tendency to produce small islands with the most important functions for a specific patient type. An example of this can be seen in the final layout of Case 1, where the most important functions for the less acute walk-in patients like waiting-room, triage, outpatient clinic, lab and x-ray are located closely.

Because of limited medical expertise among the authors of this thesis, three alternative layouts are developed. All the layouts have significant improvements from today's solution. One layout prioritizing the most acute patients, which goes at the cost of the overall performance. The last two layouts prioritize the triage levels equally but are developed based on different locking strategies, in fact, total flow and patient flow. Among the two, concerning total flow in the locking strategy, gives the most promising results. However, there are several different aspects when planning the layout of an ED. The opinions of the staff, rules for function placements need to be taken into account, and placement costs should be considered. Therefore, OR methods, in combination with medical expertise, would be an interesting base for developing improved layouts at an ED.

Chapter 10

Concluding Remarks

The purpose of this thesis is to illustrate how a combination of simulation and optimization can capture the complex nature of an ED to propose better layouts. Due to the combinatorial nature of the Emergency Department Layout Problem (EDLP), and the dynamics of the patient and staff flows, the solution framework is divided into a layout problem with an approximate objective function, and a simulation model where a given layout can be simulated and assessed based on the KPIs.

The simulation-optimization framework has proven to catch the connection between ED layout and patient flow. The two models are dependent on each other, where the output from one model serves as input in the other. The simulation model captures the flows of patients and staff between different functions in the ED, creating dependencies between them, while the optimization model uses the flows and the distances between the locations to solve the assignment problem. Through iteratively running the two models in sequence, better layouts are produced. The iterative process is run until the stopping criterion is met. When using the solution framework, a layout converges within approximately four to five iterations. It is observed that the most considerable improvements are reached in the first iterations and second iteration, before the improvements are gradually diminishing.

Optimizing patient flow is a challenging task and highly dependent on medical knowledge. This thesis improves patient KPIs by optimizing weighted walking distances. However, the connection between walking distances and KPIs is not straight-forward. Several different factors affect the delays for a patient in the ED, but two main causes stand out; waiting for staff and waiting for a room. At a function where the patients wait for a room, reduced walking for the associated staff may not result in significant reductions in the KPIs. Nevertheless, a clear tendency exists where lower walking distances result in better performing EDs in terms of KPIs.

The optimization model has features of the Quadratic Assignment Problem, and handles the relations between pairs of functions that are placed in different locations of the ED. The nature of the problem results in a complex combinatorial problem, which in turn is proved to be hard to solve to optimality. Therefore, simplifications are required to produce layouts in a reasonable time. A decomposition approach is introduced, where the functions are allocated to locations in several stages, making the mathematical optimization problem solvable in a reasonable time. A consequence of this decomposition is the placement of some functions based on a smaller information basis, and thus, an optimal final solution is not guaranteed. However, smart decomposing strategies and parameter settings reduce the negative effects of the simplifications significantly.

Several different perspectives of the model can be considered by varying the priorities of different triage levels. Determining the priority of the triage levels requires medical expertise. The best performing layout is found by prioritizing all patients equally. This proves to reduced the KPIs of the ED the most. However, the final layout of any ED is chosen to maximize the ability to save lives, not necessarily minimizing the KPIs. Prioritizing the most acute patients can be advantageous for saving lives, but increased KPIs may be the disadvantage.

Through the collaboration with Sykehusbygg and the Kalnes ED, insight into the real working-procedures of planning and evaluating hospitals is gained. At Sykehusbygg, personal experience from previously built hospitals is the primary information source when planning new ones. Conforming to the ED stakeholders, there is a common practice within ED planning to locate similar functions close. This thesis shows that utilizing OR techniques to allocate highly interactive functions close, and less interactive functions farther apart, improve the KPIs. However, the quality of the solution is highly dependent on the input data quality. As such, the results should be analyzed with care, and the model should be implemented with more realistic data before making any general conclusions. Besides, the complexity of an ED makes high claims of solid information gathering to understand the different processes in detail. Despite this, the general concepts in the framework are valid. By following this framework, the layout at any ED can be optimized with required input data and some additional problem-specific adjustments.

Chapter 11

Future Research

In this thesis, a simulation-optimization framework, utilized to optimize the layout at the Kalnes ED, is developed. In this framework, the simulation model analyzes a layout while an optimization model discovers new layouts. There are many possible extensions and alternatives to this framework, and further detail can be incorporated into the existing model to increase the relevance to the real ED. Firstly, more and better data about the patients and different processes can give more precise distributions and, thus, a more realistic framework. In an ED, a considerable amount of medical decisions are determined every day, affecting the different processes in the ED to a large extent. Therefore, an even tighter collaboration with physicians and nurses, with a following better understanding of the ED, would probably result in a better-working simulation model.

An extension of this framework is to develop a more sophisticated distance calculation. The distance between two functions is calculated from its center-location, which is close, but not equal to its geographical centers. By having the center-location at the geographical center, and not at one of the discretized blocks, a more precise distance calculation is achievable.

This model is discretized into blocks of equal size rectangles. An alternative to this discretization is a continuous model design, where functions can take different shapes than the predefined standard-care room size. With a continues representation, the solution space is increased, and even better layouts than in the discretized design, are achievable. An assumption in this thesis is the predefined placement of hallways. However, different hallway placements have the potential to affect the final optimized layout. One way of doing this is to optimize the hallways in the first stage. Another option is to solve the problem with some alternative hallway placements.

Because of the stochastic and the quadratic nature of the problem, new layouts are found by solving linearized multi-stage models. However, heuristics and metaheuristics can be utilized to solve the EDLP, and these approaches give another perspective to the problem. Even though these solution methods simplify the solution procedure to a large extent, the problem may be solved in one instead of several stages. That is advantageous since functions locked in an early stage may be located based on the wrong information basis. Several different heuristic and metaheuristic may be well suited to solve this problem, and some relevant alternatives are genetic algorithms, particle swarm optimization, and tabu search.

In this framework, the resulting layout is developed from scratch, meaning that only the input flows and the constraints of the EDLP determine the layout. This renders the optimization model to be categorized as a construction heuristic. However, the optimal solution is not guaranteed. Therefore, an improvement heuristic can be developed and run from the best solution found so far. A possible improvement heuristic is a method called re-run, optimizing the placements for a subset of functions, and having the other functions locked to the locations in the best solution found so far. Several improvement heuristics are of interest in this context, among others, simulating annealing and tabu search.

The optimization model can optimize the system based on several objectives, making it a multi-objective problem. A natural extension to the model is to include placement costs. In a standard Facility Layout Problem placement costs are usually included, and including this in the formulation of the EDLP could be relevant. Adding this, and potentially other costs involved in the ED would be a move towards making the model account for other aspects than time and utilization. However, including these parameters leads to an important discussion on how to prioritize the different objectives.

Bibliography

Acar, Y., Kadipasaoglu, S. N., and Day, J. M. (2009). "Incorporating uncertainty in optimal decision making: Integrating mixed integer programming and simulation to solve combinatorial problems". In: *Computers and Industrial Engineering* 56 (1), pp. 106–112 (Cited on pp. 27, 30, 32, 33).

Ahmadi, A., Pishvaee, M. S., and Akbari Jokar, M. R. (2017). *A survey on multi-floor facility layout problems* (Cited on pp. 22, 25).

Aleisa, E. E. and Lin, L. (2005). "For effective facilities planning: Layout optimization then simulation, or vice versa?" In: *Proceedings - Winter Simulation Conference.* Vol. 2005, pp. 1381–1385 (Cited on pp. 22, 30).

Anthony, R. N. (1965). *Planning and Control Systems: A Framework for Analysis.* Division of Research, Graduate School of Business Administration, Harvard˜... (Cited on p. 18).

Arnolds, I., Nickel, S., Shashaani, S., and Wernz, C. (2012). "Using simulation in hospital layout planning". In: *Proceedings of the 2012 Winter Simulation Conference* (Cited on pp. 27, 30, 33).

Arnolds, I. and Nickel, S. (2015). "Layout planning problems in health care". In: *Applications of Location Analysis.* Vol. 232. Springer International Publishing, pp. 109–152 (Cited on pp. 21, 22, 32).

Azadivar, F. and Wang, J. (2000). "Facility layout optimization using simulation and genetic algorithms". In: *International Journal of Production Research* 38 (17), pp. 4369–4383 (Cited on pp. 30–33).

Berdal, T. B. and Nydal, E. M. (2019). *A simulation study of the ED at Kalnes Hospital.* Tech. rep. NTNU (Cited on p. 49).

Bohannon, R. W. (1997). "Comfortable and maximum walking speed of adults aged 20-79 years: Reference values and determinants". In: *Age and Ageing* 26 (1), pp. 15–19 (Cited on p. 58).

Brailsford, S. C., Harper, P. R., Patel, B., and Pitt, M. (2009). "An analysis of the academic literature on simulation and modelling in health care". In: *Journal of Simulation* 3 (3), pp. 130–140 (Cited on p. 20).

Burgess, A. G., Morgan, I., and Vollmann, T. E. (1993). "Cellular manufacturing: its impact on the total factory". In: *The International Journal of Production Research* 31 (9), pp. 2059–2077 (Cited on p. 22).

Centeno, M. A. and Reyes, M. F. (1998). “So you have your model: what to do next. A tutorial on simulation output analysis”. In: *1998 Winter Simulation Conference. Proceedings.* Vol. 1, pp. 23–29 (Cited on p. 124).

Cocke, S., Guinn, D. E., MacBlane, E., Walshak, S., Willenbrock, N., White, K. P., Lobo, J. M., and Kang, H. (2016). “UVA emergency department patient flow simulation and analysis”. In: *2016 IEEE Systems and Information Engineering Design Symposium (SIEDS)*, pp. 118–123 (Cited on p. 30).

Das, S. K. (1993). “A facility layout method for flexible manufacturing systems”. In: *International Journal of Production Research* 31 (2), pp. 279–297 (Cited on p. 24).

Drira, A., Pierreval, H., and Hajri-Gabouj, S. (2007). “Facility layout problems: A survey”. In: *Annual Reviews in Control* 31 (2), pp. 255–267 (Cited on pp. 20–23, 25).

Duguay, C. and Chetouane, F. (2007). “Modeling and Improving Emergency Department Systems using Discrete Event Simulation”. In: *Simulation* 83 (4), pp. 311–320 (Cited on pp. 29, 30).

Elshafei, A. N. (1977). “Hospital Layout As A Quadratic Assigment Problem”. In: *Operational Research Quarterly* 28 (1), pp. 167–179 (Cited on pp. 21, 24, 27).

Eskandari, H., Riyahifard, M., Khosravi, S., and Geiger, C. D. (2011). “Improving the emergency department performance using simulation and MCDM methods”. In: *Proceedings - Winter Simulation Conference*, pp. 1211–1222 (Cited on pp. 29, 30).

Figueira, G. and Almada-Lobo, B. (2014). “Hybrid simulation-optimization methods: A taxonomy and discussion”. In: *Simulation Modelling Practice and Theory* (Cited on pp. 31, 33, 61).

Furian, N., Neubacher, D., O’Sullivan, M., Walker, C., and Pizzera, C. (2018). “GED-Mod - Towards a Generic Toolkit for Emergency Department Modeling”. In: *Simulation Modelling Practice and Theory* 87 (Cited on p. 20).

Graham, J. E., Fisher, S. R., Bergés, I.-M., Kuo, Y.-F., and Ostir, G. V. (2010). “Walking Speed Threshold for Classifying Walking Independence in Hospitalized Older Adults”. In: *Physical Therapy* 90 (11), pp. 1591–1597 (Cited on p. 58).

Hans, E., Houdenhoven van, M., and J. H. Hulshof, P. (2012). “A Framework for Healthcare Planning and Control”. In: *Hall R. (eds) Handbook of Healthcare System Scheduling. International Series in Operations Research & Management Science, vol 168.* Pp. 303–320 (Cited on pp. 17–19).

Helber, S., Böhme, D., Oucherif, F., Lagershausen, S., and Kasper, S. (2016). “A hierarchical facility layout planning approach for large and complex hospitals”. In: *Flexible Services and Manufacturing Journal* 28 (1-2), pp. 5–29 (Cited on pp. 24–27).

Henning, B., Lydersen, S., and Døllner, H. (2016). “A reliability study of the rapid emergency triage and treatment system for children”. In: *Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine* 24 (1), p. 19 (Cited on p. 6).

Jensen, B. (2014). “Helsereformer på feil premisser”. In: *Kommunenes interesseforening for lokalsykehus* (Cited on p. 1).

Kelton, W. D., Sadowski, R. P., and Zupick, N. B. (2015). *Simulation with Arena. 6th ed.* McGraw-Hill Education (Cited on p. 27).

Khadem, M., Bashir, H., Al-Lawati, Y., and Al-Azri, F. (2009). “Evaluating the layout of the emergency department of a public hospital using computer simulation modeling: A case study”. In: *2008 IEEE International Conference on Industrial Engineering and Engineering Management, IEEM 2008*, pp. 1709–1713 (Cited on pp. 29, 30).

Koopmans, T. C. and Beckmann, M. (1957). “Assignment Problems and the Location of Economic Activities”. In: *Econometrica* 25 (1), p. 53 (Cited on p. 24).

Kusiak, A. and Heragu, S. S. (1987). “The facility layout problem”. In: *European Journal of Operational Research* 29 (3), pp. 229–251 (Cited on p. 24).

Kvillum, V. N. and Vigerust, A. M. R. (2017). *A One-Stage Approach to the Facility Layout Problem in Hospital Planning.* Tech. rep. Norwegian University of Science, Technology, Institute of Industrial Economics, and Technology Management. (Cited on p. 23).

Kvillum, V. N. and Vigerust, A. M. R. (2018). *An Optimization-Based Approach to Facility Layout Planning in Hospitals.* Tech. rep. NTNU (Cited on pp. 22–24, 26, 27).

Mohiuddin, S., Busby, J., Savović, J., Richards, A., Northstone, K., Hollingworth, W., Donovan, J. L., and Vasilakis, C. (2017). “Patient flow within UK emergency departments: a systematic review of the use of computer simulation modelling methods”. In: *BMJ Open* 7 (5) (Cited on p. 28).

Montreuil, B. (1991). “A Modelling Framework for Integrating Layout Design and flow Network Design”. In: pp. 95–115 (Cited on pp. 24, 27).

Morley, C., Unwin, M., Peterson, G. M., Stankovich, J., and Kinsman, L. (2018). “Emergency department crowding: A systematic review of causes, consequences and solutions.” eng. In: *PloS one* 13 (8), e0203316 (Cited on p. 20).

Nolan, R. L. and Sovereign, M. G. (1972). “A Recursive Optimization and Simulation Approach to Analysis with an Application to Transportation Systems”. In: *Management Science* 18 (12) (Cited on pp. iv, viii, 2, 30).

OECD (2019a). *Health care resources.* URL: `https://www.oecd-ilibrary.org/content/data/data-00541-en` (Cited on p. 1).

OECD (2019b). *Health expenditure indicators.* URL: `https://www.oecd-ilibrary.org/content/data/data-00349-en` (Cited on p. 1).

Oh, C., Novotny, A. M., Carter, P. L., Ready, R. K., Campbell, D. D., and Leckie, M. C. (2016). "Use of a simulation-based decision support tool to improve emergency department throughput". In: *Operations Research for Health Care* 9, pp. 29–39 (Cited on p. 30).

Queirolo, F., Tonelli, F., and Schenone, M. (2002). "Warehouse layout design: minimizing travel time with a genetic and simulative approach—methodology and case study". In: *academia.edu* (Cited on pp. 27, 30, 32, 33).

Rais, A. and Viana, A. (2011). "Operations Research in Healthcare: a survey". In: *International Transactions in Operational Research* 18 (1), pp. 1–31 (Cited on p. 19).

Ruohonen, T., Neittaanmäki, P., and Teittinen, J. (2006). "Simulation Model for Improving the Operation of the Emergency Department of Special Health Care". In: *Proceedings of the 38th Conference on Winter Simulation.* WSC '06. Winter Simulation Conference, pp. 453–458 (Cited on p. 30).

Saghafian, S., Austin, G., and Traub, S. J. (2015). "Operations research/management contributions to emergency department patient flow optimization: Review and research prospects". In: *IIE Transactions on Healthcare Systems Engineering* 5 (2), pp. 101–123 (Cited on p. 20).

Sahni, S. and Gonzalez, T. (1976). *P-Complete Approximation Problems.* Tech. rep. (Cited on p. 20).

Salmon, A., Rachuba, S., Briscoe, S., and Pitt, M. (2018). "A structured literature review of simulation modelling applied to Emergency Departments: Current patterns and emerging trends". In: *Operations Research for Health Care* 19, pp. 1–13 (Cited on p. 28).

Sentralbyrå, S. (2011). *Påranden av sammhandling.* URL: `https://www.ssb.no/helse/artikler-og-publikasjoner/paa-randen-av-samhandling` (Cited on p. 1).

Svendsen, K. (2018). *På Sykehuset Østfold har innovativ teknologi nærmest eliminert feilmedisinering.* URL: `https://fagbladet.no/nyheter/pa-sykehuset-ostfold-har-innovativ-teknologi-narmest-eliminert-feilmedisinering-6.91.567760.2d50bf07b1` (Cited on p. 10).

Sykehusbygg (2019). *Sykehusbygg HF Purpose.* URL: `http://sykehusbygg.no/om/formal/` (Cited on p. 9).

Sykehuset Østfold (2018). *Konseptrapport del I – utvidelse av somatisk akuttmottak Kalnes.* Tech. rep. (Cited on p. 1).

Tompkins, J. A., White, J. A., Bozer, Y. A., and Tanchoco, J. M. A. (2010). *Facilities planning.* John Wiley & Sons (Cited on p. 22).

Uriarte, A. G., Zúñiga, E. R., Moris, M. U., and Ng, A. H. C. (2017). "How can decision makers be supported in the improvement of an emergency department? A simulation, optimization and data mining approach". In: *Operations Research for Health Care* 15, pp. 102–122 (Cited on pp. 1, 19, 20, 29, 30).

Vahdat, V., Namin, A., Azghandi, R., and Griffin, J. (2019). "Improving patient timeliness of care through efficient outpatient clinic layout design using data-driven simulation and optimisation". In: *Health Systems*, pp. 1–22 (Cited on pp. 21, 24, 27, 30, 32, 33).

Vanbrabant, L., Braekers, K., Ramaekers, K., and Nieuwenhuyse, I. V. (2019). "Simulation of emergency department operations: A comprehensive review of KPIs and operational improvements". In: *Computers I& Industrial Engineering* 131, pp. 356–381 (Cited on pp. 2, 20, 27, 29).

Villa-Roel, C., Guo, X., Holroyd, B. R., Innes, G., Wong, L., Ospina, M., Schull, M., Vandermeer, B., Bullard, M. J., and Rowe, B. H. (2012). "The role of full capacity protocols on mitigating overcrowding in EDs". In: *The American Journal of Emergency Medicine* 30 (3), pp. 412–420 (Cited on p. 20).

Whitt, W. and Zhang, X. (2017). "A data-driven model of an emergency department". In: *Operations Research for Health Care* 12, pp. 1–15 (Cited on p. 57).

Wikipedia (2019). *Triage.* URL: `https://en.wikipedia.org/wiki/Triage` (Cited on p. 6).

Zuo, X., Li, B., Huang, X., Zhou, M. C., Cheng, C., Zhao, X., and Liu, Z. (2019). "Optimizing Hospital Emergency Department Layout via Multiobjective Tabu Search". In: *IEEE Transactions on Automation Science and Engineering* 16 (3), pp. 1137–1147 (Cited on pp. 22, 27, 30, 32, 33).

Appendix A Revised Mathematical Model

A.1 Objective Function

$$\min\ Z = \sum_{(f,g)\in\mathcal{F}^F} \sum_{n\in\mathcal{N}_f} \sum_{m\in\mathcal{N}_g\backslash\mathcal{N}^I_{fn}} D_{nm} G^{PE}_{fg} z_{fngm} \tag{A.1}$$

$$G^P_{fg} = \sum_{t\in\mathcal{T}} F^P_{fgt} I^{PE}_t \tag{A.2}$$

$$G^E_{fg} = \sum_{t\in\mathcal{T}} F^E_{fgt} I^{PE}_t \tag{A.3}$$

$$G^{PE}_{fg} = \alpha G^P_{fg} + (1-\alpha) G^E_{fg} \tag{A.4}$$

A.2 Constraints

A.2.1 Assignment Constraints

$$\sum_{n\in\mathcal{N}_f} \sum_{k\in\mathcal{K}_{fn}} x_{fnk} = 1, \qquad f\in\mathcal{F} \tag{A.5}$$

$$\sum_{f\in\mathcal{F}_n} \sum_{(m,k)\in\mathcal{L}^C_{fn}} x_{fmk} \leqslant 1, \qquad n\in\mathcal{L} \tag{A.6}$$

$$x_{fn1} = \sum_{m\in\mathcal{N}^R_n} x_{gm1}, \quad f\in\mathcal{E}, n\in\mathcal{L}^E, g\in\mathcal{F}^R_f \tag{A.7}$$

$$\sum_{k\in\mathcal{K}_{fn}} x_{fnk} + \sum_{k\in\mathcal{K}_{gm}} x_{gmk} \leqslant 1 - z_{fngm}, \quad (f,g)\in\mathcal{F}^F, n\in\mathcal{N}_f, m\in\mathcal{N}_g\backslash\mathcal{N}^I_{fn} \tag{A.8}$$

A.2.2 Valid inequalities

$$\sum_{n \in \mathcal{N}_f} \sum_{m \in \mathcal{N}_g \backslash \mathcal{N}^I_{fn}} z_{fngm} = 1, \qquad (f,g) \in \mathcal{F}^F \tag{A.9}$$

$$\sum_{k \in \mathcal{K}_{fn}} x_{fnk} - \sum_{m \in \mathcal{N}_g \backslash \mathcal{N}^I_{fn}} z_{fngm} = 0, \qquad (f,g) \in \mathcal{F}^F, n \in \mathcal{N}_f \tag{A.10}$$

A.2.3 Variable definitions

$$x_{fnk} \in \{0,1\}, \qquad f \in \mathcal{F}, n \in \mathcal{N}_f, k \in \mathcal{K}_{fn} \tag{A.11}$$

$$z_{fngm} \in \{0,1\}, \qquad (f,g) \in \mathcal{F}^F, n \in \mathcal{N}_f, m \in \mathcal{N}_g \backslash \mathcal{N}^I_{fn} \tag{A.12}$$

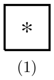
Appendix B Functions

B.1 Function table

Table B.1: Functions

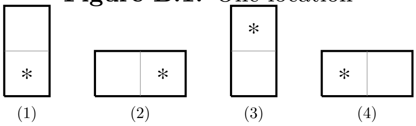
Function	**Number**	**Locations**	**Predefined**
Care rooms area 1	1	5	No
Care rooms area 2	2	8	No
Care rooms area 4	3	6	No
Triage rooms	4	2	No
Outpatient clinic	5	3	No
CT1	6	4	No
CT2	7	4	No
CT Angiography	8	4	No
X-ray1	9	2	No
X-ray2	10	2	No
Ultrasound	11	2	No
Trauma	12	4	No
Lab	13	1	No
Consumable	14	1	No
Medicine room	15	1	No
Workstation surgery physicians	16	1	No
Workstation neurological physicians	17	1	No
Workstation nurses area 1 and reception EMS	18	1	No
Workstation nurses care room area 2	19	1	No
Workstation medical physician executives	20	1	No
Workstation medical physician LIS	21	1	No
Workstation nurses area 3	22	1	No
Waiting room chair	23	1	No
Waiting room main	24	3	No
Reception walk-in	25	1	No
Mors	26	1	Yes
Bed area holding and hallway	27	1	Yes
MRI	28	1	Yes
Walk-in arrival and main exit	29	1	No
Ambulance arrival	30	1	No
Trauma arrival	31	1	Yes
Observation and admit exit	32	1	Yes
Wash room	33	2	No
Employee room 1	34	1	No
Employee room 2	35	2	No
Meeting rooms	36	5	Yes
Storage room 1	37	1	No
Storage room 2	38	1	No
Storage room 3	39	1	No
Storage room 4	40	1	No
Storage room 5	41	1	No
Bathroom1	42	1	No
Bathroom2	43	1	No
Bathroom3	44	1	No

B.2 Legal configurations



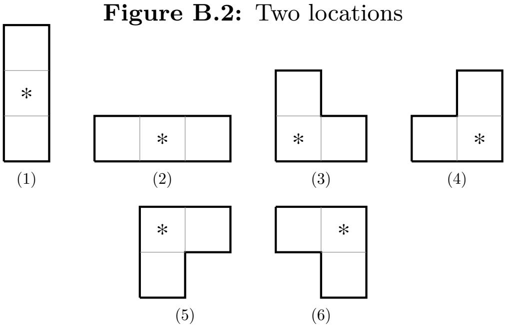
(1)

Figure B.1: One location



(1) (2) (3) (4)

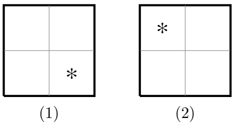
Figure B.2: Two locations



(1) (2) (3) (4)

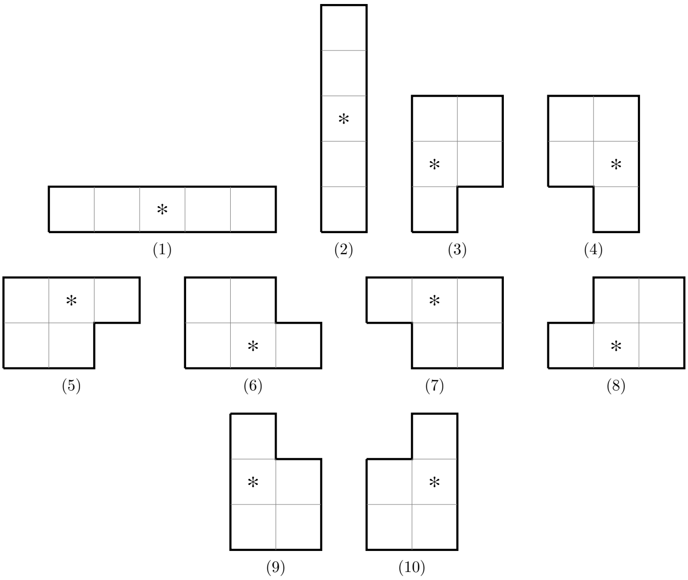
(5) (6)

Figure B.3: Three locations



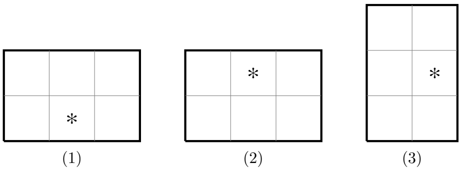
(1) (2)

Figure B.4: Four locations



(1) (2) (3) (4) (5) (6) (7) (8) (9) (10)

Figure B.5: Five locations



(1) (2) (3)

Figure B.6: Six locations

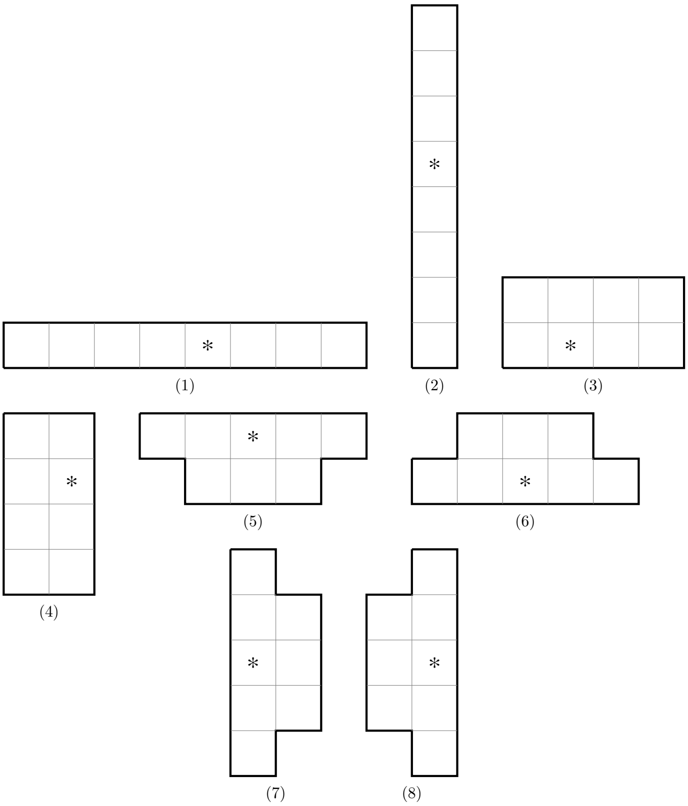


Figure B.7: Eight locations

Appendix C Simulation

In the following sections more information is given for the simulation model of this thesis.

C.1 Simulation model assumptions

In the following section, the key assumptions from the simulation model are described.

(a) Hundreds of different patient tracks are in this model aggregated into three main tracks. There is one track each for respectively walk-in, ambulance, and team patients.

(b) In this model, there are three different ways to arrive at the ED. However, in reality, it is possible to arrive at the ED directly from other parts of the hospital.

(c) The different processes are conducted in a specified order in the track, but in practice, the order may vary.

(d) The triage color for a patient will not change during the stay at the ED.

(e) The patients are categorized into internal medicine, surgical, neurological, orthopedic, and others. The last category, other, is a composition of multiple categories.

(f) The teams are divided into Trauma, MAT, Thrombolysis, and Other teams. The Other teams are an aggregation of multiple different small teams.

(g) The patients who need a team arrive at one specific entrance, the team entrance. In practice, these patients can arrive at the walk-in, ambulance or team entrance in the real world.

(h) If a walk-in patient is deemed acute, and thereby sent directly to a care room, this person will not receive a triage. Rather, the patient will be sent directly to an initial assessment by a physician.

(i) The lab at Kalnes is located in a different part of the hospital and connected to the ED with a pneumatic tube system. In our model, the lab is limited, with the ability to only analyze 20 lab samples from the ED simultaneously. This assumption correlates to the real world.

(j) Every patient, except trauma patients, take lab samples when arriving at the ED. The sample is taken either in the triage or bedside for ambulance arrivals.

(k) Every patient arriving with an ambulance has a pre-hospital triage before entering the ED and does not need a new triage in the ED.

(l) The time required by LIS physicians for patient examination and treatment is increased by 35 %, and the time for LIS1 physicians is increased with 50 % compared to the time required by a physician executive.

(m) Arriving ambulance patients are sent directly to a care room. If there are no rooms available, the patients stay in the clean bed area or the hallway in anticipation of an available room.

(n) A patient with a severe triage color will be prioritized before a patient with a less severe triage color under any circumstances.

(o) The acute imaging department is only serving the ED patients in the model. This is a simplification compared to the real world where this department also serves other patients in the hospital.

(p) In reality, the acute imaging department is not a part of the ED. However, The acute imaging department, located adjacent to the ED, is included in this model. The choice to implement this department in the model was made together with stakeholders. A majority of ED patients must take some form of images. Based on the stakeholder's experience, this is one of the main causes of high waiting times in the ED. The imaging department is implemented without any staff working with the resources.

(q) The observation unit, also located adjacent to the ED, is not modeled due to its limited impact on ED performances.

C.2 Warm up time and the length of the simulation

An ED, as is the object of the simulation in this report, can be looked at as a non-terminating system. The ED is always open, and there will always be new patients arriving. The fundamental question is, then, for how long should the simulation model run in order to obtain good qualitative results. Centeno and Reyes (1998) propose two critical issues to address; i) achieving steady-state conditions and ii) obtaining statically independent observations. Once these states are reached, it is possible to obtain valid confidence intervals. To accomplish these goals, firstly, the warm-up period must be established. The warm-up period consists of the time until the system reaches some form of a steady-state. The reasoning behind the warm-up period is to avoid bias in the simulation results. The model needs some warm-up time to fill the queues in the system to a normal state. To identify this period, Centeno and Reyes (1998) recommends plotting a metric over short simulation time. The time at which the graph hits a steady-state is the warm-up time of the model. Data collected before the warm-up period is over is not collected in the simulation results. Another approach used to reduce the bias of the startup is to run the simulation model for a very long time. After some time, one can neglect the initial results before the system hits steady-state, and the results are valid.

The simulation length needs to be long enough to reduce the standard deviation. Besides, the width of the confidence interval needs to be within an acceptable level. The required length is dependent on the degree of independence among the samples. With a lower degree of independence, longer simulation runs are essential. In the context of EDs, the number of patients in the system is regularly close to zero at night. Therefore, with independent random numbers, the measures of the KPIs for two days in a row are approximately independent. As a result of this, the requirement of long simulation runs is limited. At the same time, the observations in one replication use the same seed for random numbers. This causes dependencies within an individual replication. However, multiple replications with different seeds will give more independent observations, and thereby a lower standard deviation and a tighter confidence interval.

C.3 Activities in the Simulation Model

Table C.1: Detailed table showcasing the different processes, transports and decisions in the simulation model.

Name	Type	Milestone	Predecessors	Next Activity	Patient Destination	Staff Requirements
1_Arrival?	Process	Arrived		10 OR 20 OR 30	WaitingLineReg	
10_Walk-Ins	Patient Travels Unattended		LOCKED		WaitingLineReg	
11_Walk to Registration	Patient Travels Unattended		10		RegWalkIn	
12_Registration	Process	CheckIn	11			Health Secretary
13_Walk to Waiting Room	Patient Travels Unattended		12		Waiting room dependent on availability	
20_Gurney	Process		LOCKED			
21_Transport to registration	Transport Patient –> Process		20		RegEMS	EMS Personnel
22_Registration	Process	CheckIn	21			Health Secretary
23_EMS Transport to Bed	Transport Patient –> Process	BedPlacement	22	50	Bed Area dependent on Triage	EMS Personnel
24_Release EMS Personnel	MoveTransports>Process		23			
30_TeamAlarm type?	Decision Point		LOCKED	310 OR 320 OR 330 OR 340		EMS Personnel
310_Trauma	Transport Patient –> Process	CheckIn	LOCKED		Trauma room dependent on availability	EMS Personnel
311_CT?	Decision Point		310	312 OR 315		
312_Transport to CT	Transport Patient –> Process		LOCKED		CTArea, dependent on availability	EMS Personnel
313_CT Testing	Process	Radiology	312			
314_CT Analyze	Process		313			
315_Assemble team	Process	CheckIn	314	If no CT then 317		Relevant Physicians and Nurses
316_Return from CT	Transport Patient –> Process		313		Reserved location in activity 310	Nurse
317_Treatment	Process	Treatment	315 AND 316	600		Relevant Physicians and Nurses
320_MAT	Transport Patient –> Process	CheckIn	LOCKED		Trauma room dependent on availability	EMS Personnel
321_CT?	Decision Point		320	322 OR 325		
322_Transport to CT	Transport Patient –> Process		LOCKED		CTArea, dependent on availability	EMS Personnel
323_CT Testing	Process	Radiology	322			
324_CT Analyze	Process		322			
325_Assemble team	Process		324	If no CT then 327		Relevant Physicians and Nurses
326_Return from CT	Transport Patient –> Process		323		Reserved location in activity 320	Nurse
327_Treatment	Process	Treatment	325 AND 326	600		Relevant Physicians and Nurses
330_Thrombolysis	Transport Patient –> Process	CheckIn	LOCKED		Trauma room dependent on availability	EMS Personnel

Table C.1: Detailed table showcasing the different processes, transports and decisions in the simulation model.

Name	Type	Milestone	Predecessors	Next Activity	Patient Destination	Staff Requirements
331_CT?	Decision Point		330	332 OR 335		
332_Transport to CT	Transport Patient -> Process		LOCKED		CTArea, dependent on availability	EMS Personnel
333_CT Testing	Process	Radiology	332			
334_CT Analyze	Process		333			
335_Assemble team	Process		334	If no CT then 337		Relevant Physicians and Nurses
336_Return from CT	Transport Patient -> Process		333		Reserved location in activity 330	Nurse
337_Treatment	Process		335 AND 336	600		Relevant Physicians and Nurses
340_Other	Transport Patient -> Process	CheckIn	LOCKED		Trauma room dependent on availability	EMS Personnel
341_CT?	Decision Point		340	342 OR 345		
342_Transport to CT	Transport Patient -> Process		LOCKED		CTArea, dependent on availability	EMS Personnel
343_CT Testing	Process	Radiology	342			
344_CT Analyze	Process		343			
345_Assemble team	Process		344	If no CT then 347		Relevant Physicians and Nurses
346_Return from CT	Transport Patient -> Process		343		Reserved location in activity 330	Nurse
347_Treatment	Process		345 AND 346	600		Relevant Physicians and Nurses
39_Direct bed?	Decision Point		13	If direct bed, then 50, else 40		
40_Triage	Process		LOCKED			
41_Escort to triage	EscortPatient -> Process	Triage	40		Triage	Triage Nurse
42_ConsultAndExamine?	Decision Point		41	If Triage by Physician, then 411, else 401		
401_Conduct Triage on Patient	Process		LOCKED			Triage Nurse
402_Send Sample to Central Labs	Process > Send Item		401			Triage Nurse
403_Return to Waiting Room	Patient Travels Unattended		402		Waiting room dependent on availability	
404_Post Triage Documentation	Process		402			Triage Nurse
411_Conduct Triage on Patient	Process		LOCKED			Triage Nurse
412_Send Sample to Central Labs	Process		411			Triage Nurse
413_ConsultWithPhys	Process		412			Triage Nurse and Physician
414_ExaminePatient	Process	InitialMeetwPhys	413	49		Triage Nurse and Physician
415_Return to Waiting Room	Patient Travels Unattended		414		Waiting room dependent on availability	

Table C.1: Detailed table showcasing the different processes, transports and decisions in the simulation model.

Name	Type	Milestone	Predecessors	Next Activity	Patient Destination	Staff Requirements
416_PhysDocumentation	Process		414			Physician
417_PostTriageDocumentation	Process		413			Triage Nurse
49_Bed placement after triage?	Decision Point		403 OR 415	If bed after Triage, then 50, else 60		
50_Bed Placement	Process	Bed Placement	LOCKED		Bed Area dependent on Triage	
51_Ambulance patient?	Process		50	If arrival w/Ambulance, then 54, else 52		
52_Escort to bed	EscortPatient –> Process	Bed Placement	LOCKED		Bed Area dependent on Triage	conveyor OR Nurse
53_Prepare Bed	Process		52		Bed Area dependent on Triage	Nurse
54_Prepare Bed EMS	Process		LOCKED		Bed Area dependent on Triage	Nurse
55_Settle by 1 or 2 nurses?	Decision Point		53 OR 54	If settle by 2 nurses, then 57, else 56		
56_Get Patient Settled 1 nurse	Process		LOCKED			Nurse
57_Get Patient Settled 2 nurse	Process		LOCKED			Nurses
58_Post-Bed Placement Documentation	Process		56 OR 57	60		Nurse
60_ExtraEQ?	Decision Point		LOCKED	If patient need extra EQ, then 61, else 70		
61_Retrieve extraEQ	Process	ExtraEQ	LOCKED			
62_AdministerEQ	Process		61	70		Nurse
70_Provider Assessment poly?	Decision Point		LOCKED	If patient in waiting room, then 71, else 74		
71_Escort and examine patient Poly	EscortPatient –> Process		LOCKED		Treat Polyclinic	Physician
72_Back to waiting room	Patient Travels Unattended		71	80	Waiting room dependent on availability	Physician
73_Post Assessment documentation	Process	InitialMeetwPhys	71		Treat Polyclinic	Physician
74_Examine patient Phys	Process		LOCKED	80		Physician
75_Post Assessment documentation	Process	InitialMeetwPhys	74			Physician
80_Meds?	Decision Point		LOCKED	If patient need meds, then 81, else 90		
81_Retrieve Meds	Process		LOCKED			Nurse
82_Administer Meds to Patient	Process	Meds	81			Nurse
83_Post Meds Documentation	Process		82	90		Nurse
90_Labs?	Decision Point		LOCKED	If patient need labs, then 91, else 100		
91_Draw Lab Sample	Process		LOCKED			Nurse
92_Send Sample to Central Labs	Process>SendItem		91			Nurse
93_Post-Labs Documentation	Process		92	100		Nurse
100_Imaging?	Decision Point		LOCKED	dependent on which image nessesary, 140 OR 150 OR 160 OR 180		

Table C.1: Detailed table showcasing the different processes, transports and decisions in the simulation model.

Name	Type	Milestone	Predecessors	Next Activity	Patient Destination	Staff Requirements
101_Delay	Process		LOCKED	*Custom Code*		
140_X-Ray Available?	Decision Point		LOCKED	If patient in waiting room, then 141, else 142		
141_Escort to X-Ray	EscortPatient –> Process		LOCKED		XrayArea	conveyor OR Nurse
142_Transport to X-Ray	EscortPatient –> Process		LOCKED		XrayArea	conveyor OR Nurse
143_X-ray Testing	Process	XRay	141 OR 142			
144_X-Ray Analyze	Process		143			
145_Return from X-Ray	EscortPatient –> Process		143		Reserved location in activity 142, OR waiting room	conveyor OR Nurse
146_Xray finished	Process		144 AND 145	100		
150_CT Available?	Decision Point		LOCKED	If patient in waiting room, then 151, else 152		
151_Escort to CT	EscortPatient –> Process		LOCKED		CTArea	conveyor OR Nurse
152_Transport to CT	EscortPatient –> Process		LOCKED	100	CTArea	conveyor OR Nurse
153_CT Testing	Process	CT	151 OR 152			
154_CT Analyze	Process		153			
155_Return from CT	EscortPatient –> Process		153		Reserved location in activity 152, OR waiting room	conveyor OR Nurse
156_CT finished	Process		154 AND 155	100		
160_CT with Contrast Available?	Decision Point		LOCKED			
161_Prep for CTwC	Process		160	If patient in waiting room, then 161, else 162		
162_Escort to CTwC	EscortPatient –> Process		LOCKED		CTwCArea	conveyor OR Nurse
163_Transport to CTwC	EscortPatient –> Process		LOCKED		CTwCArea	conveyor OR Nurse
164_CTwC Testing	Process	CTwC	162 OR 163			
165_CTwC Analyze	Process		164			
166_Return from CTwC	EscortPatient –> Process		164		Reserved location in activity 162, OR waiting room	conveyor OR Nurse
167_CTwC finished	Process		165 AND 166	100		
170_Ultrasound Available?	Decision Point		LOCKED	If patient in waiting room, then 171, else 172		
171_Escort to US	EscortPatient –> Process		LOCKED		UltraArea	conveyor OR Nurse
172_Transport to US	EscortPatient –> Process		LOCKED		UltraArea	conveyor OR Nurse
173_US Testing	Process	Ultra	171 OR 172			
174_Return from US	EscortPatient –> Process		173		Reserved location in activity 172, OR waiting room	conveyor OR Nurse
175_US finished	Process		173 AND 174	100		
180_MRI Available?	Decision Point		LOCKED	If patient in waiting room, then 181, else 182		

Table C.1: Detailed table showcasing the different processes, transports and decisions in the simulation model.

Name	**Type**	**Milestone**	**Predecessors**	**Next Activity**	**Patient Destination**	**Staff Requirements**
181_Escort to MRI	EscortPatient –> Process		LOCKED		MRArea	conveyor OR Nurse
182_Transport to MRI	EscortPatient –> Process		LOCKED		MRArea	conveyor OR Nurse
183_MRI Testing	Process		181 OR 182			
184_MRI Analyze	Process	MRI	183			
185_Return from MRI	EscortPatient –> Process		183		Reserved location in activity 182, OR waiting room	conveyor OR Nurse
186_MRI finished	Process		184 AND 185	100		
190_In bed?	Decision Point	ImagingFinished	LOCKED	If all images is taken, then 200, else 100		
200_Meet with phys 2	Process		LOCKED	300		Physician
300_Consult with Specialist?	Decision Point		LOCKED	If a specialist is need, then 301, else 400		
301_Initiate Contact specialist	Process		LOCKED			Physician
302_Consultation with Specialist by Provider	Process		301	400		Physician
400_Observation Phys?	Decision Point		LOCKED	If physician check-ups is needed, then 410, else 450		
410_Phys observation	Process		LOCKED	400		Physician
450_Observation Nurse?	Decision Point		LOCKED	If nurse check-ups is needed, then 460, else 500		
460_Nurse observation	Process		LOCKED	450		Nurse
500_Treatment?	Decision Point		LOCKED	If treatment, then 510 OR 520 OR 530 OR 540 OR 550 OR 560		
510_NonProvider Treatment	Process	Treatment	LOCKED	600		Nurse
520_Provider Treatment Phys Exec	Process	Treatment	LOCKED	600		Physician
530_Provider Treatment LIS	Process	Treatment	LOCKED	600		Physician
540_Provider Treatment LIS1	Process	Treatment	LOCKED	600		Physician
550_Combined Treatment Nurse Phys Exec	Process	Treatment	LOCKED	600		Nurse and Physician
560_Combined Treatment Nurse LIS	Process	Treatment	LOCKED	600		Nurse and Physician
600_Lab result ready?	Decision Point		LOCKED	If all labs is analyzed, then 605, else 603		
603_Wait for lab results	Process		LOCKED	600		
605_Provider Final Disposition and Notify Patient	Process	FinalDisposition	LOCKED			Physician
606_Which exit?	Decision Point		605	Dependent on decision taken, 610 OR 620 OR 630 OR 640		
610_Discharge	Decision Point		LOCKED			
611_Provider Prepares Discharge Paperwork	Process		610			Physician

Table C.1: Detailed table showcasing the different processes, transports and decisions in the simulation model.

Name	Type	Milestone	Predecessors	Next Activity	Patient Destination	Staff Requirements
612_Wait for family members	Process		611			
613_Transport to Main Exit	Patient Travels Unattended	Departure	612		PatientExitArea	
620_Admit	Decision Point		LOCKED			
621_Provider Prepares Admission Report	Process		620			Physician
622_Nurse Completes Hand-off Papers	Process		621			Nurse
623_Nurse ask ward for free space	Process		622			Nurse
624_Wait for free space	Process		623			
625_Ask for conveyor	Process		624			Nurse
626_Wait for conveyor	Process		625			
627_Transport to admit exit	Patient Travels Unattended	Departure	626		AdmitExit	
630_Expire	Decision Point		LOCKED			
631_Provider Notify Family	Process		630			Physician
632_Postmortem Care and Prep	Process		631			Nurse
633_Postmortem Documentation	Process		632			Nurse
634_Ask for conveyor	Process		633			Nurse
635_Wait for conveyor	Process		634			
636_Patient transported out	Patient Travels Unattended	Departure	635		Mors	
640_Observation	Decision Point		LOCKED			
641_Provider Prepares Observation Report	Process		640			Physician
642_Ask for observation bed	Process		641			
643_Wait for observation bed	Process		642			Nurse
644_Ask for conveyor	Process		643			Nurse
645_Wait for conveyor	Process		644			
646_Patient Transported Out	Patient Travels Unattended	Departure	645		Observation	

C.4 Staff Schedules

Table C.2: Medical physicians in the ED

Where	Who	Room	Team	Schedule
Area 1 & 2	Phys.Exec			
	LIS			
	LIS1			
Area 3	Phys.Exec	Triage		
	Phys.Exec	Poly + Phone		
	LIS1			12:00 - 21:00
	LIS1			12:00 - 21:00
Area 4	Phys.Exec	Helps in Area 3		
	LIS	Helps in Area 3		
	LIS1	Helps in Area 3		

Table C.3: Other physicians in the ED

Who	Field	Schedule
Phys.Exec	Surgery	
Phys.Exec	Surgery	
Phys.Exec	Surgery	
LIS1	Surgery	
LIS1	Surgery	Weekdays 07:00 - 15:00
LIS1	Surgery	Weekdays 12:00 - 20:00
Phys.Exec	Neurologist	
Phys.Exec	Neurologist	Weekdays 17:00 - 19:00
Phys.Exec	Neurologist	Weekdays 17:00 - 19:00
LIS	Neurologist	

Table C.4: Nurse schedule in all areas at weekdays

Where	Who	Room	Team	*Hours*																																	
				00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	07:15	07:30	07:45	08:00	09:00	10:00	11:00	12:00	13:00	14:00	14:15	14:30	14:45	15:00	16:00	17:00	18:00	19:00	20:00	21:00	21:15	21:30	21:45	22:00	23:00	24:00
Area 1	Spl1-1	3 + Hallway									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
	Spl1-2	3 + Hallway									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
	Spl1-3		Traume								▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
	Spl1-4	3 + Hallway																					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Spl1-5	3 + Hallway																					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Spl1-6		Traume																				▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Spl1-7	3 + Hallway		▨	▨	▨	▨	▨	▨	▨	▨	▨																					▨	▨	▨	▨
	Spl1-8	3 + Hallway		▨	▨	▨	▨	▨	▨	▨	▨	▨																					▨	▨	▨	▨
	Spl1-9		Traume	▨	▨	▨	▨	▨	▨	▨	▨	▨																					▨	▨	▨	▨
Area 2	Spl2-1	3 + Hallway									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
	Spl2-2	3 + Hallway									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
	Spl2-3		MAT+Trombo								▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
	Spl2-4	3 + Hallway																					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Spl2-5	3 + Hallway																					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Spl2-6		MAT+Trombo																				▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Spl2-7	3 + Hallway		▨	▨	▨	▨	▨	▨	▨	▨	▨																					▨	▨	▨	▨
	Spl2-9		MAT+Trombo	▨	▨	▨	▨	▨	▨	▨	▨	▨																					▨	▨	▨	▨
Area 3	Spl3-1	Triage									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
	Spl3-2	Triage	Heart+MAT								▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
	Spl3-3	Poly									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
	Spl3-4	Triage																▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨								
	Spl3-5	Registation																▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨								
	Spl3-6	Poly																	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨							
	Spl3-7	Triage																					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Spl3-8	Triage																					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Spl3-9	Triage	Heart+MAT																				▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Spl3-10	Poly																					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Spl3-11	Triage	Heart+MAT	▨	▨	▨	▨	▨	▨	▨	▨	▨																					▨	▨	▨	▨
	Spl3-12	Poly		▨	▨	▨	▨	▨	▨	▨	▨	▨																					▨	▨	▨	▨
	Spl3-13	All	MAT+Trombo	▨	▨	▨	▨	▨	▨	▨	▨	▨																					▨	▨	▨	▨
Area 4	Spl4-1	3									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
	Spl4-2	3									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
	Spl4-3	Area 4																	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨							
	Spl4-4	3																					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Spl4-5	3																					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Spl4-6	3		▨	▨	▨	▨	▨	▨	▨	▨	▨																					▨	▨	▨	▨
	Spl4-7	3		▨	▨	▨	▨	▨	▨	▨	▨	▨																					▨	▨	▨	▨

Table C.5: Nurse schedule in all areas at weekends

Where	**Who**	**Room**	**Team**	***Hours***																																	
				00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	07:15	07:30	07:45	08:00	09:00	10:00	11:00	12:00	13:00	14:00	14:15	14:30	14:45	15:00	16:00	17:00	18:00	19:00	20:00	21:00	21:15	21:30	21:45	22:00	23:00	24:00
Area 1	Spl1-1	3 + Hallway									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
	Spl1-2	3 + Hallway									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
	Spl1-3		Traume								▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
	Spl1-4	3 + Hallway																					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Spl1-5	3 + Hallway																					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Spl1-6		Traume																				▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Spl1-7	3 + Hallway		▨	▨	▨	▨	▨	▨	▨	▨	▨																					▨	▨	▨	▨
	Spl1-8	3 + Hallway		▨	▨	▨	▨	▨	▨	▨	▨	▨																					▨	▨	▨	▨
	Spl1-9		Traume	▨	▨	▨	▨	▨	▨	▨	▨	▨																					▨	▨	▨	▨
Area 2	Spl2-1		MAT+Trombo								▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
	Spl2-2		MAT+Trombo																				▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Spl2-3		MAT+Trombo	▨	▨	▨	▨	▨	▨	▨	▨	▨																					▨	▨	▨	▨
Area 3	Spl3-1	Triage									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
	Spl3-2	Triage	Heart+MAT								▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
	Spl3-3	Poly									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
	Spl3-4	Triage																					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Spl3-5	Triage	Heart+MAT																				▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Spl3-6	Poly																					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Spl3-7	Triage	Heart+MAT	▨	▨	▨	▨	▨	▨	▨	▨	▨																					▨	▨	▨	▨
	Spl3-8	Poly		▨	▨	▨	▨	▨	▨	▨	▨	▨																					▨	▨	▨	▨
Area 4	Spl4-1	3									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
	Spl4-2	3									▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨												
	Spl4-3	3																					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Spl4-4	3																					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Spl4-5	3		▨	▨	▨	▨	▨	▨	▨	▨	▨																					▨	▨	▨	▨
	Spl4-6	3		▨	▨	▨	▨	▨	▨	▨	▨	▨																					▨	▨	▨	▨

C.5 Times on different activities in the Simulation Model

Table C.6: Times for the different activities in the simulation model

Process Step	PCI 1 (Green)	PCI 2 (Yellow)	PCI 3 (Orange)	PCI 4 (Red)	PCI 5 (Trauma)
1_Registration walk-in	T(3,6,5)	T(3, 6,5)	T(3, 6,5)	T(3, 6,5)	0
2_Registration EMS	0	T(1, 3, 2)	T(1, 3, 2)	T(1, 3, 2)	0
3_Release EMS Personnel	0	T(1.0, 3.0, 2.0)	T(1.0, 3.0, 2.0)	T(1.0, 3.0, 2.0)	0
4_CT Trauma Test Time	0	0	0	0	T(20,60,30)
5_CT Trauma Analyze Time	0	0	0	0	T(3,60,18)
6_Treatment	0	0	0	0	T(12.3,217.5,31.1)
7_Conduct Triage on patient internal medicine	T(12,17,14)	T(12,17,14)	T(12,17,14)	T(12,17,14)	0
8_Conduct Triage on patient surgical	T(6,15,12)	T(6,15,12)	T(6,15,12)	T(6,15,12)	0
9_Conduct Triage on patient orthopedic	T(6,15,12)	T(6,15,12)	T(6,15,12)	T(6,15,12)	0
10_Conduct Triage on patient neurological	T(6,15,12)	T(6,15,12)	T(6,15,12)	T(6,15,12)	0
11_Conduct Triage on patient others	T(6,15,12)	T(6,15,12)	T(6,15,12)	T(6,15,12)	0
12_Send Sample to Central Lab	T(0.30, 1, 0.45)	T(0.30, 1, 0.45)	T(0.30, 1, 0.45)	T(0.30, 1, 0.45)	0
13_Central Lab Total Turnaround Time	empirical(”labs”)	empirical(”labs”)	empirical(”labs”)	empirical(”labs”)	0
14_Post-Triage Documentation	T(4,6,5)	T(4,6,5)	T(4,6,5)	T(4,6,5)	0
15_Prepare bed	T(2,8,5)	T(2,8,5)	T(2,8,5)	T(2,8,5)	0
16_Get Patient Settled 1 nurse	T(6,8,7)	T(6,8,7)	T(6,8,7)	T(6,8,7)	0
17_Get Patient Settled 2 nurses	T(4,6,5)	T(4,6,5)	T(4,6,5)	T(4,6,5)	0
18_Retrieve extra EQ	T(1,3,2)	T(1,3,2)	T(1,3,2)	T(1,3,2)	0
19_Administer EQ	T(3,7,4)	T(3,7,4)	T(3,7,4)	T(3,7,4)	0
20_Post bed documentation	T(2,6,5)	T(2,6,5)	T(2,6,5)	T(2,6,5)	0
21_Initial Assessment by Provider, initiate order Phys.Exce	T(8, 15, 12)	T(8, 15, 12)	T(8, 15, 12)	T(8, 15, 12)	0
22_Initial Assessment by Provider, initiate order LIS	T(10, 20, 15)	T(10, 20, 15)	T(10, 20, 15)	T(10, 20, 15)	0
23_Initial Assessment by Provider, initiate order LIS1	T(15, 25, 20)	T(15, 25, 20)	T(15, 25, 20)	T(15, 25, 20)	0
24_Post Assessment documentation	T(6, 8, 7)	T(6, 8, 7)	T(6, 8, 7)	T(6, 8, 7)	0
25_Retrieve Meds from Storage	T(2, 4, 3)	T(2, 4, 3)	T(2, 4, 3)	T(2, 4, 3)	0
26_Administer Storage Meds to Patient	T(2,10,4)	T(2,10,4)	T(2,10,4)	T(2,10,4)	0
27_Post meds documentation	T(4,6,5)	T(4,6,5)	T(4,6,5)	T(4,6,5)	0
28_Draw lab sample	beta(2.34,9.02,0.26,0.42)	beta(2.34,9.02,0.26,0.42)	beta(2.34,9.02,0.26,0.42)	beta(2.34,9.02,0.26,0.42)	0
29_Send Sample to Central Lab	T(1,3,2)	T(1,3,2)	T(1,3,2)	T(1,3,2)	0
30_Post-Labs Documentation	T(3, 7, 4)	T(3, 7, 4)	T(3, 7, 4)	T(3, 7, 4)	0
31_X-Ray testing	T(5, 15, 10)	T(5, 15, 10)	T(5, 15, 10)	T(5, 15, 10)	0
32_X-Ray analyze Time	T(3,10,5)	T(3,10,5)	T(3,10,5)	T(3,10,5)	0
33_CT testing	T(20,60,30)	T(20,60,30)	T(20,60,30)	T(20,60,30)	0
34_CT analyze Time	T(3,60,18)	T(3,60,18)	T(3,60,18)	T(3,60,18)	0
35_CTwC prep	T(1, 3, 2)	T(1, 3, 2)	T(1, 3, 2)	T(1, 3, 2)	0
36_CTwC testing	T(20,60,30)	T(20,60,30)	T(20,60,30)	T(20,60,30)	0
37_CTwC analyze Time	T(3,60,18)	T(3,60,18)	T(3,60,18)	T(3,60,18)	0
38_Ultrasound testing	T(20, 40, 30)	T(20, 40, 30)	T(20, 40, 30)	T(20, 40, 30)	0
39_MRI testing	T(25, 50, 30)	T(25, 50, 30)	T(25, 50, 30)	T(25, 50, 30)	0
40_MRI analyze Time	T(9, 35, 18)	T(9, 35, 18)	T(9, 35, 18)	T(9, 35, 18)	0
41_Provider Reviews Results and Makes Initial Disposition	T(5, 15, 12)	T(5, 15, 12)	T(5, 15, 12)	T(5, 15, 12)	0
42_Initiate Contact with Specialist	T(4, 6, 5)	T(4, 6, 5)	T(4, 6, 5)	T(4, 6, 5)	0

43_Consultation with Specialist by Provider	T(4,10,5)	T(4,10,5)	T(4,10,5)	T(4,10,5)	0
44_NonProvider Treatment	T(15,30,20)	T(15,30,20)	T(15,30,20)	T(15,30,20)	0
45_Provider Treatment Phys.Exce	T(5,15,8)	T(5,15,8)	T(5,15,8)	T(5,15,8)	0
46_Provider Treatment LIS	T(7.5,22.5,12)	T(7.5,22.5,12)	T(7.5,22.5,12)	T(7.5,22.5,12)	0
47_Provider Treatment LIS1	T(10,30,16)	T(10,30,16)	T(10,30,16)	T(10,30,16)	0
48_Combined NonProvider and Provider Treatment Phys.Exce	T(5,10,6)	T(5,10,6)	T(5,10,6)	T(5,10,6)	0
49_Combined NonProvider and Provider Treatment LIS	T(7.5,15,9)	T(7.5,15,9)	T(7.5,15,9)	T(7.5,15,9)	0
50_Combined NonProvider and Provider Treatment LIS1	T(10,20,12)	T(10,20,12)	T(10,20,12)	T(10,20,12)	0
51_Physician or nurse look after patient Physician or nurse	T(3,9,5)	T(3,9,5)	T(3,9,5)	T(3,9,5)	0
52_Provider Final Disposition and Notify Patient	T(8,12,10)	T(8,12,10)	T(8,12,10)	T(8,12,10)	T(8,12,10)
53_Provider Prepares Discharge Paperwork	T(3,5,4)	T(3,5,4)	T(3,5,4)	T(3,5,4)	T(3,5,4)
54_Wait for family members	T(10, 30, 18)	T(10, 30, 18)	T(10, 30, 18)	T(10, 30, 18)	T(10, 30, 18)
55_Provider Prepares Admission Report	T(4,6,5)	T(4,6,5)	T(4,6,5)	T(4,6,5)	T(4,6,5)
56_Nurse Completes Handoff Papers	T(3,5,4)	T(3,5,4)	T(3,5,4)	T(3,5,4)	T(3,5,4)
57_Nurse ask department to transfer patient	T(0.30, 1, 0.45)	T(0.30, 1, 0.45)	T(0.30, 1, 0.45)	T(0.30, 1, 0.45)	T(0.30, 1, 0.45)
58_Wait for free space	beta(-44.9,236.7,148.8,374.9)	beta(-44.9,236.7,148.8,374.9)	beta(-44.9,236.7,148.8,374.9)	beta(-44.9,236.7,148.8,374.9)	beta(-44.9,236.7,148.8,374.9)
59_Ask for conveyor Nurse	T(0.30,1,0.45)	T(0.30,1,0.45)	T(0.30,1,0.45)	T(0.30,1,0.45)	T(0.30,1,0.45)
60_Waiting for conveyor Conveyor	T(23, 27, 25)	T(23, 27, 25)	T(23, 27, 25)	T(23, 27, 25)	T(23, 27, 25)
61_Provider Notify Family	T(3, 10, 5)	T(3, 10, 5)	T(3, 10, 5)	T(3, 10, 5)	T(3, 10, 5)
62_Postmortem Care and Prep	T(3, 10, 5)	T(3, 10, 5)	T(3, 10, 5)	T(3, 10, 5)	T(3, 10, 5)
63_Provider Postmortem Documentation	T(3,5,4)	T(3,5,4)	T(3,5,4)	T(3,5,4)	T(3,5,4)
64_Ask for conveyor Nurse	T(0.30,1,0.45)	T(0.30,1,0.45)	T(0.30,1,0.45)	T(0.30,1,0.45)	T(0.30,1,0.45)
65_Waiting for conveyor Conveyor	T(23, 27, 25)	T(23, 27, 25)	T(23, 27, 25)	T(23, 27, 25)	T(23, 27, 25)
66_Provider prepares observation report	T(3,10,4)	T(3,10,4)	T(3,10,4)	T(3,10,4)	T(3,10,4)
67_Ask for observation bed	T(0.30,1,0.45)	T(0.30,1,0.45)	T(0.30,1,0.45)	T(0.30,1,0.45)	T(0.30,1,0.45)
68_Wait for observation bed	beta(-44.9,236.7,148.8,374.9)	beta(-44.9,236.7,148.8,374.9)	beta(-44.9,236.7,148.8,374.9)	beta(-44.9,236.7,148.8,374.9)	beta(-44.9,236.7,148.8,374.9)
69_Ask for conveyor Nurse	T(0.30,1,0.45)	T(0.30,1,0.45)	T(0.30,1,0.45)	T(0.30,1,0.45)	T(0.30,1,0.45)
70_Waiting for conveyor Conveyor	T(23, 27, 25)	T(23, 27, 25)	T(23, 27, 25)	T(23, 27, 25)	T(23, 27, 25)

Appendix D Implemented Constraints

The following figures show feasible locations for different functions to be allocated within the ED. All locations covering one location with a flow can be located everywhere in the ED, thus not shown in a figure. Triage, outpatient clinic and the waiting rooms also have the ability to be located anywhere in the ED.

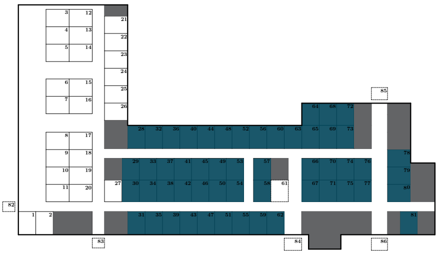


Figure D.1: Feasible locations for Care room area 1 and 2 to cover.

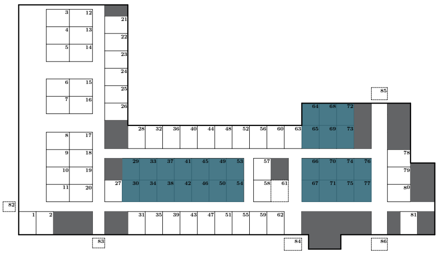


Figure D.2: Feasible locations for Care room area 4 to cover

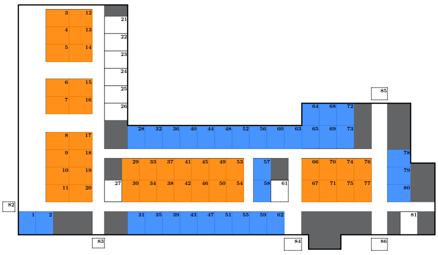


Figure D.3: Feasible locations for imaging resources to cover. All imaging resources can cover the orange locations, while only the x-rays and ultrasound can cover the blue.

Figure D.4: Feasible locations for the trauma bay, indicated in red, and reception indicated in dark green.

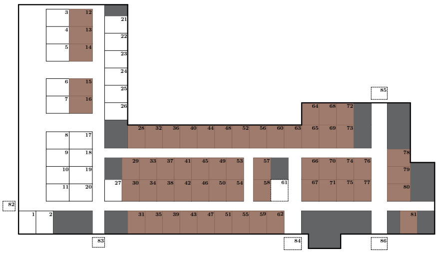


Figure D.5: Feasible locations for the employee rooms to cover.

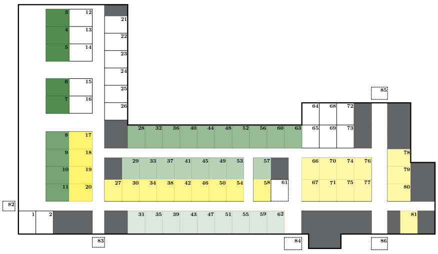


Figure D.6: Feasible locations for the storage rooms in green and the bathrooms in yellow. The different shades of each color indicate where the different storage rooms and bathrooms can be allocated.

Appendix E Case Study Layout

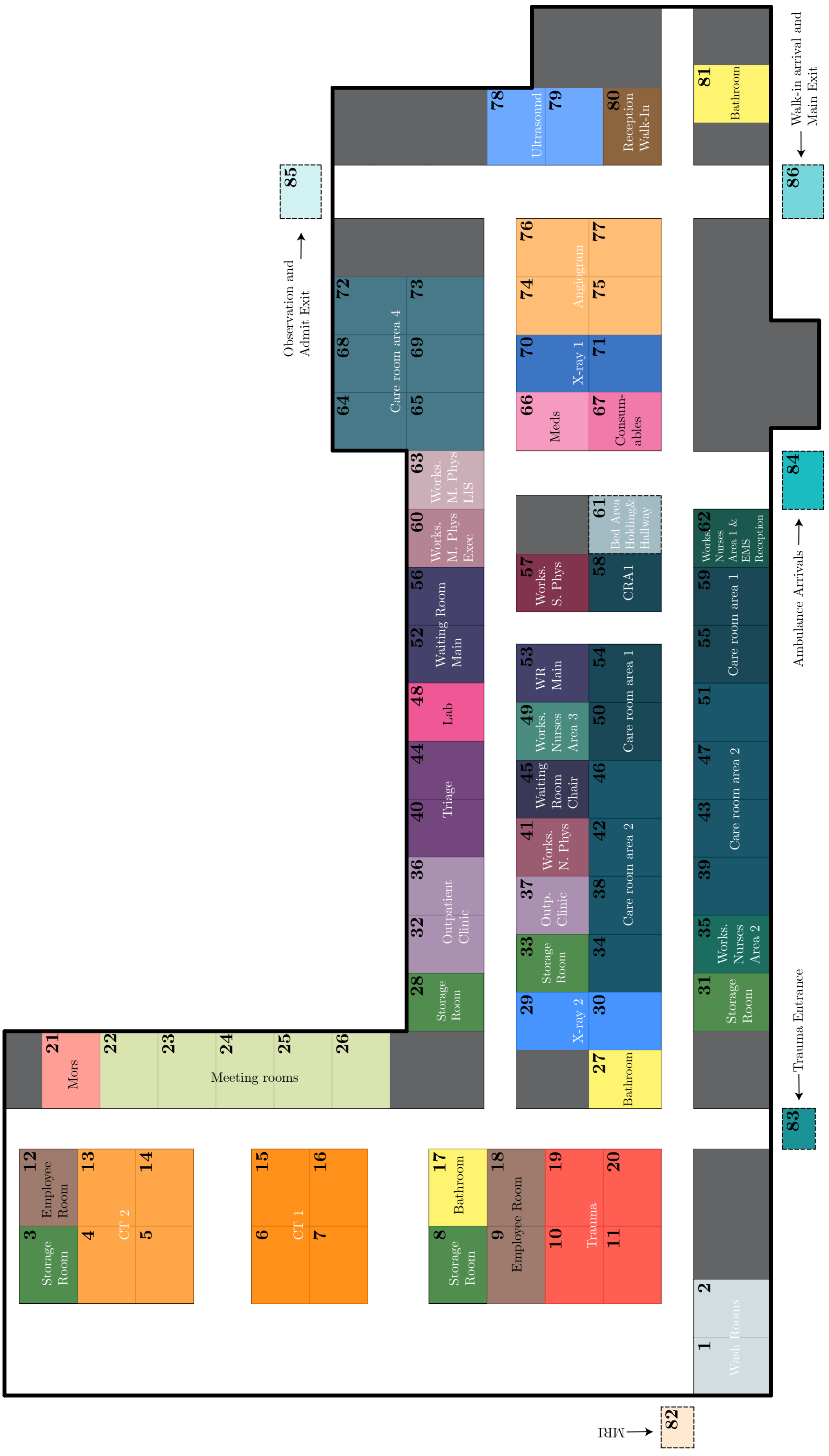


Figure E.1: Large image of the layout presented in the Case Study.

Tore Bjørseth Berdal, Erlend Moian Nydal

NTNU
Norwegian University of
Science and Technology