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All eyes on the blueprint schedule

ILP-based optimisation of UMC Utrecht's ophthalmology staff schedule

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Preface

This thesis marks the final step in completing my master's in Industrial Engineering and Management at University of Twente. It reflects months of research, analysis, and practical application in the field of operations management in healthcare.

This thesis marks the conclusion of my time as a student at the University of Twente. It has been a wonderful period during which I have had the chance to develop both academically and personally. I have thoroughly enjoyed gaining new experiences, engaging in various extracurricular activities, and making valuable friendships throughout the years. I greatly appreciated studying at a personal and student-focused university with an inspiring atmosphere fostering personal development.

This research would not have been possible without the support and guidance of the people around me. I would like to extend my gratitude to my supervisors, Erwin and Gréanne, for their feedback, interesting discussions, and expertise in the field throughout my research. Additionally, I want to thank my colleagues in the integral capacity management team (ICM) at UMC Utrecht for teaching me about ICM in healthcare in practice and the ophthalmology department for the opportunity to learn more about the healthcare process. I am grateful for the contact with my external supervisor, Suzanne, and for the opportunity to always reach out with questions, brainstorm ideas, or have a chat. Finally, I am grateful to my family, friends, and boyfriend for their encouragement and genuine interest in this thesis.

I hope this thesis provides useful insights into staff scheduling in healthcare and inspires further exploration in this area. I look forward to contributing to operations management in healthcare in the years to come to maintain a high-quality and accessible healthcare system.

Fleur Korving
January 2025

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Management summary

Ophthalmology department UMC Utrecht

This research focuses on the outpatient clinic of the ophthalmology department of University Medical Centre Utrecht, an academic hospital in the Netherlands. The ophthalmology outpatient clinic is one of the biggest in the hospital, with 26,000 appointments annually, providing care and research for maintaining eye health and treating complex eye disorders. The conditions and delivered healthcare at the department have become more complex and academic due to the triage of the complexity of the conditions seen. Patients with complex conditions continued to be seen, and other patients were referred to general hospitals. Ophthalmology is a comprehensive department, as it is a surgical speciality with a functional unit and many professionals. A high number of patients are seen at the department, and to meet this care demand, the outpatient clinic's professionals follow a monthly schedule that assigns the professionals to activities such as consultation hours, surgeries, and research.

Problem statement

The department facilitates training for residents to become medical specialists in the field of ophthalmology. The current way of working, where residents are supervised by a general whilst seeing patients individually, is not as educational as desired. The assigned supervisor is often unavailable due to scheduling infeasibility or incompatible subspecialty, which does not suit the increasing complexity of care. A new setup for the consultation hours has therefore been proposed. This change in the way of working needs to be implemented in the blueprint schedule, the concept schedule on which the monthly schedule is based. This change cannot be made currently, as the blueprint schedule contains twenty-three unscheduled activities and requires many adjustments to create a feasible schedule. As a result, the healthcare professionals, including the residents, are working with a schedule that does not adequately fit the current situation of the ophthalmology department. Additionally, many reallocations are needed in the schedule, therefore, the schedule feels unstable for the professionals during the planning horizon. The reallocations allow the department to see fewer patients, and the residents to attend fewer educational activities. Therefore, our objective is the following:

To develop a method for optimising the scheduling of professionals at the ophthalmology outpatient clinic to improve the suitability and stability of the blueprint schedule

Methodology

We propose a three-step approach. First, we perform a systematic literature review to obtain methods for solving staff-scheduling planning problems in an outpatient clinic. Second, we develop an integer linear programming model using AIMMS software to optimise the schedule by minimising the number of unscheduled activities. The model aims to create a feasible schedule by assigning professionals to specific activities within a time slot. Using constraints, the model complies with the requirements and characteristics of the department. Third, we evaluate the performance of our model through computational experiments.

Results computational experiments

We evaluate the schedule generated by the model using input values representing the current real-world situation of the department based on our KPIs: the number of patients seen per week, the number of unscheduled activities, and the number of educational activities scheduled. The weekly number of patients seen increases slightly to 512. All activities can be scheduled, which is a significant improvement compared to the current twenty-three unscheduled activities in the blueprint schedule. The number of monthly educational activities increases by 41.7%, reaching 210. The experiments highlighted the model's ability to adapt to varying professionals' availability, available rooms, scheduling restrictions and the number of residents assigned. The experiments show a decrease in model performance on the KPIs when the presence and capacity of the professionals are lowered.

Conclusions and discussion

Our model significantly increases schedule stability by the ability to schedule all activities instead of twenty-three unscheduled activities in the current situation. Our model can improve training quality for residents by increasing scheduled educational activities and resource utilisation by keeping the weekly number of patients seen stable. Furthermore, allows the department to create a schedule that is suitable for their current care and educational processes. However, the model is not robust enough to address changes in professional capacity and presence, and we recommend extending the model to identify shortages in professionals with specific specialities or competencies.

Implementation

We provide the department with instructions on how to implement the model in the planning process of the department. Next, our study complements UMC Utrecht's efforts to improve tactical planning in outpatient clinics as our model facilitates responding to fluctuating care demand and capacity, helps to reduce the waiting list, and provides more insight into the number of patients seen. Last, as a supplement to our model, we provide scheduling guidelines, e.g., requesting absence. This allows ophthalmology outpatient clinic professionals to operate with stability in their schedule.

List of Acronyms

DES	Discrete event simulation
DHS	Division of surgical specialties
HER	Electronic Health Record
HiX	Healthcare information eXchange
ICM	Integral capacity management
ILP	Integer linear programming
KPI	Key performance indicator
MIP	Mixed integer programming
OCT	Optical coherence tomography
OR	Operations research
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
TOA	Technical ophthalmology assistant
UMC Utrecht	University Medical Centre Utrecht
UU	Utrecht University

1. Introduction

This research report addresses the problems with the staff scheduling at the ophthalmology department of UMC Utrecht, an academic hospital in the Netherlands. This first chapter presents the research plan and is structured as follows. Section 1.1 introduces the context of this research. Section 1.2 discusses the motivation for this research. Section 1.3 discusses the problem statement. Section 1.4 discusses the statement of the research objective and questions.

1.1 Context

In this section, we discuss the context of our research by elaborating on the concerned organisation and department.

University Medical Centre Utrecht (UMC Utrecht) is one of the biggest hospitals in the Netherlands, employing around 12.000 staff, of which 1,000 are in research (cited from "Organisatie", n.d.). It is an academic hospital affiliated with Utrecht University (UU). Therefore, research and education are pillars of UMC Utrecht, next to healthcare. UMC Utrecht comprises the academic hospital, the Wilhelmina Children's Hospital, and the Faculty of Medication of UU. Every year, 220.000 unique patients are seen for treatment and/or diagnostics. In 2023, 28,000 clinical hospital intakes, 87,000 first visits to the outpatient clinic and 33,000 operating room treatments took place (cited from "Jaarverslag 2023", n.d.). UMC Utrecht aims to deliver innovative medical treatment to its patients and strives for high-quality care, research, and education (cited from "Organisatie," n.d.).

This research focuses on the ophthalmology department. Ophthalmology belongs to the Division of Surgical Specialties (DHS) of UMC Utrecht (cited from "Oogheelkunde polikliniek," n.d.). Ophthalmology is 'the speciality that focuses on the prevention, recognition, diagnosis and treatment of disorders and diseases of the eye, of the visual system, of the eyelids, of the tear ducts and the eye socket (cited from "Oogheelkunde specialisme," n.d.). As diminished vision has a big negative impact on one's life, ophthalmology can significantly contribute to maintaining the quality of life (World Health Organisation, n.d.). The ophthalmology department of UMC Utrecht offers highly specialised care for diagnosing and treating (acute) complex eye disorders. Ophthalmology has one of the largest outpatient clinics in the hospital, with some 70,000 appointments, 8,000 initial consultations and 3,500 surgeries annually (cited from "Oogheelkunde specialisme", n.d.). The ophthalmology department consists of an outpatient clinic, an inpatient clinic, and a diagnostic department. To provide high-quality care, medical specialists, residents, orthoptists, optometrists, nurses, technical ophthalmic assistants (TOA), doctor's assistants, and medical secretaries work closely together in the outpatient clinic and the diagnostic department of the ophthalmology department. The care delivered at the department is rewarded with an 8.2 out of 10 by their patients. Besides care, the department conducts scientific research and provides medical education to residents in training to become an ophthalmologist.

This research will be conducted for the outpatient clinic of the ophthalmology department in collaboration with the integral capacity management (ICM) department of UMC Utrecht. ICM strives for a comprehensive approach that optimises the utilisation of healthcare professionals, facilities, and resources to enhance the hospital's care delivery. ICM is currently working on a project called 'Tactical Planning in the Outpatient Clinic,' aiming to improve the alignment of the demand for care with the capacity of outpatient clinics. The research is executed with the support of the unit manager of the

DHS. He is responsible for the division's outpatient clinics and, therefore, for the ophthalmology outpatient clinic. Last, the department's professionals will be frequently consulted throughout the research.

1.2 Research Motivation

This section discusses the research motivation and elaborates on the relevance of the research.

Improving the scheduling of healthcare professionals is becoming increasingly important in healthcare nowadays. The demand for healthcare in the Netherlands will continue to rise in the coming decades, partly due to the ageing population, the increase in chronic illnesses, and lifestyle factors such as obesity (RIVM, 2023). Next to that, the shortages of qualified healthcare professionals are high and rising. De Visser et al. (2021) stated that in 2060, one out of three employees should work in healthcare, compared to the current number of one out of seven. Besides, healthcare costs are rising, mainly due to the higher demand for healthcare services, advancements in medical technology, and the development of more expensive treatments (Zorginstituut Nederland, 2024). In conclusion, the pressure on the Dutch healthcare system is high, and it faces the challenge of maintaining the current high quality and accessibility of patient care.

With the capacity of healthcare professionals being a big challenge, improving the scheduling of the professionals can help. An efficient schedule can make the best use of available professionals. This reduces unnecessary costs and improves efficiency. Furthermore, the workload of healthcare professionals is high, partly due to the shortages (Friele, 2024). Therefore, providing professionals with a stable schedule is important to maintain work satisfaction (Holden et al., 2011). Poorly managed schedules can lead to a higher workload as the professionals may have to work overtime or reallocate tasks. By improving the scheduling, healthcare facilities can better balance the workload, help to reduce stress and improve job satisfaction of the increasingly scarce healthcare professionals.

1.3 Problem Description

This section introduces the problem description, the problem, and the stakeholders of our research experience.

The ophthalmology outpatient clinic operates on a monthly schedule, assigning healthcare professionals to tasks on certain days. This schedule is aligned with the agendas of the operating theatre of the hospital (the master surgery schedule) and the support staff of the department. The realised schedule is based on a blueprint schedule containing the same elements, including absenteeism. The schedule for the ophthalmology outpatient clinic is set up for each month by two planning coordinators approximately fourteen weeks before the date.

The ophthalmology department aims to change its way of working. The department strives for this change as the healthcare provided has become more complex. This is because of a triage executed on the waiting list, on the extent of the complexity of care. Patients requiring academic care could still be seen, whereas those with non-academic conditions were referred to general hospitals. This led to the healthcare delivered at the ophthalmology outpatient clinic being too complex for residents to provide independently, while the schedule does not always allow ophthalmologists to supervise. This has led to less educational training for the residents. Therefore, the ophthalmology department strives for supervised consultation hours, including an ophthalmologist and one or two residents. However, such a change is difficult to implement within the current framework of the blueprint schedule.

This is because the department currently faces problems with the practical realisation of the schedule. Many reallocations are needed to make the schedule feasible for each month because of infeasibility and absenteeism. The professionals must change their schedule because of the reallocations, even during the week itself. Therefore, the professionals cannot completely rely on their schedule as it is unstable. This leads to an increased workload experienced by the professionals. The adjustments sometimes lead to fewer available timeslots for patients during a consultation hour, resulting in a longer access time to visit the hospital than the doctor prescribes. It is undesirable, as the department already faces problems with a waiting list. Besides, processing the adjustments is time-consuming and complex, as the professionals have individual requirements. Therefore, the planning coordinators feel they cannot comply with the professional's requests.

In conclusion, the schedule does not comply with the current situation of the ophthalmology department and is unstable due to infeasibility.

1.4 Research objective and questions

In this section, we discuss the research objective and present the research questions, which guide the research toward achieving the objective.

With this research, we aim to develop a method for improving the staff scheduling of healthcare professionals at the ophthalmology outpatient clinic so that the suitability and stability of the schedule can be improved.

To achieve this research objective, the following research questions have been developed:

1) *How is the healthcare process in the ophthalmology department currently organised?*

   In Chapter 2, we obtain a clear view of the current healthcare process within the ophthalmology department of UMC Utrecht through meetings with healthcare professionals, shadowing care processes, data analysis, and literature research. We discuss the personnel and resource types of the department and present the journey of a patient visiting the department. The current planning & control and performance of the ophthalmology department follows this. We discuss the problem analysis and the current improvement projects of UMC Utrecht. We will combine the aforementioned to determine the scope of our research.

2) *How can optimisation techniques and scheduling algorithms be effectively employed to set up a feasible and adjustable schedule for an outpatient clinic?*

   Chapter 3 elaborates on the existing literature on optimisation techniques and scheduling algorithms for staff scheduling at an outpatient clinic. We conduct a systematic literature review to evaluate the research performed in this field and its effects.

3) *How can we generate a feasible model for the ophthalmology outpatient clinic through a comprehensive model?*

   In Chapter 4, we explain how we model the characteristics and requirements of the ophthalmology department into a mathematical model to optimise the planning of healthcare professionals. In Chapter 5, we evaluate our model by computational experiments.

4) *How can we successfully implement the model at the ophthalmology outpatient clinic?*

   In Chapter 6, we discuss our proposed implementation of the model. We align the model with the current planning process and projects. We provide scheduling guidelines to supplement the model.

2. Current situation

This chapter addresses the context of the ophthalmology department, which includes the care and planning processes, performance monitoring, perceived problems, and ongoing improvement efforts. This chapter is structured as follows: Section 2.1 introduces the care process at the ophthalmology department at UMC Utrecht. Section 2.2 discusses the planning and control of the care process. Section 2.3 discusses the performance. Section 2.4 elaborates on the problems experienced by the different stakeholders through a problem analysis. Section 2.5 discusses the current improvement projects enrolled at UMC Utrecht. Section 2.6 discusses the scope of our research.

2.1 Current process

In this section, we discuss the current healthcare process delivered at the ophthalmology department. Subsequently, we will introduce the healthcare professionals and the important resources in the care process. Last, we will discuss the patient journey of a patient visiting the department and the variability in this process.

2.1.1 Healthcare process

Good eye health and clear vision are of significant importance to maintaining one’s quality of life (Assi et al., 2021). A patient can visit a general practitioner or general hospital when experiencing eye health problems or diminished vision. When a patient is visiting a general practitioner or general hospital with a complex eye disorder or needing an advanced eye exam, the patient is referred to an academic hospital for specialised eye care. The ophthalmology department of UMC Utrecht provides third-line care, and since a triage solely treats patients referred from general hospitals (cited from Oogheelkunde verwijsprocedure, n.d.) (Ministerie van Algemene Zaken, 2023). Therefore, healthcare professionals exclusively see patients with complex complaints and eye disorders. The ophthalmology department at UMC Utrecht provides high-quality, top-referral patient care

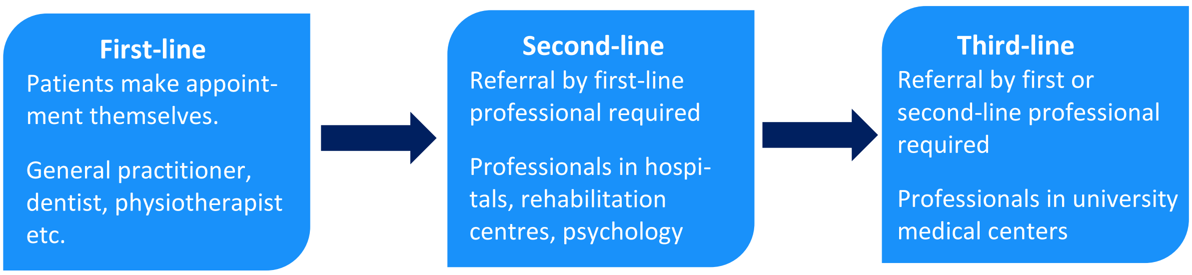


Figure 1: Categories Dutch healthcare system

2.1.2 Personnel and resources

Healthcare professional types

During a visit to the ophthalmology department, a patient sees diverse types of healthcare professionals. This subsection elaborates on the nine types of professionals working at the ophthalmology department of UMC Utrecht. The professionals are the ophthalmologists, residents, optometrists, orthoptists, a nurse practitioner, TOAs, nurses, medical secretaries and doctor's assistants. We provide an overview of the professionals employed in the department, including their main tasks, in Table 1.

Table 1: Types of staff at the ophthalmology department

Staff types	Main tasks
Medical specialist	Diagnose and treat eye conditions, perform surgeries, and supervise. Responsive for patients.
Resident	Assist in patient care and surgeries, retrieve education
Optometrist	Screen eye conditions and conduct eye exams
Orthoptist	Diagnose and treat eye movement disorders
Nurse practitioner	Diagnose and treat eye conditions, provide advanced nursing care
TOA	Conduct diagnostic examinations, support consultations hours
Nurse	Administer medication and educate patients
Medical secretary	Coordinate appointments and patient records, work on administration
Doctor's assistant	Assist medical procedures and perform eye measurements

We will elaborate on each professional type in the following subsection.

First, the ophthalmologists. Ophthalmologists are medical specialists who have specialised training for five years in ophthalmology after their studies in medicine of six years (Churchill et al., 2024). After the ophthalmologist training, one can further specialise in a subspecialty through a fellowship at the department (cited from "Ziektebeelden", n.d.). Currently, nineteen ophthalmologists are employed in the department (cited from "Oogheelkunde polikliniek", n.d.). Ophthalmologists have their focus areas, which can be specific fields in ophthalmology, specific types of surgery, and/ or subspecialties. The role of an ophthalmologist extends from executing consultation hours and performing surgeries to conducting research, attending multidisciplinary meetings, supervising residents, and handling administrative tasks. Ophthalmologists have the responsibility over a patient. The ophthalmologists each have their subspeciality, meaning that only ophthalmologists specialised in a specific subspecialty can perform the consultation hours of a corresponding subspecialty.

Second, the residents. Resident physicians are doctors in training to become ophthalmologists. UMC Utrecht provides training in ophthalmology in cooperation with three regional general hospitals (cited from "Oogheelkunde opleiding", n.d.). A new resident starts the training every three months, resulting in four new residents yearly. Seventeen residents are being trained in the ophthalmology department at UMC Utrecht, and four in the general hospitals (cited from "Oogheelkunde specialisme", n.d.). The training consists of fourteen phases of three months, starting with an introduction and two general phases, followed by each part (orbit, uveitis, pediatric, anterior, and posterior segment) of the ophthalmology twice, once as a junior and once as a senior resident. Afterwards, the residents continue their training in a general hospital for one year, followed by a general and advanced specialisation phase in one of the subspecialties. If a resident misses a phase due to leave, illness, etc., this training phase must be completed after their regular training period. During a training phase, residents perform consultation hours, assist with surgeries, and perform proceedings related to a specific part of ophthalmology. Besides, they retrieve education. The department aims for the residents to attend many elements of the training phase so that the training is as educational as possible. Besides, the training phase of the residents determines which tasks they are allowed to execute (Bard et al., 2016) (Hong et al., 2019).

Third, the optometrists. An optometrist is a care provider that examines eye health and diagnoses vision problems and ocular diseases. Unlike an ophthalmologist, an optometrist cannot prescribe medication or perform medical procedures (Churchill et al., 2024). The two optometrists at the department cooperate with the medical specialist for the allergy, transplantation and glaucoma consultation hours. The optometrists also perform examinations in the diagnostic department, such as fundoscopy, corneal topography, optical coherence tomography (OCT) scans, and fluorescein angiograms.

Fourth, the orthoptists. An orthoptist diagnoses and treats eye movement disorders and the collaboration of the eyes (Catharina Ziekenhuis, n.d.) (Huzzey, 2022). These can be caused by defects in the muscles around the eyes or nerves. Five orthoptists work at the ophthalmology department and cooperate with the medical specialist to execute the orbit, paediatric, cataract, and pre-post consultation hours.

Fifth, a nurse practitioner. A nurse practitioner provides advanced nursing care and manages patient care (Beroepsvereniging voor Verpleegkundig Specialisten, n.d.). One nurse practitioner works at the department and is involved in performing the transplantation and orbit consultation hours. She sees her own patients, for instance, with a tumour of the orbits or eyelids. The nurse practitioner can diagnose, treat, and prescribe medication, while the ophthalmologist remains responsible for the patient.

Sixth, the technical ophthalmologic assistants. A TOA independently performs eye examinations, such as eye measurements, visual field tests, and echography (Oogvereniging, n.d.). They also assist with minor procedures and administer eye drops. A TOA is essential for conducting various examinations in the diagnostic department.

Seventh, the nurses. A nurse in the department specialised in ophthalmology. They educate the patients and perform medical-technical procedures.

Eighth, the medical secretaries. The medical secretaries at the ophthalmology department are responsible for scheduling the patients for an appointment slot during the consultation hours. The medical secretary belongs to a specific subspeciality of the ophthalmology department and knows the details about this subspeciality. Besides, the medical secretaries serve as the point of contact for patients, mainly when the patients arrive at the reception of the outpatient clinic (Oogvereniging, n.d.). They verify the information of patients and manage the administration and phone calls.

Ninth, the doctor’s assistants. The doctor’s assistants perform general eye measurements and administer eye drops. They also assist a medical specialist/ resident with medical procedures by removing stitches, preparing materials, etcetera. The doctor’s assistants guide the patients and perform administrative tasks.

Resource types

When visiting the ophthalmology department, there are four locations the patient can visit: the outpatient clinic, diagnostic department, nursing ward, and operating theatre. We will elaborate on them in this subsection.

First, the outpatient clinic. The ophthalmologists, residents, orthoptists, and nurse practitioner work at the outpatient clinic (cited from “Oogheelkunde polikliniek”, n.d.). The ophthalmology outpatient contains thirty rooms. Thirteen consultation rooms contain the specific equipment the staff needs to see patients during a consultation hour, such as a split lamp. The other rooms are equipped for specific treatments or supporting consultations. Therefore, the outpatient clinic's activities must occur in certain rooms. Some rooms are rented out for educational activities during the week. At these moments, they are unavailable for the activities of the ophthalmology outpatient clinic.

Second, the diagnostic department. The optometrists, nurses, TOAs, and doctor’s assistants work in the diagnostic department. At the diagnostic department, all ophthalmologic examinations are executed with special equipment, such as OCT scans, electroretinography, and fluorescein angiograms (cited from “Onderzoeken”, n.d.). The outcomes of these examinations help the ophthalmologists and residents diagnose and set up a treatment. The diagnostic department is located next to the outpatient clinic.

Third, the nursing ward. Patients with ophthalmic conditions are admitted after surgery in the ophthalmology nursing ward. The nursing ward is on another floor than the outpatient clinic and diagnostic department. One or two ophthalmology patients stay in the nursing ward every day.

Fourth, the operating theatre. For ophthalmology, there is a set availability of one or two operating rooms daily for surgeries in the operating theatre. The surgery is performed by a medical specialist and eventually supported by a resident. Surgical assistants of the operating theatre assist with the surgeries, and in general anaesthesia, they are performed by anaesthetists. The OR department of UMC Utrecht operates on a yearly blueprint and a realisation schedule. The blueprint assigns all surgical departments of UMC Utrecht to an OR on a day for an entire year. There is a small chance for these slots to get cancelled. This is shown in a realisation schedule released twelve weeks before the date. As the operating time is critical to the ophthalmology department, they always ensure that a medical specialist and a resident are available at this slot to perform the surgeries.

2.1.3 Patient journey

This subsection describes the journey of the diverse types of patients visiting the ophthalmology department. The patient journeys are visualised in flowcharts and presented in Appendix C. Figure 2 shows an example of the patient journey flowcharts, for a recurrent patient seeing a resident.

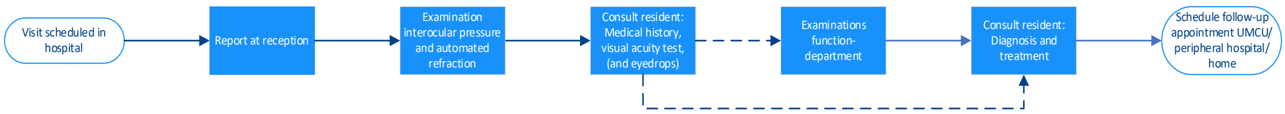


Figure 2: Patient journey flowchart of a recurrent patient visiting a resident

New patient

After the referral by a general hospital, the patient is called by a doctor's assistant or medical secretary of the ophthalmology department to schedule an appointment during a consultation hour with a doctor: an ophthalmologist or a resident (cited from "U bent verwezen", n.d.). A patient's medical data is reported in the electronic health record of UMC Utrecht, Healthcare Information eXchange (HiX). The patient is assigned an appointment slot during the consultation hour of a medical specialist in one particular subspeciality or during the consultation of a resident, where multiple subspecialties are combined. A consultation hour takes place in the morning from 8:30h to 12:00h and from 13:00h to 16:30h. Currently, the access time for an appointment is longer than desired due to a waiting list at the department (cited from "Oogheelkunde polikliniek", n.d.).

On the day of the appointment, the patient reports to the reception of the ophthalmology department. The patient reports their presence there, which the medical secretary records in the electronic health record. In this way, the doctor at the outpatient clinic knows the patient is present. The patient receives stickers with their details and a form indicating where to go first. The patient can then proceed to the diagnostic department, where a TOA examines the patient's automated refraction and administers eyedrops. Afterwards, the patient is referred to a medical specialist/ resident at the outpatient clinic. The patients can sit in the waiting area until the doctor summons them. The doctor has an overview of patients seen in this consultation hour in HiX and calls them into the consultation room. The doctor prepared a patient's visit before or during the consultation hour. During the consult, the medical history is taken, and the patient's visual acuity and intraocular pressure are checked through examinations by a resident. If a medical specialist sees the patient, a TOA will perform the visual acuity test and administer eye drops to the patient before the consultation by the medical specialist. Based on these results, the medical specialist/resident decides on the follow-up of this first visit. When a resident is executing a consultation hour on their own, supervision is provided by medical specialists. Preferably by a medical specialist of the same subspecialty, but sometimes this is impossible due to infeasibility in the schedule. The resident can approach the medical specialist to check their conclusion and follow-up. In complex cases, the medical specialist will see the patient as well.

When an examination is needed about the condition of the eye, a patient must proceed with their appointment to the diagnostic department. During an appointment, it is common to visit the diagnostic department on the same day for (multiple) examinations.

After the examinations at the diagnostic department, the patient can return to the doctor. The doctor bases the diagnosis and treatment plan on consultation with the patient, the examination in the consultation room, and the results of the examination(s) of the diagnostic department. A treatment can hold specific medicine, surgery, further examination, or monitoring of complaints for a set time. The proposed treatment is explained to the patient, followed by a discussion and room for questions. When surgery is needed, the patient is placed on a waiting list. The admission office calls the patient when there is an available time slot for surgery. The surgery will be performed in the operating theatre by a medical specialist in cooperation with a fellow or resident. The day after the surgery, a resident will check the patient. The doctor prescribes a recurrent appointment within a set amount of time.

Recurrent patient

If a patient needs a follow-up appointment, this will be scheduled by the medical secretary based on the prescribed recurrence date. The patient is scheduled within the consultation hour of a medical specialist of the specific subspeciality or the consultation hour of a resident. The follow-up appointment will follow the same process as the first appointment, without checking the interocular pressure and automated refraction.

Emergency patient

If a patient has acute complaints or pain around the eye, there is a possibility of visiting an emergency consultation hour. The patient is immediately referred to the ophthalmology department without visiting the emergency department. The ophthalmology emergency consultation hours take place each afternoon and are executed by a junior and senior resident. The patient sees a resident whom a medical specialist supervises. The patient will undergo the same process as a ‘new patient’.

Child

If a child needs to visit the ophthalmology department, the child will be seen by a medical specialist, a resident, and an orthoptist together. This is because the child experiences it as calmer compared to split visits. During the process, additional examinations must sometimes be performed after the consultation. The patient will undergo the same process as a ‘new patient’.

2.1.4 Variability Analysis Patient Journey

This subsection discusses the variability experienced in the patient journey at the ophthalmology department. When shadowing the care processes, we noticed processes that include variability. During our meetings, the stakeholders also described situations that do not operate optimally. The patients visiting the ophthalmology department follow a journey prescribed in Subsection 2.1.3. There are sources of variability in this process, which we will describe in this subsection. Variability reduces performance and should, therefore, be aimed at being omitted.

Report at reception

- The medical secretary verifies whether the patients brought their stickers with them. This is often not the case, so the secretary must print each patient's stickers individually.
- Sometimes, multiple patients arrive simultaneously, or the medical secretary is busy with other tasks, and the patients must wait for the secretary to be received. This results in doctors waiting for patients to arrive at the consultation room.

Diagnostic department

- Sometimes, the patients do not know how to find the right examination room. Therefore, they arrive at the appointment later than planned.
- The number of requests for an OCT scan varies and is unknown beforehand as these are set up on a walk-in basis. If the examination is busy, patients must wait before the examination can be executed.
- A doctor must make a so-called order in HiX for the TOA to be allowed to execute an examination. Sometimes, the order is not made, and the TOA must do this, causing a delay in the execution of the examinations.
- Patients place their sheet in a holder at the diagnostic department. The TOA must regularly check the sheets outside the consultation room to see who is present. The sheets' placement order is unknown, meaning the patients are not helped based on their arrival time.
- On Tuesday and Thursday, many examinations must be performed to support the scheduled consultation hours. More support TOAs and nurses are scheduled these days; however, the crowdedness still sometimes causes delays in the diagnostic department.

Consultation hour

- When a doctor is ill, another doctor must see more patients during a consultation hour or cancel appointments, resulting in a varying number of patients seen.
- Sometimes, the patients do not know how to get to the right room at the outpatient clinic. Therefore, they arrive at the room later than the doctor expects, or the doctor must assist in finding the location.
- The doctor cannot see whether the patient is present in the waiting room. The doctors must check themselves, which takes up time.
- A doctor sometimes must wait for this patient to return from the examinations due to crowdedness at the diagnostic department. This leads to delays within the consultation hour and, therefore, expiration, which is undesirable for professionals as it leads to overtime work.
- Sometimes, there is no TOA available to assist the doctors due to capacity shortages. In that case, the doctor has to perform more tasks herself, taking more time for a consult. Therefore, the duration of an appointment varies.

2.2 Planning and Control

Within this section, we discuss the planning and control process of the ophthalmology department. First, we provide some theoretical background. Subsequently, we will apply this theory to the planning process of the ophthalmology department.

2.2.1 Theoretical background

The scheduling process for the staff of the ophthalmology outpatient clinic will be described according to the framework of Hans et al. (2012), who were the first to introduce the hierarchical levels of control in the healthcare setting. We will briefly discuss the levels of control. First, the strategic level. Strategic planning involves long-term decision-making that defines an organisation's mission and structures its healthcare delivery processes. Strategic planning comprises a long horizon and involves resource capacity expansion and insurer contracts. The planning at the operational level deals with short-term decision-making related to the execution of healthcare. Activities like appointment scheduling and staffing belong to this level, with limited flexibility due to constraints from the higher-level decisions.

Offline operational planning is executed in advance, while online operational planning reacts to unforeseen events in the healthcare setting. Tactical planning serves as an intermediate between strategic and operational planning. It focuses on organising healthcare operations with moderate detail and flexibility, addressing tasks like patient admission planning and block planning.

2.2.2 Application to Ophthalmology Planning Process

The ophthalmology outpatient clinic's schedule is set up following a standard process each month. This process is visualised in a flowchart in Figure 1 and will be explained in this subsection via the hierarchical control levels.

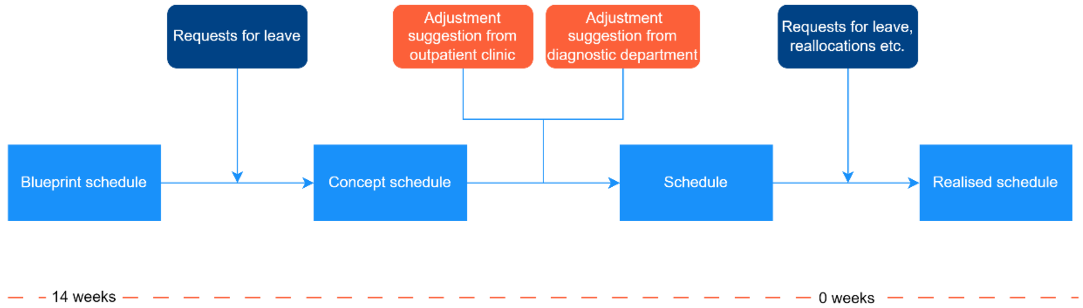


Figure 3: Scheduling process healthcare professionals ophthalmology outpatient clinic

Strategic level

The business office of the division DHS supports management information, process control, and operations management. The business office sets up production agreements for the department with the planning and control department of UMC Utrecht. The planning and control department enforces the production agreements and coordinates them with the various healthcare insurers, which pay for the delivered healthcare (Prestatiebekostiging ziekenhuizen, 2022). This results in healthcare products. A healthcare product includes all activities and costs related to diagnosing and treating a patient's health issue. The number of treatments, etcetera, are based on the healthcare products, resulting in guidelines for the department on how many patients to treat in a specific subspeciality a year. Strategic planning also involves determining the case mix (Hulshof et al., 2012). As UMC Utrecht is an academic hospital, the department mainly treats complicated eye health issues.

Tactical level

When the planning coordinators set up the monthly schedule on an operational level, they adhere to a standard schedule format, the blueprint. The blueprint schedule can be seen as a block plan, as it entails the tactical allocation of blocks to the subspecialties (Hans et al., 2012). This shift scheduling includes the guidelines of the outpatient clinic for the number of consultation hours and other procedures. Besides, it consists of the availability of the medical and supporting staff. Last, the activities of the residents are assigned to the phase of their training. Notably, the shift scheduling is static and not based on the (varying) demand for care at the subspecialties. Steering on staff-shift scheduling, capacity allocation, and admission control can improve the departments' acting on varying care demands and waiting lists (Hulshof et al., 2012). We obtained that these are hardly discussed, focusing more on individual professional arrangements. We conclude that little tactical planning is applied in the department.

Offline operational level

Two planning coordinators execute the staff-to-shift scheduling, assigning the activities to professionals on a timeslot (Hans et al., 2012). The planning coordinators operate on the blueprint to make the monthly schedule for the outpatient clinic. The blueprint forms the basis and contains information about the medical specialists, residents, orthoptists, optometrists, nurse practitioner, and the operating theatre. The professionals are assigned to specific tasks. These tasks include consultation hours, surgeries, educational activities, multidisciplinary meetings (MDO), research projects, supervision, and administration. Creating the schedule starts with the blueprint, and this concept schedule can be adjusted using a checklist to set up the final schedule. This checklist consists of twenty-three pages and incorporates the department's requirements. The planning coordinators process the adjustments manually. It is time-consuming and complex, requiring significant effort from the planning coordinators. The department aims for a suitable schedule that allows the staff to see many patients, the residents to attend many activities during their training phase, and the professionals to have enough time for research and administration.

With the setup of the schedule, the planning coordinators receive requests from the staff to consider regarding leave, parental leave, or vacation. After incorporating these requests, a concept schedule is mailed to the outpatient clinic staff. Within this mail, the coordinators list the shortages and bottlenecks of this concept schedule, for instance, a consultation hour lacking supervision of medical staff or a resident missing a phase-related training activity. The professionals act on this by suggesting how to make the schedule as fulfilling as possible. The planning coordinators process these suggestions and realise the final schedule. This schedule is sent by mail to the outpatient clinic professionals.

Within the schedule of the healthcare professionals, time is reserved for the consultation hours of the specific subspecialties. The consultation hours contain grids of appointment slots where patients can visit the medical specialist or resident. Each medical specialist has determined a particular number of patients they can see during the consultation hour, varying from ten to twenty appointment slots per consultation hour. Besides, the number of patients able to be seen depends on how many residents assist in executing the consultation and whether supporting staff, such as nurses or TOAs, can assist during the consultation hour. If support staff is unavailable, appointment slots are blocked beforehand, so no patient can be scheduled in this time slot anymore. This means the availability of professionals significantly impacts the number of appointments available for the patients and, therefore, the number of patients seen. After the planning coordinators determine the available time slots, patients can be allocated to the time slots. The medical secretary of the ophthalmology department assigns patient-to-appointment based on a waiting list of patients and their date to be seen, determined by a doctor. The medical secretary notifies the patients of their appointment time by post or phone.

Online operational level

After the schedule is in use, the planning coordinators often receive requests from the professionals for adjustments to the schedule because of absenteeism. The planning coordinators do their best to comply with all requests. If rescheduling or reallocation is required, the schedule is updated. Absenteeism often leads to blocking appointment slots.

2.3 Performance

In this section, we discuss the current performance of the ophthalmology department. The current performance is measured using performance indicators (KPI). The first KPI is the number of patients seen per week in the subspeciality and emergency consultation hours. This is considered the production of the ophthalmology department. The second KPI is the number of unscheduled activities in the blueprint schedule. The third KPI is the total monthly number of educational activities of the residents.

2.3.1 Number of patients seen per week

The ophthalmology department aims to keep the number of patients seen a week constant. As described in Subsection 2.2.4, patients are seen in consultation hours in varying numbers, depending on the number of residents co-executing and the number of nurses/ TOAs assisting the medical specialist. More patients can be seen when the planning is made so that these are available during the consultation hours. In 2024, 411 patients are seen on average weekly during the subspecialty and emergency consultation hours. Figure 3 shows the distribution of the number of patients seen in a week. The low-end outlier represents week 52, which can be explained by the fact that few appointments are typically scheduled during that week. The department currently faces problems with a waiting list, as many patients should have been seen by a doctor already. Still, their appointment cannot be scheduled, as insufficient appointment slots are available due to insufficient consultation hours or blocked appointment slots. Therefore, it is unfavourable that appointment slots must be blocked because of an infeasible schedule.

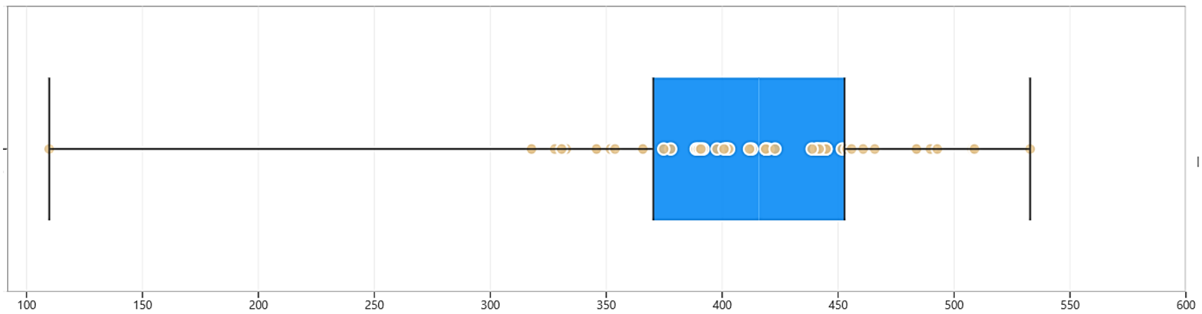


Figure 4: Patients seen per week in subspecialty and emergency consultation hours

2.3.2 Number of unscheduled activities

The ophthalmology department faces problems with realising its monthly schedule. The blueprint does not comply with the department's current situation. Therefore, the planning coordinators must make many adjustments to the concept schedule for the schedule to become feasible so that sufficient patients can be seen and residents can attend the right activities. This is because the healthcare demand and professional capacity incorporated in the blueprint are outdated.

First, outdated capacity has been used, mainly for the residents. Over the years, residents have been working less than the currently assigned full-time capacity. Residents more frequently have part-time days, and longer parental leave has been introduced nationally (Ministerie van Sociale Zaken en Werkgelegenheid, 2021). Besides, part of their training in general hospitals has been introduced, in which they are not present at the department. Significant reallocations must be made to the concept schedule to ensure that activities continue. Second, the blueprint is based on the 2023 operating theatre blueprint schedule. There has been a reduction in the available number of operating rooms for ophthalmology, making these used numbers too high compared to the 2024 blueprint schedule. For this reason, the concept schedule needs to be adjusted as well. This leads to reallocations in the professional's monthly schedule, making it unstable, which is unfavourable for the professional's workload.

The feasibility of the schedule is focused on the number of activities that cannot be planned. Due to the outdated blueprint schedule and the scheduling requirements, it is complex for the planning coordinators to create a feasible schedule each month. Currently, it is often impossible to schedule all activities, which mainly leads to a reduced number of supervision and consultation hours. In the blueprint schedule, twenty-three activities, primarily supervision, cannot be scheduled. As many adjustments must be incorporated to schedule the supervision, the staff must perform two activities simultaneously or cancel an activity. Besides, the schedule is inflexible for later adjustments to handle absenteeism.

2.3.3 Number of educational activities

The ophthalmology department of UMC Utrecht provides training for doctors to specialise in ophthalmology. A new resident starts their training every three months, as described in Subsection 2.1.2. The healthcare delivered by the ophthalmology department has become more complex and academic. This is because of the executed triage on the waiting list on the extent of the complexity of care during the COVID-19 pandemic (Wisse et al., 2021). This led to healthcare being delivered at the ophthalmology outpatient clinic being too complex for residents to deliver on their own, leading to more supervision of an ophthalmologist needed. Residents see patients with varying disorders in one consultation hour. However, the supervising ophthalmologist is specialised in only one subspecialty. Therefore, the supervisor cannot always educate the resident as aimed for. Besides, the residents sometimes must search for an ophthalmologist as they are not particularly assigned to supervise them at that moment, resulting in delays and a shorter moment for discussion. Besides, the residents feel this way of working is less educational as they constantly only check with an ophthalmologist instead of being guided. It is also inconvenient for the medical specialists as they must interrupt their tasks at that moment.

Therefore, the ophthalmology department strives to provide supervised consultation hours, with an ophthalmologist supervising one or two residents. However, this type of considerable change is exceedingly difficult to implement within the current framework of the schedule. Therefore, this new working method is only half implemented in the department. The residents still perform part of the consultation hours by themselves. Next to this being less educational, residents can also attend fewer educational activities during their training phase due to the reallocations needed to make the schedule feasible. We determined the difference between the scheduled training activities in the blueprint and realised training activities, where the realised training activities are based on the department's monthly schedule. Calculating the total number of educational activities scheduled in the blueprint schedule among all training phases, the blueprint schedule holds 210 educational activities, where the average of the realized schedules is 150.1 educational activities in a month, which is a difference of 28.7%.

2.4 Problem analysis

In this section, we analyse the problem of our research. Through meetings with the stakeholders, we categorise the problems experienced in the department. The stakeholders of this research include the department's healthcare professionals, planning coordinators, managers, and the patients visiting the department. We did not speak with patients but obtained this information from the other stakeholders and through shadowing care processes. By shadowing, we have also identified observable problems. A listing of the shadowed care and planning processes can be found in Appendix D. We present and explain the problems experienced by each stakeholder. We will then determine the main research problem that will be the focus of our research.

2.4.1 Stakeholder problems

Patient

- Patients could see a doctor who is not specialised in their disorder.
    - Patients have to share their medical history multiple times and receive less specialised care than they are used to at the department. Sometimes, this requires a revisit to see an ophthalmologist of the belonging subspecialty.
- Patients have a longer access time than prescribed by an ophthalmologist.
    - The doctor prescribes a moment for a recurrence appointment to check on the disorder and complaints. Sometimes, it is not possible to schedule a patient within this timeframe. Patients could have symptoms worsening when waiting longer for their appointment.
- Patients have to wait in the waiting room.
    - Patients sometimes have to wait a considerable amount of time in the waiting rooms for their appointments. It is considered uncomfortable to wait and to have uncertainty about the waiting time.

Ophthalmologist

- Ophthalmologists must supervise another subspeciality, which is complex.
    - Ophthalmologists perform general supervision over the emergency and resident consultation hours, in which patients with complaints of varying subspecialties are combined. Because of the increasingly complex care delivered at the department, patients' complaints sometimes require an ophthalmologist of the belonging subspecialty. It is complex for an ophthalmologist to supervise all subspecialties.
- Ophthalmologists have to interrupt tasks to supervise.
    - Due to the need for reallocations, ophthalmologists sometimes have to supervise next to another task, such as a research project. This can be communicated last minute. It requires much effort to perform activities simultaneously. Besides, they can be called away by a resident during their task to perform supervision, which is experienced as unpleasant.
- Ophthalmologists cannot rely on their schedule because of instability.
    - The schedule often requires reallocations or cancellations of activities on the offline and online operational level to be feasible in the practical setting of the ophthalmology department. Therefore, ophthalmologists have to deal with adjustments in their schedule, making it unreliable. This is experienced as restlessness.
- Ophthalmologists experience performing consultation hours is intensive

  - Due to the triage, explained in Subsection 2.3.3, all seen medical conditions are complex. This makes it more intensive for the ophthalmologists to perform their consultation hours, as these patients require extensive anamnesis and specialised treatment. Besides, it takes up more time to see a patient.

Resident

- Residents have fewer opportunities to consult with ophthalmologists, which makes executing consultation hours less educational
  - Due to the reallocations in the schedule, ophthalmologists supervise next to other tasks, or no ophthalmologist is available to supervise. The residents must diagnose and set up a treatment plan by themselves and can only check this with the supervisor shortly instead of being guided with their decisions. This is less educational for the residents.
- Residents can perform or attend fewer activities of their training phase than aimed for
  - Residents perform many emergency, follow-up, and own consultation hours because of reallocations, as a set number of these must be performed weekly. When fewer residents are available, these consultation hours are reallocated to the remaining residents. However, the training is designed to educate residents about all ophthalmology subspecialties by executing subspecialty activities. Due to the reallocations, residents can perform or attend fewer of these activities, leading to less educational training.
- Residents see patients with complex medical conditions for the first time, making executing consultation hours on their own difficult
  - Due to the triage, explained in Subsection 2.3.3, all seen medical conditions are complex. This makes it more intensive to perform consultation hours, as these patients require extensive anamnesis and specialised treatment. Residents are not familiar with all disorders yet, making them feel incompetent in treating patients with complex conditions.
- Residents work overtime
  - A set number of consultation hours must be performed. As described in Subsection 2.3.2, reallocations are needed to staff these. Sometimes, the administration block of a resident is cancelled to achieve this. The residents must do their administration beyond working hours, which leads to a highly experienced workload.
- Residents mainly learn about complex medical conditions
  - Residents mainly learn about complex medical conditions in UMC Utrecht and only get acquainted with common conditions during a short period in their general training and training phases in a general hospital. However, after training, they will also see common conditions when working in a general hospital.

Orthoptist

- Orthoptists experience performing consultation hours is intensive.
  - Due to the triage, explained in Subsection 2.3.3, all seen medical conditions are complex. This makes it more intensive to perform consultation hours, as these patients require extensive anamnesis and specialised treatment.
- Orthoptists cannot rely on their schedule because of reallocations.
  - The schedule often requires reallocations or cancellations of activities on the offline and online operational level to be feasible in the practical setting of the ophthalmology department. Therefore, orthoptists have to deal with changes in their schedule, making it

unreliable as they mention always checking the schedule multiple times. This is experienced as restlessness.

- Orthoptists feel that their availability is always expected
    - Orthoptists collaborate with an ophthalmologist and resident to perform the pediatric consultation hours. There is a waiting list, which makes the orthoptists feel burdened when requesting absence.

Optometrist

- Optometrists cannot rely on their schedule because of reallocations.
    - The schedule often requires reallocations or cancellations of activities on the offline and online operational levels to be feasible in the practical setting of the ophthalmology department. Therefore, optometrists have to deal with adjustments in their schedule, making it unreliable.
- Optometrists must use two schedules, which is unclear.
    - The optometrists also perform TOA tasks. The TOA tasks are scheduled by the diagnostic department's professionals based on the outpatient clinic schedule. Therefore, they operate on two schedules. The diagnostic department schedule risks not aligning due to the reallocations in the outpatient clinic schedule. This causes the optometrists to be expected simultaneously at two places, leading to inefficiency and frequent coordination.

Nurse Practitioner

- The nurse practitioner cannot rely on their schedule because of reallocations.
    - The schedule often requires reallocations or cancellations of activities on the offline and online operational level to be feasible in the practical setting of the ophthalmology department. Therefore, the nurse practioner has to deal with adjustments in her schedule.

Staff diagnostic department (TOAs, nurses, doctor's assistants)

- Staff diagnostic department is always expected.
    - The staff of the diagnostic department are scheduled based on the outpatient clinic schedule. Their availability is not taken into account when creating the outpatient clinic schedule. Still, they are necessary to see patients, as the diagnosis and treatment are based on the examination's results. This leads the diagnostic department staff to always be expected to be present. This places pressure on the staff's shoulders.
- Staff diagnostic department experiences a high workload due to increased examination demand.
    - Due to more complex conditions being seen in the department, more examinations are required. This makes the examinations crowded, which requires much of the staff. The schedule of the outpatient clinic, including consultation hours, is not set to the crowdedness of the diagnostic department.
- Staff diagnostic department experiences problems with shortages.
    - The diagnostic department faces problems with the capacity of nurses and TOAs. This is because vacancies are not filled. Therefore, the tasks have to be executed with less capacity.

Medical secretary

- Medical secretaries experience stress because of the high waiting list.

    - Patients call the medical secretary about longer access times, worrying about whether the order is registered well or their appointment is not forgotten. The patients are not informed about the waiting list. The medical secretaries must handle these concerned and sometimes angry patients.
- Medical secretaries have difficulties planning a patient's appointment.
    - Planning a patient on an appointment slot is complex and time-consuming. The process must be individually memorised and manually booked. Besides, HiX does not provide an overview of available appointment slots, leading to much time spent searching for the correct appointment slots.

Management department

- The management of the department faces challenges in ensuring a decent work environment
    - The employee satisfaction of the professionals is important for the management. However, they noticed this could be an improvement and fear the work pressure impacts employee satisfaction.
- The department should provide high-quality training for the residents
    - The department is responsible for maintaining the high quality of the training for the residents. However, the residents indicated dissatisfaction with attending less educational activities and receiving less supervision.
- The department does not reach production agreements
    - The department has agreements with healthcare insurers about the amount of healthcare delivered, which must be fulfilled yearly, as discussed in Subsection 2.3.1. The department does not meet the agreements, which is an undesirable situation.

Planning coordinators

- Planning coordinators must perform complex tasks
    - Due to the outdated blueprint schedule, many reallocations must be performed to create a feasible schedule. Including the individual requirements of the professionals leads to a complex scheduling puzzle each month.
- Planning coordinators experience a high workload
    - Besides creating the schedule, the planning coordinators incorporate the requests of professionals regarding absenteeism or adaptations. A high number of emails are sent with requests during the planning horizon. The department determined that these requests should be approved if they align with the schedule. This leads to the planning coordinators feeling responsible for processing all requests, even if they greatly impact the schedule. Constantly complying with the requests leads to a high workload.

2.4.2 Research Problem Definition

We conclude from the identified problems that multiple stakeholders face issues with schedule instability because of frequent reallocations. These adjustments limit the residents from getting supervision and attending educational activities. They often have to handle complex cases independently, which is intense. The unstable schedule also affects ophthalmologists, orthoptists and optometrists. They have to deal with frequent reallocations, interruptions and varying tasks simultaneously and can not rely on their schedule. This, in turn, impacts the schedule of the diagnostic department's professionals. Carrying out these complex reallocations leads to a high workload for the planning coordinators. This instability also impacts patient care. Patients have to wait longer for their appointments and have the chance of not seeing an ophthalmologist of their subspecialty.

These problems show the need for improved scheduling and training processes. Improving these areas can improve the work environment for healthcare professionals and provide higher-quality patient care, which is both important for the department's management.

2.5 Current Projects

This section discusses two current projects enrolled at UMC Utrecht. To determine the scope of our research, we investigated the current projects focused on improvements at the organisation affiliated with our research. By getting acquainted with these projects, we can identify gaps in the current improvement projects and determine how our research can complement them.

UMC Utrecht runs the programme ‘Healthcare of Tomorrow’. This programme introduces innovations and improvements within the entire UMC Utrecht step by step to work more cleverly. The programme focuses on uniform processes, digitalisation, and people-oriented working across specialisations. The programme aims to improve the quality of care and employee satisfaction. Besides, the programme ensures that appropriate and affordable healthcare is provided despite the increasing demand for care and the tight labour market. ‘Healthcare of Tomorrow’ is deployed in the entire hospital.

2.5.1 Uniformisation of Processes

The first project included in ‘Healthcare of Tomorrow’ is the ‘Uniformisation of Processes’. This project aims to create more uniform and modular care processes to better deploy and coordinate the available capacity of healthcare professionals. Furthermore, it aims to optimise the working processes among the outpatient clinics of the various departments by improving efficiency. Concrete examples of the project are a central patient registration point, the digitalisation of appointment scheduling, and the facilitation of the scheduling process with the improved use of HiX.

The ‘Uniformisation of Processes’ project aims to streamline care processes, which can help address the variability in the patient journey at the ophthalmology department, described in Subsection 2.1.4. By implementing a central patient registration point and digitalising appointment scheduling, the project can reduce waiting times and lower the workload of the medical secretary. Additionally, optimising the use of HiX can ensure that examination orders are made more easily. Overall, these measures can enhance efficiency and minimise the variability in the care process.

2.5.2 Tactical Planning in the Outpatient Clinic

The second affiliated project is the ‘Tactical Planning in the Outpatient Clinic’. This project is deployed in collaboration with the ICM department. It aims to implement integrated capacity management at all sixty-two outpatient clinics of UMC Utrecht to create insight into the available capacity towards the demand for care and optimise the capacity via control on a tactical level. We will shortly state the project’s goals and methods. The goals are the following:

- Reduction in the number of general consultation rooms required because of increased room utilisation.
- Reduction in support staff needed because of increased consultation hour utilisation, less rescheduling and process optimisations.

- An increase in patient satisfaction because of fewer appointment rescheduling and reduction of access times.

The following processes will achieve this:

- Using data dashboards to gain more insight into the healthcare delivered at the outpatient clinic.
- Validate the data analysis and provide insights to the department.
- Determine the number of patients per consultation hour and length of appointment interval.
- Setting up and maintaining tactical planning at the department.
- Proactive monitoring and adjusting of the production.

As stated in Subsection 2.2.2, the planning process of the ophthalmology department is hardly executed at the tactical level. This project aims to optimise capacity management through data dashboards and proactive monitoring. This can help to adapt the current static shift scheduling to align professional availability with varying care demands for the subspecialties. By improving room and consultation hour utilisation, the project can reduce the need for rescheduling and increase the number of patients seen with the current capacity. Implementing these measures will enable tactical planning and improve the handling of the waiting list and care demand.

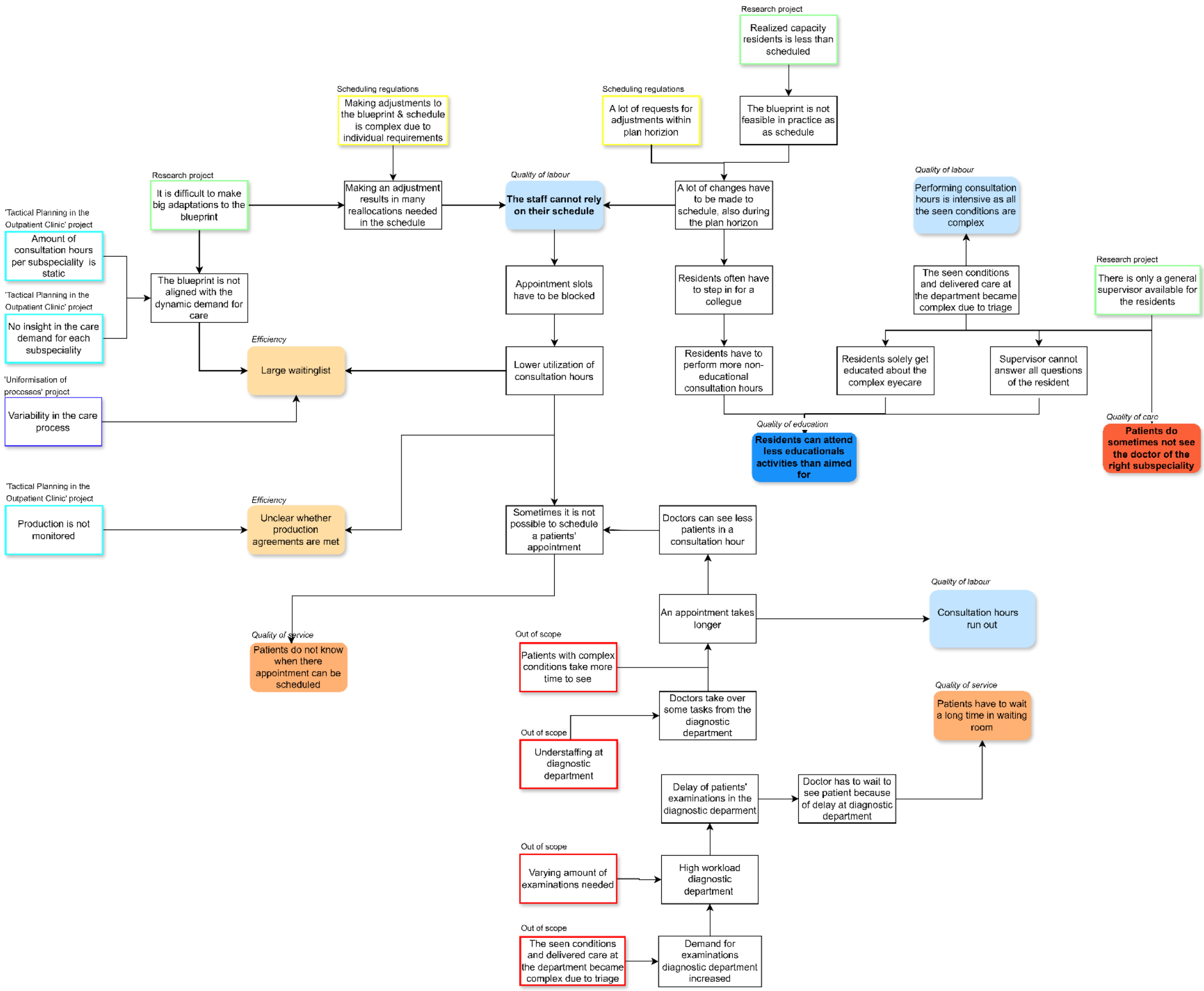
2.6 Conclusion and Scope

In this section, we discuss the scope of our research by incorporating the results obtained when examining the current situation of the care processes and planning.

In Section 2.3, we discussed the department's performance in terms of production, planning and education. In Section 2.4, we elaborated upon the problems experienced by the healthcare professionals, management, and patients in the ophthalmology department. In Section 2.5, we described all sources of variability throughout the patient journey. In Section 2.6, we explain the content of the programme ‘Healthcare of Tomorrow,’ the current improvement project of UMC Utrecht. Combining these four, we can decide on our scope for this research project.

The problem analysis shows that each stakeholder encounters difficulties during the care process. We visualised the relationship of the problems faced through a problem cluster. Figure 5 and Appendix F present the problem cluster. The problem cluster also includes the core problems and to which category they belong: quality of care, quality of service, quality of education, quality of labour, and efficiency. The core problems are stated in a curved box. We determined which problems were too complex and/or extensive to work on during the period of our research, which involves the increasing demand for examinations and the expected increased appointment duration. That is why we will not focus on the planning of the diagnostic department and will not investigate appointment scheduling. Furthermore, we have identified which problems lie beyond our sphere of influence. Therefore, we determined that the understaffing at the diagnostic department and the increased complexity of care were out of the scope of this research. These problems are stated in a red-aligned box in the problem cluster. The problem cluster also shows the relationship between the problems and UMC Utrecht's current improvement project. The problems managed with this project are stated in a blue-aligned box. The issues highlighted in the green-aligned boxes represent gaps in current projects, offering opportunities for our research to address and help resolve the problems faced by the department.

Figure 5: Problem cluster including categorisation



Notably, our problem analysis shows that the unstable schedule bothers all professionals. The problem cluster includes green-aligned boxes with problems related to the core problems, which are solvable with a suitable blueprint schedule. By improving the suitability and practical feasibility of the schedule, we can improve employee satisfaction and the quality of residents' training. It contributes to the problems with the waiting list, as fewer activities must be reallocated or cancelled. By aligning it with the 'Tactical Planning at the Outpatient Clinic' project, it facilitates the department to anticipate the varying demand for care. Furthermore, it increases the possibility of a patient seeing an ophthalmologist of the right subspecialty, contributing to the quality of care. Therefore, this research will focus on the outpatient clinic's blueprint schedule involving the ophthalmologists, residents, orthoptists, optometrists and nurse practitioner. This will impact the patients and management of the department as well. As mentioned, the professionals of the diagnostic department are left out of scope due to time constraints. The yellow-aligned boxes comprehend issues experienced because of the current scheduling guidelines. We should also focus on the scheduling guidelines to ensure the secure implementation of our model. Focussing on both the staff-to-shift schedule and the scheduling guidelines can solve the unstable schedule problems experienced by the stakeholders. Furthermore, improving the staff-to-shift scheduling requires revising agreements on tactical planning, helping deal with the varying care demand.

We can now answer our first research question. We obtained information about the current healthcare and planning processes by meeting with the stakeholders and shadowing care processes. We gained insights into the performance of these components and could, therefore, determine the weaknesses in these processes, next to analysing the problems stated by stakeholders. By creating a problem cluster, we could visualise the relationships between problems and incorporate the current improvement projects at UMC Utrecht. With this problem cluster, we could determine which part we could make the most positive impact on the current process. This led to the decision to improve the outpatient clinic's schedule for suitability and feasibility. We examine approaches to achieve this objective by executing a systematic literature review, discussed in Chapter 3. Chapter 4 will propose a solution to improve the scheduling process, and Chapter 5 discusses an implementation plan to secure the use of the model.

3 Systematic literature review

This chapter presents a systematic literature review of the existing research focused on optimising staff scheduling in an outpatient clinic. Section 3.1 introduces the goal of the systematic literature review. Section 3.2 discusses the method used for the systematic literature review. Section 3.3 presents the results obtained. Section 3.4 discusses the conclusions drawn from the systematic literature review.

3.1 Introduction and Objective

In this section, we introduce our literature review and discuss the objective. This systematic literature review aims to retrieve a suitable method for our planning problem by providing an overview of recent research on optimising hospital staff scheduling, highlighting the approaches, applications, and outcomes. Hospitals worldwide face complex staff scheduling challenges that impact patient care quality and efficiency. Various approaches have been incorporated to address these challenges, including optimisation techniques, simulation models, and game theory. We aim to obtain an overview of the approaches used and their outcomes, serving as inspiration for our model.

3.2 Method

In this section, we will discuss the method of our literature review. The literature is reviewed according to the guidelines of the Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) (Moher, 2009). This method provides a step-by-step approach to report a systematic literature review. The methodology applied to our research, including the PRISMA flow diagram and overview of the obtained sources, can be found in Appendix F.

A comprehensive search of the existing literature is performed in Scopus and Pubmed databases. These results were obtained using the following search words: 'Optimisation,' AND 'Staff scheduling' AND 'Outpatient clinic' and the corresponding synonyms of these terms to include a broad range of available, relevant literature in the review. To determine which study to include in the literature review, the titles and abstracts of the studies were screened for suitability based on our inclusion criteria. We extracted research information is stated in Appendix F.

3.3 Results

In this section, we discuss the most important lessons learned from the systematic literature review.

This literature review aimed to explore the various methods of staff scheduling in a hospital, particularly in outpatient clinics. Our review highlighted multiple approaches that have been used to improve the scheduling of healthcare professionals, succeeding in reducing waiting times, increasing resource utilisation, or improving employee satisfaction. Our review obtained optimisation and simulation models as the most appropriate approaches. A simulation model is useful for improving resource scheduling and utilisation. Multiple obtained sources apply a simulation model to evaluate different policies (Barros et al., 2021; Berg et al., 2018; Patel et al., 2020) and Al-Hawari et al. (2022) praise this approach for incorporating all details of the system modelled. However, with our research, we aim to find the optimal solution to our scheduling problem. This is less emphasised in the studies that use simulation modelling, where this is a component and where the focus is mainly on evaluating different scenarios. Besides, accurate input data on multiple topics is required, which is unfortunately unavailable for our research.

We saw that in several studies that use optimisation, an optimal schedule was created, improving employee satisfaction (Bovim et al., 2022; Yu et al., 2024) and succeeding in meeting care demand without increasing the capacity of professionals (van de Vrugt et al., 2018; Hua et al., 2023; Mu et al., 2021). Three studies also incorporated professional preferences (Koruca et al., 2023; Li et al., 2022) (Vissers, 2022). As noted in these studies, a structured problem that can be captured with little detail is required. This is feasible for our problem. For our problem, we require an approach that can handle multiple requirements for it to fit with the ophthalmology department. This can be incorporated with optimisation modelling using constraints, as shown in Davarian et al. (2022). The ophthalmology department is a complex system. We conclude from the systematic literature review that an optimisation model suits our research. Eleven sources apply integer programming (Bikker et al., 2015; Hoffmans-Holtzer et al., 2024; Hong et al., 2019; Hua et al., 2023; Keshtzari et al., 2024; Mu et al., 2021; Munavalli et al., 2017; Vali-Sair et al., 2018; van de Vrugt, 2018; Vissers, 2022; Wang et al., 2021; Wang et al., 2020; Zhou et al., 2022; Zimmerman et al., 2021). An integer programming model is an optimisation model that helps to make efficient use of limited resources within a defined set of constraints. An ILP model aims to allocate resources such as time, personnel, or materials to maximise or minimise outcomes. By defining specific constraints, the model can ensure that each solution respects real-world limitations, such as capacity and availability. In an ILP, the solution variables are restricted to integer values, making it ideal for problems where decisions must be discrete.

Furthermore, the scheduling of the residents, incorporating their training phases, is scarcely studied. Two studies incorporated resident scheduling, discussing the importance of balancing quality of care, sufficient staffing, and high-quality training (Eskandarani et al., 2024; Hong et al., 2019). Both studies apply linear programming to generate a schedule incorporating these objectives and considering preferences. No study has been found on scheduling residents and other professionals, including their tasks. Our research aims to address this gap by developing a scheduling approach that balances resource utilization and training requirements.

3.4 Conclusion

We can now answer our second research question. Our systematic literature review has highlighted the effectiveness of various staff scheduling approaches in outpatient clinics. Optimisation modelling is the most applied approach to generate a staff schedule. This approach has shown success in creating optimal schedules that improve employee satisfaction and meet care demand without increasing professional capacity. In particular, ILP is a widely studied method in these publications and can provide an optimal, linear solution in high-complex systems. Besides, this approach can respect requirements and preferences; a given that is important within our research because of the complexity of the ophthalmology department. Therefore, we conclude from our literature review that integer linear programming is a suitable method for our research to generate a suitable staff-shift schedule.

4 Solution approach

This chapter elaborates on the solution approach developed to the problem described. We aim to improve the quality of labour and education at the department by creating a feasible blueprint schedule. In the literature search in Chapter 3, we obtained that an ILP model is a suitable method to generate a schedule on a tactical level in a hospital. In this chapter, we develop and apply an ILP to model the system of the scheduling procedure of the ophthalmology outpatient clinic. In Section 4.1, we discuss the requirements of the model and the assumptions made to set up the model. Section 4.2 provides the components of our model in the formal problem description. Section 4.3 discusses the output of our model and proposes a visualisation of the output variables. We conclude with the verification and validation of the model in Section 4.4.

4.1 Model requirements and assumptions

In this section, we discuss the requirements for our scheduling model. Next, we present our assumptions made to create a model approach for the scheduling system for tactical planning in the department.

4.1.1 Model objective and requirements

We aim to improve the scheduling procedure at the ophthalmology outpatient clinic, as the current schedule is not conducive to the training of the residents and is not feasible as a schedule on an operational level. With our model, we aim to compose a feasible blueprint schedule that complies with the characteristics and guidelines of the ophthalmology department. We aim to create a model that optimally uses the available resources and the healthcare professionals to set up a schedule that is accurate and feasible. We focus on creating a model that assigns the professionals to specific activities on a time slot. The ILP model is written using AIMMS version 4.94, a software applicable for mathematical optimisation and modelling.

4.1.2 Assumptions and data

For the model to be realistic, we obtained the characteristics of the ophthalmology department. This was done through meetings with the healthcare professionals at the department, conversations with the planning coordinators and analysis of current documentation about the blueprint schedule. Throughout the process, there was close collaboration with the unit manager and the planning coordinators to ensure all characteristics were accurate and up-to-date. With this research, we listed the activities, healthcare professionals, rooms, and specialities. We created a list of activities the healthcare professionals can provide, consisting of several types of consultation hours, surgeries, meetings, and examinations. Next, we became acquainted with the requirements of executing a consultation hour regarding professionals and resources and the residents' competence in the phases of their training programme.

We needed to make assumptions about the ophthalmology department's healthcare and scheduling processes while defining an accurate problem description. We made the following general assumptions:

- All activity blocks have the same fixed duration of an entire part of the day: 3.5 hours.
- There are no transition times between the activities.

- All activities can be scheduled individually and are unrelated, except for those performed by residents. Planning an activity for a resident on a part of the day also entails planning another activity on the same day.
- The schedule alternates between even and odd weeks, each containing five working days.
- All professionals competent for an activity can be scheduled for the activity.
- All professionals are scheduled independently for each part of the day.
- All activities and professionals are equally valuable in objective.

The specific assumptions are incorporated in the model constraints and elaborated on in Subsection 4.2.4.

4.2 Optimisation model

This section provides the notation of the proposed ILP model, introduces the decision variables, the objective, and the constraints, and concludes with the formal model formulation.

4.2.1 Sets

This subsection provides the notation of the formal problem description. Table 7 shows the notation of sets and indices. Sets represent groups over which variables and constraints are defined (e.g., types of professionals, periods). Indices reference elements within the sets, such as the specific days, and are used to define variables and constraints compactly. The set 'CareActivities' include direct and indirect patient care, such as consultation hours, surgeries, and multidisciplinary meetings. The care activities are aimed to be conducted a fixed number of times a week. 'ProfessionalActivities' encompass administration and research, and the number of times these activities are performed a week varies per professional.

Table 2: Overview and description of sets

Set	Description
$p \in P = \{1,2,3,\dots,\lvert P\rvert\}$	Healthcare professionals
$s \in S = \{1,2,3,\dots,\lvert S\rvert\}$	Specialty of a healthcare professional
$d \in D = \{1,2,3,4,5\}$	Days in a week, where $d = 1$ represents Monday and $d = 5$ represents Friday
$h \in H = \{1,2\}$	Periods in a day, where $h = 1$ represents morning and $h = 2$ represents afternoon
$w \in W = \{1,2\}$	Weeks
$k \in K = \{1,2,3,\dots,\lvert K\rvert\}$	Rooms
$ca \in CA = \{1,2,3,\dots,\lvert CA\rvert\}$	Care activities
$pa \in PA = \{1,2,3,\dots,\lvert PA\rvert\}$	Professional activities

4.2.2 Parameters

Table 8 provides an overview of the model's parameters. Parameters represent fixed inputs or constants, values that do not change during the optimisation but affect the solution. The parameters' names are abbreviated with uppercase letters. Note that the capacity of the residents is updated to numbers reflecting reality, as the department noticed the current full-time capacity is outdated, leading to frequent reallocations. The numbers are based on data analysis of the capacity of residents in each training phase in 2019, 2022, and 2023. The required number of care activities is based on the current blueprint and the number of patients seen each week in 2024, as analysed in Subsection 2.3.1. Using a norm schedule of 42 weeks, the number of subspecialty and emergency consultation hours each week needed can be determined.

Parameter	Full Name	Description
PT_{ca}	PatientsSeenNumProfessionalRequired	Patients seen with each activity block of activity ca
$NPR_{ca,s}$	NumProfessionalRequired	The number of professionals of speciality s required for an activity ca
$PC_{p,w}$	ProfessionalCapacity	Total capacity of professional p in week w in dayparts
RR_{ca}	RoomsRequired	The number of rooms required for activity ca
$RA_{ca,w}$	RequiredNumberCareActivity	Required number of blocks per week for activity ca in week w
$RPA_{p,pa,w}$	RequiredNumberProfessional Activity	Number of blocks for activity pa for professional p in week w
$PA_{p,d,h,w}$	ProfessionalAvailability	1 if professional p is available on day d, part of the day h, in week w
$SP_{p,ca}$	CompetenceProfessionals	1 if care professional p can provide activity ca
$PR_{ca,s}$	SpecialtyRequired	1 if a professional of speciality s is required for an activity ca
$ST_{ca,d,h,w}$	SpecificTimeSlot	1 if activity ca needs to take place on day d, a part of the day h in week w
$SPS_{p,s}$	SpecialtyProfessional	1 if professional p belongs to speciality s
ED_{p}	EntireDay	1 if professional p can solely work an entire workday

Table 3: Overview and description of parameters

4.2.3 Decision variables

Decision variables represent the quantities or choices we must consider in an optimisation problem. These are the unknowns that the model will solve based on the defined objective function and the constraints. The values of the decision variables determine the solution to the problem. Table 9 provides an overview of the variables of the problem. As our problem is an ILP, the variables are restricted to positive integer values. The names of the variables are abbreviated with lowercase letters. The first set of variables comprehends the planning decisions of our model; the decision variables are the components of the problem the model aims to optimise. Performance auxiliary variables are specific aspects of the model's performance. Remaining auxiliary variables are additional variables that assist in structuring the model and include intermediate calculations.

The decision variables $x_{\mathrm{ca,d,h,w}}$ and $y_{\mathrm{pa,d,h,w}}$ form the basis of our model. It involves deciding whether to schedule a care or professional activity at a specific timeslot: a part of the day, a day, and a week. The planning decision variables $px_{\mathrm{p,ca,d,h,w}}$ and $py_{\mathrm{p,pa,d,h,w}}$ follow the same structure and determine whether a professional is scheduled for an activity at a specific timeslot. The model can optimise the solution by determining which professional will provide the activity and on which day, part of the day, and in which week. The planning decision variables are all binary, meaning they can only hold 0 or 1.

Table 4: Overview and description of decision variables

Variable	Full name	Index	Description
Decision variable			
$px_{p,ca,d,h,w}$	ProfessionalCareActivity	(p, ca, d, h, w)	1 if professional p provides care activity ca on day d, part of the day h, in week w.
$x_{ca,d,h,w}$	PlannedCareActivity	(ca, d, h, w)	1 if care activity ca is provided on day d, part of the day, and week w.
$Y_{p,pa,d,h,w}$	PlannedProfessionalActivity	$(p, pa, d, h, w,)$	1 if professional p provides professional activity pa on day d, part of the day h, in week w.
Performance auxiliary			
$nx_{ca,w}$	CountNotPlannedCareActivity	(ca, w)	The number of unscheduled blocks of demand for care activity ca in week w.
$ny_{p,pa,w}$	CountNotPlannedProfessionalActivi ty	(p, pa, w)	The number of unscheduled blocks of demand for professional activity pa for professional p in week w.
Remaining auxiliary			
ax	AmountNotPlannedCareActivity		Total demand of care activities that are unscheduled
ay	AmountNotPlannedProfessional Activity		Total demand of professional activities that are unscheduled
an	TotalNotPlannedActivity		Total demand of activities that are unscheduled
tp	TotalPatientsSeen		Total number of patients seen

4.2.4 Constraints

Constraints are linear inequalities or equalities that the planning decision variables must satisfy for the model to be feasible. A constraint consists of a left-hand side and a right-hand side. The left-hand side of a constraint involves the decision variables. It represents what is restricted or controlled in the model. This is pursued by setting a constant or parameter as the limit for the left-hand side: the right-hand side.

The constraints the model must satisfy are so-called hard constraints, which cannot be violated. For example, our model's constraints are that the capacity of a healthcare professional is not being exceeded, and activities can only be executed by authorised professionals. In addition, we introduced soft constraints. Soft constraints can be violated if needed, but this incurs a penalty in the objective function. This penalty is stored in a slack or excess variable. The soft constraints are more flexible than the hard constraints, as they represent preferences in the model. By incorporating soft constraints into our model, we ensure feasibility. The model aims to minimise these penalties while achieving the best solution under hard constraints. In our model, two excess variables, 'NotPlannedCareActivity' and 'NotPlannedProfessional activity,' convert an inequality into equality by representing the number by which the left-hand side is below the required minimum, represented by the parameter 'RequiredNumberActivity.

In the following subsection, we explain the argumentation behind each constraint. The complete mathematical formulation of each constraint is shown in the formal problem description, presented in Appendix F.

Hard constraints

1. A professional can only be scheduled up to their available capacity. The sum of the care and professional activities that a professional can perform in a week must be less than or equal to the number of dayparts a professional works in a week.
$$\sum_{ca}\sum_{d}\sum_{h} px_{p,ca,d,h,w} + \sum_{pa}\sum_{d}\sum_{h} y_{p,pa,d,h,w} \leq PC_{p,w} \qquad \forall\, p, w$$
2. A professional can only perform activities for which they are competent. A professional can solely be scheduled for a care activity at a timeslot when the activity is one for which they are authorised, listed in the parameter 'CompetenceProfessionals'.
$$px_{p,ca,d,h,w} \leq CP_{p,ca} \qquad \forall\, p, ca, d, h, w$$
3. The number of available rooms must be within the maximum. Executing a care activity requires one or multiple consultation rooms. The number of rooms used for care activities at a specific part of the day cannot exceed the number of consultation rooms available at the ophthalmology outpatient clinic.
$$\sum_{ca} x_{ca,d,h,w} * RR_{ca} \leq |k| \qquad \forall\, d, h, w$$
4. The professionals can only be scheduled for an activity when they are available. To prevent the model from creating a practically unfeasible schedule, an activity can only be scheduled at a part of the day when a professional is available to work at the outpatient clinic. Summing the activities ensures a professional can only perform one activity simultaneously, as ProfessionalAvailability' is a binary parameter.
$$\sum_{ca} px_{p,ca,d,h,w} + \sum_{pa} y_{p,pa,d,h,w} \leq PA_{p,d,h,w} \qquad \forall\, p, d, h, w$$
5. Certain activities must take place at specific timeslot. When an activity must be performed at a particular timeslot in a week, for instance, surgery of a specific subspecialty, as they are virtually impossible to reschedule due to agreements with the operating theatre. If an activity belongs to this list of activities and a timeslot is specified, the activity must be scheduled at this timeslot.
$$x_{ca,d,h,w} \geq 1 \qquad \forall\, ca, d, h, w \mid ST_{ca,d,h,w} = 1$$
6. Certain activities cannot be scheduled at the same timeslot. This constraint ensures that certain activities cannot be scheduled simultaneously, resulting in an inefficient department healthcare process. This is because the consultation hours for macula and uveitis require many examinations in the diagnostic department, resulting in a high workload, as described in Subsection 2.4.1. When this is the case, the doctors must wait for the patients to return to the outpatient clinic, which makes the care process inefficient.
$$x_{'CHUveitis',d,h,w} + x_{'CHMacula',d,h,w} \leq 1 \qquad \forall\, d, h, w$$

7. Certain professionals can solely be scheduled for an entire workday. We aim to prevent professionals from being scheduled for multiple stand-alone parts of days instead of a whole workday. Therefore, professionals have an entire day off when working part-time, and with that, the quality of labour is improved.

$$\sum_{ca} px_{p,ca,d,'1',w} + \sum_{pa} y_{p,pa,d,'1',w} = \sum_{ca} px_{p,ca,d,'2',w} + \sum_{pa} y_{p,pa,d,'2',w} \qquad \forall\, p,d,w \mid \mathrm{ED}_p = 1$$

8. Care activities can only be scheduled when sufficient competent professionals are scheduled. This constraint allows the model to schedule an activity only when sufficient professionals of the required specialities are scheduled for this care activity by summing over the scheduled professionals and their specialities. For instance, when both an ophthalmologist and a resident are required, this constraint ensures that a professional of each speciality is available instead of two ophthalmologists or residents. When sufficient professionals of the required specialities are scheduled, 'PlannedCareActivity' can take a value of 1.

$$\sum_{p} SPS_{p,s} \times px_{p,ca,d,h,w} \geq NPR_{ca,s} \times x_{ca,d,h,w} \qquad \forall\, ca,d,h,w,s$$

9. Calculating the total number of patients treated. This constraint sums the number of patients treated with all activities to obtain an insight into the total number of patients seen in the two weeks with the proposed blueprint schedule.

$$\sum_{ca}\sum_{d}\sum_{h}\sum_{w} x_{ca,d,h,w} \times PT_{ca} = tp$$

10. Calculating the total number of unscheduled care activities. The constraints calculate the total number of unscheduled care activities by summing the care activities that cannot be scheduled over the days, parts of days, and weeks.

$$\sum_{ca}\sum_{w} nx_{ca,w} = ax$$

11. Calculating the total number of unscheduled professional activities. The constraints calculate the total number of unscheduled professional activities by summing the care activities that cannot be scheduled at a timeslot for a professional over the professional days, parts of the day, and weeks.

$$\sum_{p}\sum_{pa}\sum_{w} ny_{p,pa,w} = ay$$

Soft constraints

12. Care activities must be scheduled a certain number of times a week. This soft constraint aims to ensure that care activity requirements are met in terms of quantities for each type of activity. Summing over the days and parts of the day allows the constraint to measure the deviation between the required number of scheduled activities of a type of activity per week and the scheduled number. This deviation is stored in the excess variable 'NotPlannedCareActivity.'

$$\sum_{d}\sum_{h} x_{ca,d,h,w} + nx_{ca,w} = RA_{ca,w} \qquad \forall\, ca,w$$

13. Professional activities must be scheduled a certain number of times a week per professional. This soft constraint aims to ensure that professional activity requirements are met in terms of quantities for each type of activity for each professional. Summing over the days and parts of the day allows the constraint to measure the deviation between the required number of scheduled

activities of a type of activity per week per professional and the scheduled number. This deviation is stored in the excess variable 'NotPlannedProfessionalActivity.'

$$\sum_{d}\sum_{h} y_{p,pa,d,h,w} + ny_{p,pa,w} = RPA_{p,pa,w} \qquad \forall\, p, pa, w$$

4.2.5 Objective function

The objective function describes the goal of the optimisation model, denoted as a linear function of the decision variables. Our objective function aims to minimise the number of unscheduled activities, so the number by which the model does not meet the requirements for care and professional activities. The department wants to operate a new way of working to improve the residents' education quality. It was unfeasible for the planning coordinators to incorporate this into a new schedule while complying with the department's requirements. Activities could not be scheduled, which is unfavourable for both the training of the residents and the number of patients that can be seen. The ophthalmology department could not create a schedule that involves consultation hours executed by both an ophthalmologist and resident without cancelling activities in the schedule. By aiming to keep the number of unscheduled activities low, the model focuses on planning the activities optimally in a configuration that allows the maximum number of activities to be scheduled.

Another option for the objective value function would be to maximise the number of patients treated. However, this setting risks leaving certain activities unscheduled, as the focus would shift to consultation hours, where most patients are seen. Activities like research and administration directly serve fewer or no patients. However, administration contributes to patient care as doctors manage patient records, document medical histories, update treatment plans, and handle necessary paperwork to ensure accurate healthcare. As UMC Utrecht is an academic hospital, research is one of the pillars of the hospital, and leading research is performed in the department. Besides, activities like surgeries and multidisciplinary meetings are based on external agreements, such as the schedule of the operating theatre of UMC Utrecht. The ophthalmology department must adhere to these specific timeslots, and the model should ensure that these commitments are met. An objective function focused solely on maximising patient visits does not account for these aspects, whereas one that minimises unscheduled activities helps ensure these important tasks are prioritised as much as possible while still allowing the department to see the maximum number of patients within its capacity.

The objective value function focuses on care activities (ax) and professional activities (ay). By incorporating weights ω_1 and ω_2, the department can prioritise the scheduling of either care or professional activities based on their relative importance. The objective value function is as follows:

$$min.\ \omega_1 ax + \omega_2 ay$$

Our model focuses on improving how healthcare professionals are assigned to activities, ensuring each activity has the right number and type of professionals based on their specialisations.

4.3 Model output

In this section, we discuss the output format of the developed model.

We aimed for the model to create an output in Microsoft Excel. This aligns with the current planning process, and maintaining the output format supports the implementation of our model. We created a procedure in AIMMS that writes the output data in a macro-enabled Microsoft Excel file in the current layout of the schedule. We developed a Visual Basic for Applications (VBA) code that transforms the names to improve the readability of the schedule. Visualising the outputs creates a clear overview and assists in interpreting them. The visualisation shows which activity is performed in which week, on which day, at which part of the day and by which healthcare professional. Figure 4 presents the proposed output format of our model.

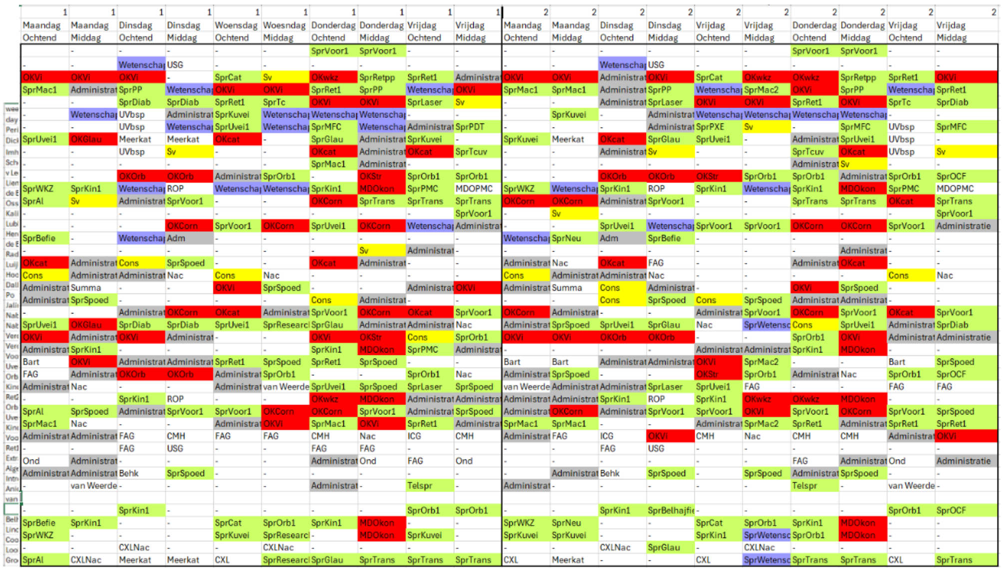


Figure 4: Output format model

4.4 Model verification and validation

In this section, we discuss the verification and validation of our model. This section demonstrates the model's accuracy and suitability for addressing the problem context.

4.4.1 Verification

Model verification is an important process in developing our mathematical model, as we aim to ensure that the model accurately reflects the underlying mathematics. During the programming phase, we checked for errors in the code and consistency in the definition of the sets and parameters. Each constraint was evaluated individually to confirm that it behaves as intended with the conceptual model. Last, we verified that the model focuses on minimising unscheduled activities.

4.4.2 Validation

With model validation, we determine the composed model alignment with the real-world situation at the ophthalmology outpatient clinic. We involved the planning coordinators, healthcare professionals, and managers to check if the model meets the requirements and practical expectations. With these stakeholders, we validated the assumptions made and the characteristics of the outpatient clinic incorporated into the model. Next, we validate the model's output against historical data by incorporating the former guidelines of the planning process of ophthalmology into our model. We validated our model by comparing the new schedule based on updated requirements against a schedule based on the current requirements, both generated by the model. This way, we could compare the results against historical data to check accuracy. This comparison allowed us to observe assignment changes, ensuring the new requirements were met without unexpected issues. By analysing our output values, we can confirm that the model with the updated requirements responds appropriately.

4.5 Conclusion

With these results, we can answer our third research question. We developed an ILP model to generate a schedule aiming to maximise the number of healthcare activities that can be scheduled. By defining clear sets, parameters, constraints, and optimisation objectives, the characteristics and requirements of the ophthalmology department are guaranteed. The output format is aligned with the current format of the schedule, increasing the practical usability for the planning coordinators. By verifying and validating our model, we have seen that our model provides an accurate and feasible schedule for the department.

5 Experiments

This section discusses the experiments executed on our ILP model. With our literature research, we obtained that computational experiments are a common method to evaluate and validate an optimisation model's performance. We perform experiments on our model to evaluate the model and gain more insights into the impact of the available resources in the ophthalmology department. Section 5.1 introduces our experiments and their reasoning. Before designing the experiments, questions were formulated based on topics frequently discussed with stakeholders. These questions guided the development of the experiments, and the experiment design is presented in Section 5.2. Section 5.3 presents the results of the experiments, followed by the interpretation.

5.1 Introduction Experiments

In this section, we will introduce our experiments and discuss the motivation behind each experiment.

During the research, there was frequent contact with healthcare professionals, managers, and scheduling coordinators through conversations and meetings. In these meetings, the practical implementation of the model was often discussed. Concerns were also raised about the model's feasibility, for instance, when several professionals were absent. Since we aim for the model to align well with the practical setting of the ophthalmology department, experiments were conducted to verify this aspect. Therefore, we set up an experiment design to evaluate the model's performance under different conditions on the KPIs: the number of unscheduled activities in the blueprint, patients seen in a week, and educational activities scheduled in the blueprint, as discussed in Section 2.3, under different conditions. Key components in this setup include identifying the objectives of the experiments and selecting the parameters to vary. To determine which parameters to vary, we incorporated the topics discussed in the meetings with the stakeholders, and questions arose during the research. Based on this information, questions were set up to obtain insights into the impact of our resources on the KPIs. The questions and their reasoning will be discussed in this section.

1. What is the impact of the number of residents attending a consultation hour?

Certain consultation hours can operate with one or two residents, impacting the number of patients seen in a single consultation hour. During the meetings, the stakeholders expressed curiosity about which option would be best for the blueprint schedule and for maximising the number of patients seen. We aim to understand if scheduling an additional resident for a consultation hour directly impacts the KPIs.

2. What is the impact of the availability of healthcare professionals?

This experiment considers how the presence of healthcare professionals on a given day affects the number of unscheduled activities and patients seen. Currently, the ophthalmologists, orthoptists, optometrists and a nurse practitioner have set part-time days, days when they are not available at the department to see patients or execute other activities. The number of professionals available at the outpatient clinic differs per day and can affect the possibility of the model scheduling activities. This experiment gains insight into how dependent the model’s solutions are on the professionals' set part-time days without altering their capacity.

3. What is the impact of the capacity of the healthcare professionals?

Healthcare professionals currently have a set capacity of working days a week at the department. During the meetings, we noticed that the stakeholders often worried about a lack of capacity of healthcare professionals and the impact of this on unscheduled activities. With this experiment, we decrease and increase the capacity of each professional to help reveal whether the capacity leads to reduced performance of the solution.

4. What is the impact of the number of rooms?

Some activities, such as the consultation hours, require rooms to be executed. The activities need a certain number of consultation rooms, as some consultation hours are performed by multiple healthcare professionals, affecting the number of consultation rooms needed. This question assesses whether room shortages increase the number of unscheduled activities and whether the model can optimise the use of consultation rooms.

5. What is the impact of the absence of professionals?

The healthcare professionals are sometimes absent from the department due to illness or leave. This question considers how the presence or absence of professionals affects the model's ability to meet scheduling objectives. Limited availability can create bottlenecks for the model, potentially impacting the KPIs. This question helps determine how dependent the model is on the presence of professionals to schedule the activities.

6. What is the impact of scheduling activities at a specific timeslot?

Certain activities must be scheduled at a specific timeslot in the week because of agreements with other departments for multidisciplinary meetings and the availability of external resources, such as assigned timeslots of the operating theatre. When certain activities are set into fixed timeslots, the available options of the model for scheduling other activities and professionals are limited, decreasing flexibility. This requirement can increase the number of unscheduled activities due to the unavailability of necessary professionals during those specific time slots. With this question, we aim to create insights into the impact of this restriction on the model's solutions.

Interaction effects

Besides the impact of alternating the value of one parameter, we are curious about interaction effects: the impact that combinations of parameter values have on the outcomes. Since, in practice, values of multiple parameters can be different, it is also worthwhile to explore the interaction effects. Because of the time intensity of analysing every possible combination, we will focus on the combinations that we expect to provide valuable insights for the ophthalmology department. This is because it is the most likely scenario in practice is that sometimes professionals will be absent. We will examine the interaction effect of the presence and availability of professionals and the effect of the presence and capacity of professionals.

5.2 Experiment design

In this section, we discuss our method for each question presented in Section 5.1.

With our literature research, we obtained that computational experiments are a common method to evaluate and validate an optimisation model's performance. We will apply this method to evaluate our model and detect the impact of the requirements on the solution. To perform our experiments, we introduce an experiment setup. An experiment setup refers to the arrangement of conditions designed to perform a controlled experiment and collect data to achieve specific research objectives. To ensure validity, the experiment setup includes a baseline scenario, a setting that reflects the real-world conditions of the ophthalmology department. Table 6 presents the parameter values of the baseline scenario.

Parameter	Value baseline scenario
Number of professionals	41
Ophthalmologists	18
Residents	17
Nurse practitioner	1
Orthoptists	5
Optometrists	2
Number of rooms	11
Number of residents required	1
Availability of professionals	Current availability
Capacity of professionals	100% of their current capacity
Presence of professionals	100%
Activities restricted to a specific timeslot	Current restrictions

For the experiments, we provide all parameter settings in tables. With each setting, we adapt one value of one parameter. By analysing the outcomes of these various settings, we can assess how the model can adjust to varying availability of resources and requirements in the practical situation. Besides, these experiments contribute to the insights of the ophthalmology department about the impact of their resources and requirements on the KPIs.

1. *Number of residents required*

The number of residents assigned to a consultation hour affects the number of patients seen during that time. The stakeholders are therefore interested in whether adjusting the number of scheduled residents would make the model more efficient and, specifically, which number results in the highest number of scheduled activities, patients seen in a week and educational activities. In the experiments, we evaluate with one and two residents present, and in the final experiment, we allow the model to determine the optimal value.

Table 5: Parameter experiment settings: number of residents required at consultation hours

Parameter	*Professional availability*	*Residents required*	*Professional capacity*	*Rooms available*	*Presence professionals*	*Specific timeslot*	*N(P)*
	Current	1 (Current)	Current	11	100%	Current	41
	Current	2	Current	11	100%	Current	41
	Current	Adaptable	Current	11	100%	Current	41

To perform the third experiment, we had to adapt our model to create the capability of choosing the optimal number of residents for each activity. The consultation hours of orbit, anterior segment, posterior segment, pediatric eyecare, retina, and uveitis are the consultation hours are all executed multiple times a week and, therefore, comprise the majority of the patients seen at the department. Consequently, we focus on these activities with this adaptation of our model. We introduced the parameter 'PatientsPerWeek.' With this parameter, we can determine how many patients should be seen for the consultation hour of each subspeciality in a week. These numbers are based on the current blueprint. We have introduced new activities: consultation hours assisted by two residents instead of one. In coordination with the management, we determined that twenty patients could be scheduled in a consultation hour assisted by two residents. In contrast, twelve patients can be seen in a consultation hour with one resident. By incorporating the following constraint, we restrict the model to create a schedule that treats enough patients. The model can determine whether scheduling one or two residents for each consultation hour is better. We loosened the constraint focusing on the required number of activities planned for the activities of these subspecialties as we let the model decide on the optimal number of activities as long as the required number of patients is seen. The following constraint is set up for each type of consultation hour:

$$\sum_d \sum_h x_{'CHCareline1resident',d,h,w} * PS_{'CHCareline1resident',d,h,w} + \sum_d \sum_h x_{'CHCareline2residents',d,h,w} * PS_{'CHCareline2residents',d,h,w} \geq PW_{'Careline',w} \qquad \forall\, w$$

2. Availability of professionals

Some professionals work part-time, meaning there are specific days in their current schedule when they are absent. With this experiment, we aim to determine if these fixed part-time days impact the KPIs. In this experiment, the part-time days are not restricted in the parameter. The capacity of the professionals remains the same.

Parameter	*Professional availability*	*Residents required*	*Professional capacity*	*Rooms available*	*Presence professionals*	*Specific timeslot*	*N(P)*
	Current	1	Current	11	100%	Current	41
	Always available	1	Current	11	100%	Current	41

Table 6: Parameter experiment settings: Availability of the professionals

3. Capacity of professionals

Each professional has a specific capacity in terms of working days. With these experiments, we aim to understand if the capacity of professionals is a significant factor in scheduling activities and seeing patients. Therefore, in this experiment, we increase and decrease the capacity of all professionals in increments of 20%, followed by lowering the capacity of specifically ophthalmologists and residents.

Parameter	*Professional availability*	*Residents required*	*Professional capacity*	*Rooms available*	*Presence professionals*	*Specific timeslot*	*N(P)*
	Current	1	-40%	11	100%	Current	41
	Current	1	-20%	11	100%	Current	41
	Current	1	Current	11	100%	Current	41
	Current	1	+ 20%	11	100%	Current	41
	Current	1	+ 40%	11	100%	Current	41
	Current	1	*+20% (Ophthalmologists)*	11	100%	Current	41
	Current	1	*+20% (Residents)*	11	100%	Current	41

Table 7: Parameter experiment settings: Capacity of the professionals

4. *Availability of rooms*

With this experiment, we aim to gain insight into the impact of the available consultation rooms on the objectives. Currently, there are eleven consultation rooms located in the department. There is a possibility that this number will be lowered to nine available rooms, so the stakeholders are curious about the consequences of this reduction. The experiments included a downward and upward adjustment by two intervals.

Parameter	*Professional availability*	*Residents required*	*Professional capacity*	*Rooms available*	*Presence professionals*	*Specific timeslot*	*N(P)*
	Current	1	Current	7	100%	Current	41
	Current	1	Current	9	100%	Current	41
	Current	1	Current	11 (Current)	100%	Current	41
	Current	1	Current	13	100%	Current	41
	Current	1	Current	15	100%	Current	41

Table 8: Parameter experiment settings: available number of rooms

5. *Presence of professionals*

In the practical setting of the ophthalmology department, professionals can be absent and, therefore, unavailable for activities. These experiments focus on the model's responsiveness to fewer professionals available. Some professionals are randomly indicated as unavailable. The fourth and fifth experiments focus solely on unavailable residents and ophthalmologists.

Parameter	*Professional availability*	*Residents required*	*Professional capacity*	*Rooms available*	*Presence professionals*	*Specific timeslot*	*N(P)*
	Current	1	Current	11	100%	Current	41
	Current	1	Current	11	90%	Current	37
	Current	1	Current	11	80%	Current	33
	Current	1	Current	11	90% (Ophthal-mologists)	Current	39
	Current	1	Current	11	90% (Residents)	Current	39

Table 9: Parameter experiment settings: Presence of the professionals

6. *Activities at a specific timeslot*

Currently, some activities are scheduled at a specific moment in the week. This decreases the model's flexibility to schedule the remaining activities. With the experiments presented in Table 10, we aim to determine the impact of the current restrictions, compared with the results on the KPIs when there are no restrictions to the timeslots.

Parameter	*Professional availability*	*Residents required*	*Professional capacity*	*Rooms available*	*Presence professionals*	*Specific timeslot*	*N(P)*
	Current	1	Current	11	100%	Current	41
	Current	1	Current	11	100%	No restrictions	41

Table 10: Parameter experiment settings: certain activities restricted to specific timeslot

Interaction effects

We will investigate the interaction effects of the parameter values. We expect the model to deliver lower performance when the professionals are absent and as this scenario is the most likely to occur in practice, we will examine the interaction effects of the capacity and availability of professionals with the presence of the professionals.

Increasing the capacity of professionals could possibly help in dealing with the absence of professionals. Within these experiments, we lower the presence of the professionals in steps by 10% by randomly selecting absent professionals. The capacity of the professionals is increased by 20%.

Presence and capacity

Parameter	*Professional availability*	*Residents required*	*Professional capacity*	*Rooms available*	*Presence professionals*	*Specific timeslot*	*N(P)*
	Current availability	1	Current	11	100%	Current	41
	Current availability	1	+20%	11	90%	Current	41
	Current availability	1	+20%	11	80%	Current	41

Table 10: Parameter experiment settings: Presence and capacity of professionals

Restricting the professionals' availability to the current situation limits the model's flexibility in scheduling the activities. We are curious about the effects of relaxing the availability restriction and lowering the presence of the professionals. Therefore, we will set the professionals' availability to always be available and decrease their presence by ten per cent.

Parameter	*Professional availability*	*Residents required*	*Professional capacity*	*Rooms available*	*Presence professionals*	*Specific timeslot*	*N(P)*
	Current availability	1	Current	11	100%	Current	41
	Always available	1	Current	11	90%	Current	41
	Always available	1	Current	11	80%	Current	41

Table 11: Parameter experiment settings: Presence and availability of professionals

5.3 Computational results

This section presents the outcomes of the experiments. By interpreting the results, we examine how parameters and constraints impact the performance of our scheduling model. Our baseline scenario, where the model incorporates the department's current restrictions and requirements, is run in AIMMS using CPLEX 22.1 as a solver with a running time of 0.76 seconds. This results in zero unscheduled activities, 526 patients seen in a week, and a total of 210 educational activities scheduled. The ability to schedule all activities in the blueprint is an improvement, as in the current blueprint twenty-three activities cannot be scheduled. The number of patients that can be seen in a week has increased by 3.4%. The total number of educational activities scheduled for the residents remains the same with 210. This can be explained by the fact that, in the current blueprint schedule, the number of scheduled OR timeslots is too high compared to the operating theatre blueprint schedule, while these timeslots cannot be used. Additionally, this number is significantly higher than the current realised number of educational activities scheduled at 150.1, which is an increase of 42.7%.

The analysis discusses how variations in values of parameters such as professional presence, restricted working days, and consultation room capacity influence the KPIs. With the experiments, we show the model's adaptability to the practical challenges of the ophthalmology department. Therefore, these results provide insights into the model's responsiveness and the impact of alternating parameter values.

1. *Number of residents required*

Number of residents required	Unscheduled activities	Patients seen in a week	Total education activities in a month
1 (Current)	0	440	210
2	0	500	214
Adaptable	0	526	212

Table 11: Results experiments number of residents required for a consultation hour

Restricting the model to schedule one or two residents to a consultation hour of the subspecialties impacts the number of unscheduled activities, as it increases the number of patients seen by 15.9%. This increment can be declared by a consultation hour being more efficient when executed by two residents, as more patients can be seen per professional. Letting the model decide whether to schedule one or two residents leads to the optimal solution. All activities can be scheduled, the number of educational activities is stable, and 19.5% more patients can be seen compared to the baseline schedule. This number of patients is sufficient to comply with the norm. From this, we conclude that the number of assigned residents impacts the solution positively.

2. *Availability of professionals*

Availability of professionals	Unscheduled activities	Patients seen in a week	Total education activities in a month
Current availability	0	440	210
Always available	0	446	210

Table 12: Results experiments availability professionals

The professionals' availability and working days are determined by their preferences, which reduces the model's flexibility in scheduling the professionals. In this experiment, we compared the current working days of the professionals to when they would be available during the whole week, keeping the same capacity for each professional. The number of unscheduled activities and education activities is the same, and the number of patients seen has increased slightly. In conclusion, the availability of professionals slightly impacts the KPIs.

3. Capacity of professionals

Capacity of professionals	Unscheduled activities	Patients seen	Total education activities in a month
-40%	54	76	50
-20%	19	272	136
Current	0	440	210
+20%	0	460	210
+40%	0	460	210
+20% (Ophthalmologists)	0	440	210
+20% (Residents)	0	440	210

Table 13: Results experiments capacity of professionals

As described in Section 2.4, delivering a complete and suitable schedule is often difficult. The stakeholders think that the capacity of the professionals impacts this. With this experiment, we aimed to gain insights into the impact of the capacity of professionals on the feasibility of the schedule. We see that when we lower the capacity, the number of unscheduled activities significantly increases, next to a reduction in the number of patients seen and educational activities scheduled. On the other hand, raising the capacity of ophthalmologists, residents, or all healthcare professionals does not reduce the number of unscheduled activities and solely slightly increases the number of patients seen. From this, we conclude that reducing the capacity has a great negative impact on the feasibility of the schedule, and increasing the capacity of the current professionals has hardly any effect.

4. Number of rooms available

Rooms available	Unscheduled activities	Patients seen	Total education activities in a month
7	-	-	-
9	0	440	210
11 (Current)	0	440	210
13	0	440	210
15	0	446	210

Table 14: Results experiments available consultation rooms

The number of unscheduled activities is the same for each number of consultation rooms, except for reducing four rooms to seven rooms, which results in infeasibility. This can be declared by the fact that the activities restricted to a specific timeslot, that have to take place, require a specific number of rooms. If this number of rooms is not available, the model will result in infeasibility. Increasing the number of rooms does not alter the number of unscheduled activities and scheduled activities, and only slightly the number of patients seen per week. From this, we conclude that the number of available consultation rooms has a minimal impact on the KPIs.

5. Activities at a specific timeslot

Activities scheduled at a specific timeslot	Unscheduled activities	Patients seen	Total education activities in a month
Current restrictions	0	440	210
Without restrictions	0	460	210

Table 15: Results of experiment restriction activities at a specific timeslot

Currently, some activities are restricted to be scheduled at a specific timeslot. This reduces the flexibility of the model in scheduling the remaining activities. For this experiment, we loosened this restriction. The number of activities that cannot be scheduled remains the same, and a few more patients can be seen with the solution without restrictions. From this, we conclude that restricting activities to a specific time slot only slightly impacts the solution.

6. Presence of professionals

Presence of professionals	Unscheduled activities	Patients seen	Total education activities in a month
100%	0	440	210
90%	11	430	168
80%	17	404	150
90% (Ophthalmologists)	2	452	184
90% (Residents)	8	404	152

Table 16: Results experiments presence of professionals

Our base model assumes that all professionals are present in the department. However, in reality, professionals can be absent due to illness, leave, or conferences. With this experiment, we aim to determine the feasibility of the schedule, including absences. We see that the number of unscheduled activities increases significantly when the presence of professionals is lowered, declarable by that there are fewer professionals available to perform the activities. The number of patients seen reduces by 1.4% and 10.9%, respectively. The total number of scheduled educational activities is reduced with respectively 20.0% and 28.6%. From this, we conclude that the absence of professionals impacts the KPIs negatively. We also investigated the impact of the absence of ophthalmologists separately. The absence of 10% of the ophthalmologists leads to an increase in unscheduled activities and a decrease in patients seen at 8.2%. The absence of ophthalmologists negatively impacts the feasibility of the schedule, and the absence of residents has a bigger negative impact. Note that the absent professionals are determined at random, and the results of these experiments could be influenced by this given.

Interaction effects

Presence and availability of professionals

Presence of professionals	Availability of professionals	Unscheduled activities	Patients seen	Total education activities in a month
100%	Current	0	440	210
90%	Always available	11	434	205
80%	Always available	22	332	204

Table 17: Results experiments presence and availability of professionals

The number of unscheduled activities significantly increases when professionals are absent, to eleven and twenty-two activities. The number of patients seen and monthly educational activities decreases by 1.4% & 24.5% and 2.3% & 2.9%, respectively. We see that the model performs worse when professionals are absent, even though the model is allowed to schedule the professionals at all periods.

Presence and capacity of professionals

Presence of professionals	Capacity of professionals	Unscheduled activities	Patients seen	Total education activities in a month
100%	Current	0	440	210
90%	+20%	8	440	204
80%	+20%	19	440	202

Table 18: Results experiments presence and capacity of professionals

The number of unscheduled activities increases when professionals are absent, to eight and nineteen activities. The number of patients seen remains the same and the number of monthly educational activities decreases by 2.9% and 3.8%, respectively. The model performs worse when professionals are absent than with the baseline scenario, but the impact is less than when only the presence is lowered. Increasing the workload capacity of the remaining professionals helps mitigate the impact of absences.

5.4 Conclusion

In this chapter, we present the outcomes of the experiments conducted to validate and evaluate the performance of our proposed scheduling model. The results demonstrate its effectiveness in setting up a schedule and show the impact of the parameters on the model’s results in terms of scheduling activities.

The experiments also highlighted the model's ability to adapt to varying parameters, such as professional’ availability, the number of residents, scheduling restrictions, and available rooms. Furthermore, it provided insights into the critical factors influencing the scheduling outcomes. The experiments show decreased results on our KPIs when the presence and capacity of the professionals are lowered. The impact of the reduced presence of professionals is smaller when the capacity of the remaining professionals is increased. Showing the impact of the capacity and presence of the professionals on the ability to generate a feasible schedule can be a valuable insight for the department. Steering on these factors can help the department to maintain a feasible schedule.

Overall, the experiment results confirm that the proposed model offers a robust framework for creating a suitable outpatient clinic blueprint schedule and holds its potential for practical application in the ophthalmology department of UMC Utrecht.

6 Implementation

This chapter discusses the implementation of our solution within the ophthalmology department. Implementing the optimisation model well bridges the gap between theoretical design and practical application within the department. This section outlines the necessary steps to integrate the model into the scheduling process. Furthermore, we discuss how our solution is aligned with the 'Tactical Planning at the Outpatient Clinic' project and introduce the proposed scheduling guidelines.

6.1 Implementation of the model

Decisions made on the tactical planning level serve as input for our model. By combining our model and the project 'Tactical Planning at the Outpatient Clinic', the ophthalmology department can react to the fluctuating demand for care of the subspecialties. Currently, the demand for care is not insightful and, therefore, not known by the department. As described in Section 2.4, the department faces a waiting list for a long time, leading to stress for the healthcare professionals. With the 'Tactical Planning at the Outpatient Clinic' project running at UMC Utrecht, the department is getting more and more insights into waiting lists, consultation hour utilisation, and care demand. These insights allow the department to execute tactical planning, which is the control that is currently lacking, as concluded in Subsection 2.4.3.

Our model can contribute to this project, as the actual demand can be incorporated into it. The demand for care shows how many patients should be seen for a specific subspeciality to keep a stable system. The demand for care is becoming insightful by the implementation of the project, including patterns and weekly numbers. This weekly number for a subspeciality can be included in our model using the 'PatientsPerWeek' parameter, as described in Section 5.2. The model will then provide a schedule to see this number of patients. Integrating the project and our model facilitates capacity allocations to act on (varying) care demand, lowering the current scheduling boundary.

The delivered model is based on the department's current characteristics. In case of changes in these characteristics such as professionals entering or leaving the department, the model needs adaptations in the input to maintain feasibility. The ICM team can implement these changes in input in the parameters of the AIMMS model. We provide a handout with instructions about changing the characteristics of the department in the model and running the model again. This process can be performed at most monthly to create a suitable schedule while maintaining stability. Running the model generates a suitable and feasible schedule for the department. By running the 'ExportSchedule' function in AIMMS, the schedule is exported to an Excel file. This generates a schedule in Excel based on code names. Running the VBA module 'Transformation' converts the generated schedule into an easily interpretable format for the planning coordinators. The schedule can then be shared with the scheduling coordinators, who make minor adjustments to finalise it. The consultation room assignment can also be set up based on this schedule.

Changing the blueprint of a department may encounter resistance, as it impacts the schedules of healthcare professionals. Professionals will need to adapt to the new circumstances, which may evoke varying reactions. Therefore, it is essential that this implementation is well-supported by management and, if necessary, guided by a change management expert. Models for change management, such as Kotter's eight-step Change Model (Kotter, 1996) can assist with the implementation.

6.2 Planning recommendations

In this section, we will discuss the recommendations for the 'Tactical Planning at the Outpatient Clinic' project and provide the scheduling guidelines to comply with our model to secure the stability of the schedule.

6.2.1 Recommendations Processes

During the research, we encountered several suboptimal care and planning processes within the ophthalmology department. Discussing these processes and potential improvements during the set-up of the 'Tactical Planning in the Outpatient Clinic' can improve the care processes at the department. Within the following paragraphs, we bring suggestions for the topics.

Currently, the department has a relatively high repetition factor of 6.0, which indicates the proportion of follow-up appointments scheduled compared to new patient appointments. A high repetition factor leaves less capacity for scheduling new patients at consultation hours, which could lead to a waiting list for patients referred from general hospitals. This situation is unfavourable for the department. By aiming to reduce the repetition factor, this problem can be solved.

Second, the absence of professionals in the outpatient clinic and diagnostic department is not coordinated. It occurs that a patient's appointment cannot be scheduled for a while because the concerned ophthalmologist and TOAs are alternatingly absent while the patient should have been seen. By aligning the presence of professionals in both the outpatient clinic and diagnostic department who see patients of the same subspecialty, patients can be seen within the set time horizon more often.

Third, the number of examinations performed at the department has risen over the years, especially since the triage on the complexity of care. However, the number of spots available for examinations is based on outdated data. Investigating the current demand for examinations can give the department insights and allow them to respond to this given.

Fourth, the appointment slots of a consultation hour all have the same interval. When shadowing the consultation hours, we noticed that doctors sometimes had to wait for the patient to arrive at the beginning of the consultation hour. In contrast, a consultation hour often ran out. We recommend reviewing the appointment grid of the consultation hours. By decreasing the interval at the beginning of the consultation hour and increasing it at the final part, consultation hours are less likely to run over, and patients will experience less waiting time.

Fifth, as discussed in Subsection 2.4.4, appointment slots are sometimes blocked at the last minute due to absenteeism. This lowers the utilisation of the consultation hours and makes them less efficient. Steering on the utilisation increases the efficiency and the number of patients that can be seen with the capacity.

Sixth, emergency appointments are scheduled in separate consultation hours. Investigating this policy regarding emergency scheduling can demonstrate whether this is indeed the optimal policy or whether scheduling emergency patients within subspecialty consultation hours would improve the quality of care and efficiency.

6.2.2 Scheduling guidelines

In this subsection, we present the scheduling guidelines supporting our model. As described in Section 2.4, one of the stakeholders' problems concerns an unreliable and alternating schedule. Our model generates a suitable and stable schedule for the department. However, without scheduling guidelines, the monthly schedule can still be adapted often or require reallocating activities. Applying scheduling guidelines at the department secures a strong model implementation and reduces the online-operational rescheduling.

Setting up scheduling periods.

Setting up scheduling periods, for instance, three periods a year, allows the department to look ahead to the available capacity. The planning coordinators can look three months ahead for eventual bottlenecks in the available capacity to meet the care demand. The department can resolve these eventual capacity shortages by cooperating with managers and professionals on time to work extra hours or hire additional professionals temporarily. Furthermore, determining scheduling periods allows setting a deadline for notifying absences three months ahead, such as a congress or paternity leave. This leads to fewer unexpected absences and fewer late adjustments to the schedule.

Setting up guidelines regarding notifying absence

Setting up guidelines about notifying absences creates stability in the schedule by reducing the unexpected takeover of activities and reallocations. These currently lead to much restlessness in the professionals' schedules and a high workload for the planning coordinators. By setting a strict deadline for reporting absences considerably in advance, these absences can all be incorporated into the monthly schedule. Enforcing this deadline can significantly reduce the adjustments made to the schedule during the month itself, providing the professionals with a stable schedule. For the deadline, it is important to account for exceptions, such as illness or funeral attendance. Incorporating these guidelines reduces the restlessness in the schedule, a problem frequently identified with our research.

Determining a minimum number for each activity

Determining a minimum number for each activity to occur each week allows the planning coordinators to steer on these numbers, ensuring sufficient patients are seen to meet the care demand. There are no clear guidelines on how often an activity should occur weekly. Therefore, it is not possible to steer on these numbers. This leads to uncertainty and the inability to meet the care demand. By clearly defining these numbers, the department can compare them to the available capacity and anticipate any potential bottlenecks in availability. This allows for proactive measures, such as scheduling additional consultation hours for medical specialists if fewer residents are available.

Determining the priority of the continuation of activities

Creating a prioritisation in the continuation of activities ensures clarity in the scheduling process and prevents the department from seeing fewer patients than possible. It is not clear to the stakeholders which activities are essential to continue. This generates restlessness and variability in the process, as varying decisions about discontinuing activities are made when a professional is less available. This variability leads to less educational training for residents as they are reallocated. By prioritising activities, the scheduling process becomes more unambiguous for all stakeholders.

Uniform guidelines on grids for the consultation hours of each subspeciality

By integrating uniform grids for the consultation hours of each subspeciality, the workload of the planning coordinators can be lowered. Currently, each medical specialist prefers a specific grid for their consultation hour, a layout of the appointment slots within a consultation hour. The planning coordinators must incorporate these requirements when setting up the consultation hours in HiX. This includes seventeen different grids, creating more workload than when the planning coordinators could focus on six types of grids. Furthermore, this also creates the opportunity to set the grids efficiently, which we elaborated on in Subsection 6.2.1.

6.3 Conclusion

We can now answer our fourth research question on the implementation of the model in the ophthalmology department. We provided an implementation plan, which includes the alignment with the 'Tactical Planning in the Outpatient Clinic' project and instructions for the ICM team and department on working with the model to create a schedule. We identified improvement points in the current healthcare and planning process and presented scheduling guidelines to ensure stability in the realized schedule for the professionals.

7. Conclusion

This chapter discusses the conclusion of our research. We will summarise the key findings and contributions of this research.

With this research, we focused on the ophthalmology department of UMC Utrecht and examined the healthcare process and its control and performance. We have identified that the blueprint schedule is outdated, and there is minimal steering at the tactical level of control. This leads to schedule instability, resulting in either reallocation or cancelled activities. This resulted in a lower quality of training for residents. Consequently, the work pressure for professionals is experienced higher, and fewer patients are seen than intended. We aimed to set up a model that creates a feasible schedule, aligning with the characteristics and requirements of the ophthalmology department.

We developed an ILP scheduling model capable of generating an optimal staff-to-schedule addressing a healthcare setting's characteristics and requirements. The model offers a systematic approach to creating a suitable schedule by optimising resource utilisation. By the ability to incorporate characteristics such as professional availability, capacity, and care demand requirements, the model is applicable in a practical setting and can deal with varying input. This model allows the department to incorporate a new working method, improving residents' education quality as 42.7% more educational activities are incorporated into the schedule than currently realized. It provides a suitable schedule as all activities can be scheduled, considerably lower than the current number of twenty-three. The schedule generated by the model allows the department to see 3.4% more patients a week while incorporating the new way of working. Executing the model including the scheduling guidelines lowers the need for reallocations thereby increasing stability. Additionally, this model makes it easier for the ophthalmology department to implement tactical planning, as it can effectively incorporate changes in care demand into the schedule. The model is robust for changes in the number of rooms, scheduling requirements, and availability of professionals. It delivers the best blueprint schedule with the option to determine the optimal number of assigned residents. Decreasing the capacity and presence of professionals negatively impacts the results.

In conclusion, the optimisation model is a valuable healthcare staff scheduling tool. It improves the scheduling process, provides insights into current processes and paves the way for more robust and scalable solutions in the future.

8. Discussion

This chapter assesses the discussion of our research. While the results provided in Chapter 5 demonstrate the model's potential to generate a feasible schedule, several aspects need refinement and further exploration for improvement. Section 8.1 discusses the model's limitations. Chapter 8.2 provides aspects for further research.

8.1 Limitations

This section discusses the limitations of the proposed model. The model has several limitations that could impact its practical application and effectiveness, which will elaborated on. We create an overview of the models' capabilities and improvement points by discussing these points.

- The model is set to optimise towards minimising the number of unscheduled activities by which the required number of patients can be seen. In practice, multiple objectives may be important. The model cannot explain how different objectives (such as minimum workload versus maximum scheduled activities) relate.
- The model relies on inputs such as capacities, availability, and activity requirements. When the input data is incomplete or inaccurate, this can result in an unrealistic schedule.
- The model focuses exclusively on ophthalmology. This narrow scope restricts the generalizability of the model. This makes the model less applicable to other medical specialities, as they can have different care processes, characteristics and scheduling requirements. As a result, the model must be adapted to be transferable to other medical specialities.
- In the experiments, increasing the capacity of healthcare professionals had little impact on the KPIs. For this experiment, the current professionals, including their specific competencies, from the department were used. However, it is possible that the results would improve if the capacity for other competencies were to increase.
- We assumed that professionals are assigned to activities independently for each part of the day. Consequently, it can be challenging to perform two consultation hours in a day in practice. This is not beneficial for the quality of labour, which is not incorporated into the model.
- The model is specified for the ophthalmology department's situation. This decreases its scalability, as setting it to a different outpatient clinic requires work.
- The experiments showed us that the model is not robust for changes in the capacity and presence of professionals. This leads to our model being less applicable in the practical setting.
- The model is not synchronised with the current scheduling software and EPR. The planning coordinators must manually incorporate the outcomes into this software, which could lead to efficiencies. Besides, the manual integrations risk potential data inconsistencies.
- Currently, a few professionals combine two activities in one part of a day, as this is feasible for some activities, making the processes more efficient. However, we assumed that a professional could execute only one activity per part of a day. This is the case for the majority of the activities, but for a few activities, this is not necessarily the case. This leads to fewer activities being scheduled, decreasing efficiency.
- Some activities require multiple professionals to be scheduled, for instance, an ophthalmologist, an orthoptist, and a resident are required to perform the pediatric consultation hour. This leads to less flexibility for the model to schedule this activity than an activity only requiring one professional to be executed. This results in activities requiring multiple professionals being more

difficult to schedule. In case of lower capacity or presence of a professional, the model is more likely to schedule the activities solely requiring one professional, as this contributes more to minimising the number of unscheduled activities.

- The model's outcomes are complex to interpret. For the stakeholders to interpret the results, the model requires a transformation to a spreadsheet format using VBA code.

8.2 Further research

This section discusses suggestions for further research on our model, which can strengthen its capabilities and/ or increase its practical suitability.

The planning coordinators manually assign the consultation rooms to a specific consultation hour. This is a complex process and takes up much time. Currently, the model solely checks whether sufficient consultation rooms are available at the department to schedule the activities requiring one or multiple. Expanding the model by assigning consultation rooms to activities would make the scheduling process more efficient and lower the workload of the planning coordinators.

The model is designed specifically for the ophthalmology department. When setting up the model, certain assumptions were made about scheduling specific activities at particular timeslots based on predefined agreements with other departments. However, this limits the model's flexibility and may result in suboptimal outcomes. Expanding the model to include multiple departments would enable the model to determine the optimal time slot for these activities, ensuring the availability of professionals in all required departments. This extension would increase scheduling flexibility and enhance the outcomes.

The designed model can generate a feasible schedule incorporating the current professionals of the department. The model can schedule the activities so that sufficient patients can be seen. The department's care demands can be transformed into weekly numbers, which can be included in the model. However, when the care demand strongly increases or the capacity decreases for the leave of professionals, the model cannot schedule all activities as resources are insufficient. It would provide important insides for the department when the model could show what type of professionals, including competencies, are necessary to create an adequate schedule.

Currently, the planning for the professionals of the outpatient clinic (ophthalmologists, residents, orthoptists, optometrists and nurse practitioner) is set up separately from the planning of the professionals of the diagnostic department (nurses, TOAs, doctors’ assistants). However, as seen with the patient journey at the department, described in Subsection 2.1.3, a patient sees both types of professionals during a visit at the department. Therefore, the availability of professionals at the outpatient clinic and the diagnostic department is necessary to schedule a patient’s appointment. However, the scheduling is not performed simultaneously. The scheduling of professionals from the diagnostic department is based on the outpatient clinic’s schedule after this schedule is delivered. Diagnostic department professionals can assist with specific examinations or support consultation hours. It is assumed that there are always enough diagnostic department professionals available to fulfil both tasks, which cannot always be guaranteed in reality. This results in nurses and TOAs experiencing high workloads, as their presence is always expected. Additionally, appointment slots must be blocked, or patients must be rescheduled for later if insufficient TOAs or nurses are available. This can lead to fewer patients being seen than possible. Expanding the model to schedule the professionals of both the outpatient clinic and diagnostic department can improve the scheduling and, therefore, the number of patients seen.

Appendix

A. Sources

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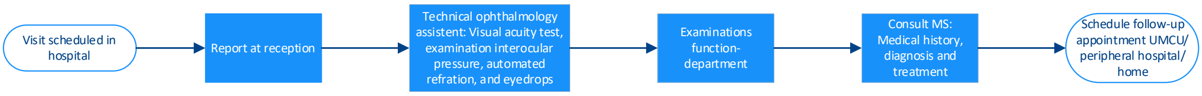
B. List of figures and tables

B.1List of Figures

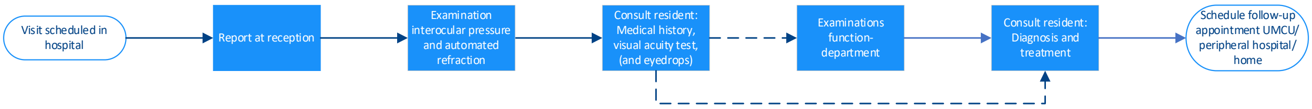
B.2 List of Tables

C. Flowcharts patient journey

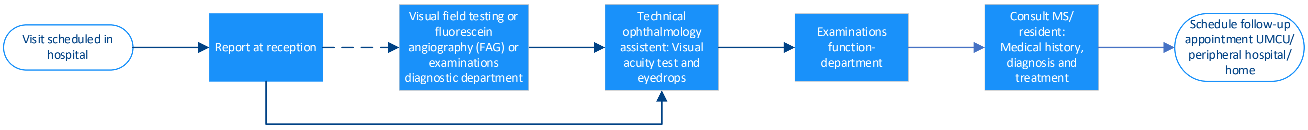
C.1 New patient visiting medical specialist



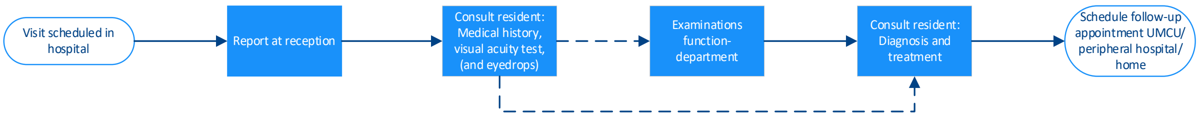
C.2 New patient visiting resident



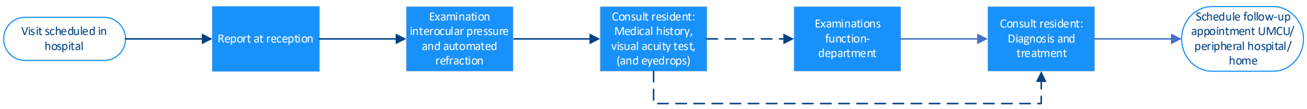
C.3 Recurrent patient visiting medical specialist



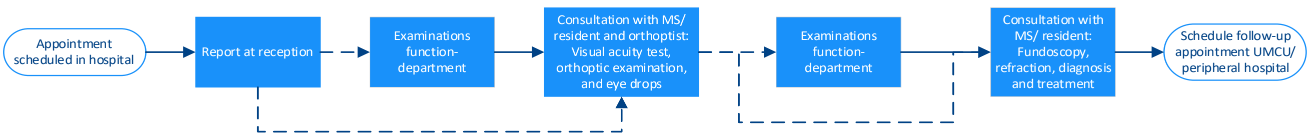
C.4 Recurrent patient visiting resident



C.5 Emergency patient



C.6 Child



D. Overview shadowed processes

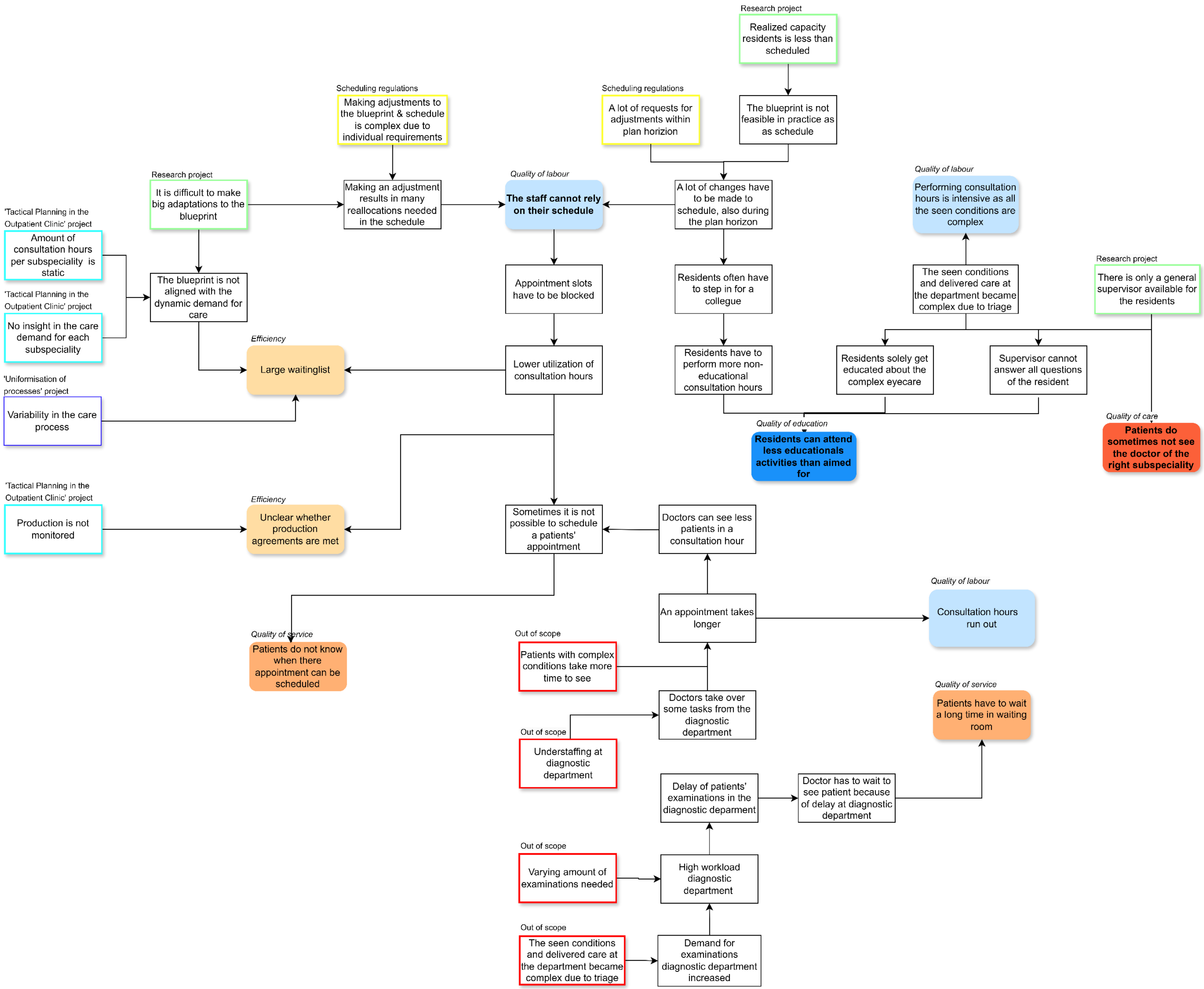
Healthcare processes

- Supervised consultation hour of a resident
- Unsupervised consultation hour of a resident
- Emergency consultation hour of a resident
- Consultation hour of a medical specialist with the support of a TOA
- Consultation hour of a medical specialist without the support of a TOA
- Consultation hour of an optometrist
- Strabismus surgery
- Examinations diagnostic department
- Reporting of patients at reception

Planning processes

- Set-up of the monthly schedule based on the blueprint
- Process adjustment requests in the schedule
- Surgical admission scheduling
- Scheduling diagnostic department
- Operational planning meeting

E. Problem cluster



F. Method systematic literature review

F.1 Search terms, including synonyms

Search term	Synonyms
Optimisation	Optimisation Techniques, Optimization Models, Mathematical Optimization, Algorithmic Optimization, Computational Optimization, Combinatorial Optimization, Operations Research, Decision Analysis, Linear Programming, Nonlinear Programming, Dynamic Programming, Heuristic Methods, Constraint Programming, Simulation Optimization, Systems Optimization, Quantitative Analysis.
Staff scheduling	Personnel Scheduling, Shift Planning, Employee Rostering, Resident Scheduling, Physician Scheduling, Labor Scheduling, Workforce Optimization, Scheduling Optimization, Scheduling Algorithms, Staff Allocation, Scheduling Techniques, Scheduling Models, Resource Scheduling, Staffing Models, Scheduling Strategies, Scheduling Systems, Scheduling Efficiency, Staffing.
Outpatient clinic	Ambulatory Services, Outpatient Facility, Outpatient Care Center, Ambulatory Care Center, Outpatient Department, Outpatient Healthcare Facility, Ambulatory Service Center, Outpatient Treatment Center, Ambulatory Treatment Facility, Outpatient Medical Center

F.2 Search query

("Optimization" OR "Optimization Techniques" OR "Optimization Models" OR "Mathematical Optimization" OR "Algorithmic Optimization" OR "Computational Optimization" OR "Combinatorial Optimization" OR "Operations Research" OR "Decision Analysis" OR "Linear Programming" OR "Nonlinear Programming" OR "Dynamic Programming" OR "Heuristic Methods" OR "Constraint Programming" OR "Simulation Optimization" OR "Systems Optimization" OR "Quantitative Analysis") AND ("Staff Scheduling" OR "Staffing" OR "Personnel Scheduling" OR "Shift Planning" OR "Employee Rostering" OR "Labor Scheduling" OR "Workforce Optimization" OR "Scheduling Optimization" OR "Scheduling Algorithms" OR "Staff Allocation" OR "Scheduling Techniques" OR "Scheduling " OR "Resource Scheduling" OR "Staffing Models" OR "Scheduling Systems" OR "Physician scheduling" OR "Resident Scheduling" OR "Blueprint") AND ("Outpatient clinic" OR "Ambulatory Services" OR "Outpatient Facility" OR "Outpatient Care Center" OR "Ambulatory Care Center" OR "Outpatient Department" OR "Outpatient Healthcare Facility" OR "Ambulatory Service Center" OR "Outpatient Treatment Center" OR "Ambulatory Treatment Facility" OR "Outpatient Medical Center") AND PUBYEAR > 2014

F.3 Selection criteria

To determine which study to include in the literature review, the titles of the studies were screened for suitability. Table 2 presents the screening criteria, including a description.

Screening criteria	Description
Study design	Scheduling model optimisations for outpatient clinics in hospitals.
Population	Outpatient clinic department or similar healthcare contexts.
Model Type	Mathematical models, simulations, heuristics.
Outcome Measures	Measures of efficiency, waiting times, workload, or resource utilisation.
Publication Type	Peer-reviewed journals, conferences, and academic books.
Period	Studies from July 2015 to July 2024.

F.4 Exclusion criteria accesibility

After the titles were screened, the remaining studies were checked for availability and language. Inaccessible and non-English studies were excluded from the review.

Exclusion criteria accessibility	Description
Accessibility	Articles not available in full-text format
Language	Studies not published in English

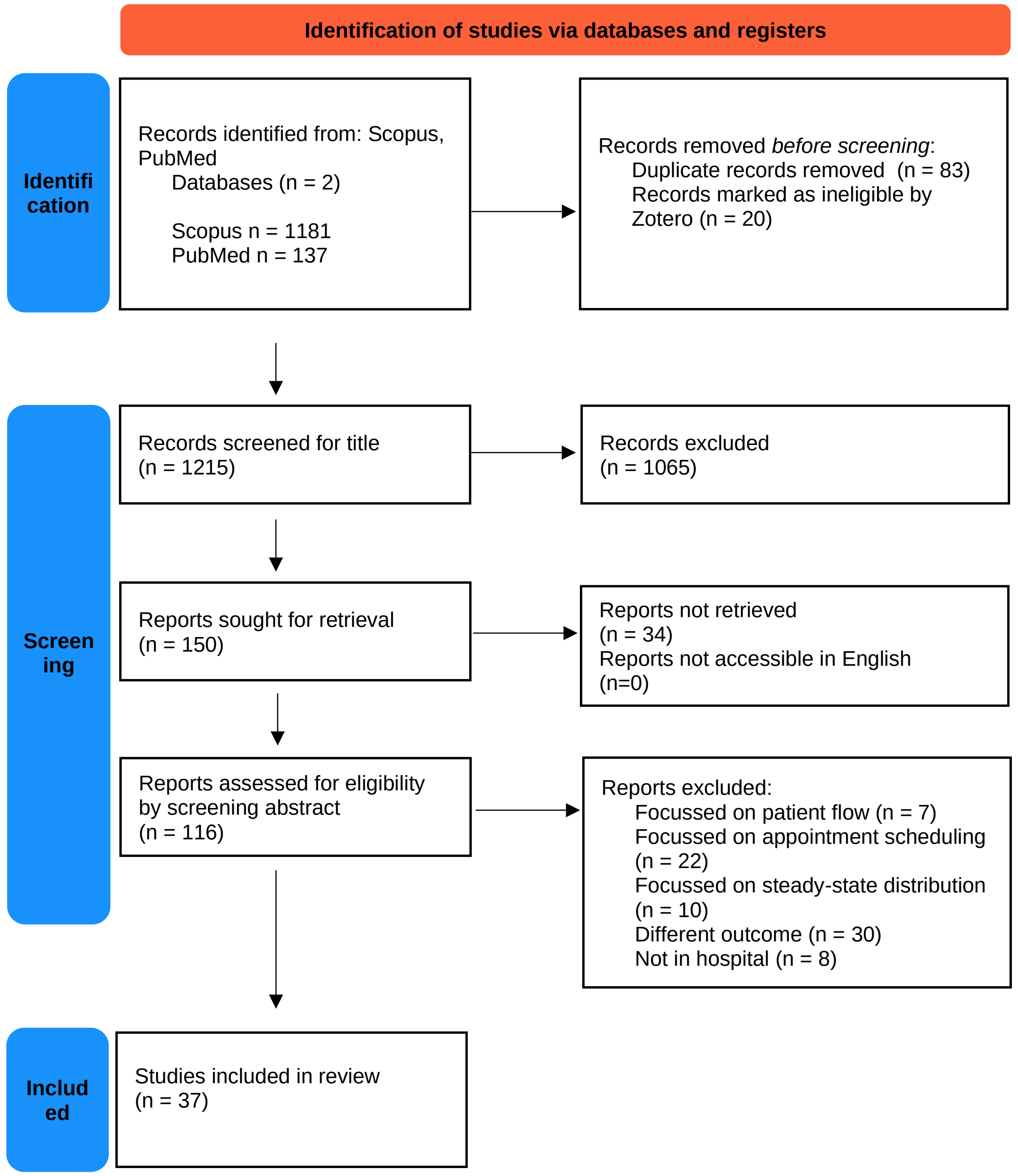
F.5 Exclusion criteria

The abstracts of the remaining publications were read and screened for suitability. Studies were excluded from the systematic review if they focused on patient flow, appointment scheduling, or steady-state distribution. The studies were also excluded if a different type of outcome was obtained or if the studies were not executed in a hospital.

Exclusion criteria abstract	Description
Study focussed on patient flow	Studies focused on the flow of the patients during their visit to the hospital.
Study focussed on appointment scheduling	Studies focused on patient scheduling on an appointment.
Study focussed on steady-state distribution	Studies focused on obtaining a steady state based on the healthcare demand and resource capacity.
Study obtains different type of outcome	Studies obtaining a different type of outcome then a schedule, such as a study focused on the theoretical part of the model.
Study not executed in hospital setting	Study executed in a setting outside a hospital.

F.6 PRISMA flow diagram

The systematic literature review was executed step-by-step using the PRISMA flow diagram. Figure 4 presents the diagram, including the studies covered in each phase.



F.7 Extraction

Certain information from all studies was extracted to a table to obtain a clear overview of the included publications. First, general information is noted: Title, authors, year, and country. Second, the general information about the study is listed: Population, approach, results, conclusion, and discussion. To serve as inspiration for our model, the following is presented: Software, input data, outcome measures, and validation.

Information	Description
Title	Title of the study
Authors	List of authors involved
Year	Publication year of the study
Country	Country where the study was conducted
Objective	Purpose of the study
Population	Study sample or target group
Approach	Methodology or type of model used
Software	Software tools used in the study
Input data	Type of data used in the study
Outcome measures	Metrics or outcomes evaluated
Results	Main results and insights
Validation	Methods used to validate results
Conclusion	Summary of study conclusions
Discussion	Key points discussed and implications

F.8 General characteristics

Information	Variables	Count	Percentage
Year of publication	2015	1	2,6%
	2016	3	7,7%
	2017	2	5,1%
	2018	3	7,7%
	2019	4	10,3%
	2020	2	5,1%
	2021	6	15,4%
	2022	9	23,1%
	2023	5	12,8%
	2024	4	10,3%
Continent	Asia	13	33,3%
	Europe	11	28,2%
	North America	11	28,2%
	South America	2	5,1%
	Africa	2	5,1%
Approach	Optimisation Model	20	54,1%
	Stochastic Optimization Model	6	16,2%
	Simulation model	6	16,2%
	Queueing theory	2	5,4%
	Artificial Intelligence	1	2,7%
	Case study	1	2,7%
	Game Theory	1	2,7%

Software	Not specified	16	48,7%
	Arena	3	7,7%
	IBM CPLEX	2	5,1%
	Matlab	2	5,1%
	C++	2	5,1%
	GAMS CPLEX	2	5,1%
	AIMMS CPLEX	2	5,1%
	Python	1	2,6%
	AIMMS Gurobi	1	2,6%
	Python Gurobi	1	2,6%
	C++ CPLEX	1	2,6%
	IVE Express	1	2,6%
	Gurobi	1	2,6%
	C#	1	2,6%
Validation	Case-study	9	23,1%
	Numerical experiments	8	20,5%
	Discrete event simulation	5	12,8%
	Simulation	5	12,8%
	Not specified	5	12,8%
	Monte-Carlo simulation	2	5,1%
	AI-based tools	1	2,6%
	Particle swarm optimization algorithm	1	2,6%
	Regression model	1	2,6%
	Validated by staff	1	2,6%

F.9 Summary papers

In this section, we discuss the results of our systematic literature review. We will elaborate on the most used approaches and their application to resource scheduling problems. We have obtained two systematic literature reviews elaborating on staff planning. Vieira et al. (2016) reviewed papers addressing operations research (OR) to solve logistical problems, among which staff resource capacity planning in radiotherapy and identifying effective applications of analytical models. Zhu et al. (2019) reviewed operating room planning and surgery scheduling techniques from different perspectives, summarising effective methods and their impact.

Optimization model

The most used approach among the obtained studies is an optimisation model. Bovim et al. (2021) studied an integrated master surgery and outpatient clinic scheduling problem. With an optimisation model, they schedule the specialities, activity types, and physicians to time slots in the outpatient clinic and operating rooms throughout the week to meet the demand efficiently. The paper by Munavalli et al. (2017) proposes a predictive resource planning model for outpatient clinics that uses an integer linear programming model to allocate resources dynamically.

Koruca et al. (2023) developed a personalised staff scheduling method focusing on work-life balance using generic algorithms. It considers physician preferences regarding working hours and starting times and allows management to determine the number of physicians at specific moments. Li et al. (2022) optimised physician scheduling in outpatient clinics, anticipating the care demand and also respecting physician preferences.

Ren et al. (2016) present a plant growth simulation algorithm, solving optimal scheduling of doctor outpatient departments effectively to increase patient satisfaction and reduce operating costs in a hospital. Díaz-López et al. (2018) designed a mixed integer linear programming model using a greedy randomised adaptive search procedure to improve OR utilisation. The model shows that a decrease in tardiness or waiting time entailed a decrease in OR utilisation. Hong et al. (2019) created resident shift schedules using an integer programming model, considering multiple objectives and improving scheduling by providing multiple Pareto-dominant solutions.

Bikker et al. (2015) developed an integer linear programming (ILP) model to design a weekly physician schedule that minimises the expected access times and matches the number of consultation time slots with the demand. Hua et al. (2023) modelled the delivered healthcare at an outpatient clinic as an integer linear programming problem. The case study by van de Vrugt et al. (2018) examines how integrated scheduling of tasks and gynaecologists can enhance patient appointment scheduling in gynaecology departments. Using a mixed-integer linear programming model, the study demonstrates that integrating these elements leads to more efficient appointment scheduling, improving patient flow and resource utilisation. Similarly, Mu et al. (2021) used mixed-integer programming to optimise an obstetric ward, highlighting improvements in the capacity of the service in obstetric hospitals. The study of Keshtzari et al. (2024) introduces a mixed-integer linear programming model designed to optimise capacity allocation in cancer centres, particularly under demand uncertainty. It demonstrates that (slightly) increasing the flexibility of physicians significantly enhances the centre's ability to meet patient demands. Zimmerman et al. (2020) developed a schedule optimisation model based on mixed-integer linear programming, which maximises time spent with clients by nurses without increasing the capacity of the nurses. Similarly, Vissers (2022) focuses on master scheduling for physicians at a gynaecology outpatient clinic, showing that using integer quadratic programming models enhances the access times and compliance with the preferences of the gynaecologists and lowers the time needed for creating the schedules. The study of Wang et al. (2021) presents a mixed-integer linear programming model for outpatient care, incorporating capacity allocation and a risk-averse decision criterion to balance operational costs and capacity shortage risk in mental disorder outpatient clinics. Wang et al. (2020) focus on resource allocation and surgery scheduling problems considering assistant surgeons. A two-stage (mixed) integer programming model is proposed, and a bound-based algorithm is developed to solve the model to minimise operating theatre costs.

Heuristics and meta-heuristics are also employed to optimise staff scheduling. Yu et al. (2024) combined meta-heuristics and Q-learning to address rescheduling problems in multi-objective surgery scheduling, showing improved staff satisfaction. Bolsi et al. (2022) applied a local search heuristic to optimise server scheduling in an outpatient clinic, minimising tardiness.

Bakker and Tsui (2017) introduce a minimal-variability resource allocation model for the flexible allocation of physicians to outpatient schedules, combined with appointment scheduling. This algorithm addresses the complexity of fluctuating demand and physician availability. The study demonstrates improved patient service levels and reduced waiting times without increasing resource capacity.

Stochastic Optimization Model

A stochastic optimisation model, an optimisation model incorporating uncertainty, is applied within multiple obtained resources. Aslani et al. (2021) implemented a robust optimisation model for tactical capacity planning of physicians in an outpatient setting. Using cardinality-constrained robust optimisation, the model protects against uncertainty about the number of incoming patients and guarantees the feasibility of the tactical capacity plan. Bai et al. (2023) used a stochastic optimisation model to improve scheduling in speciality outpatient clinics. The paper proposes partially partitioned templating strategies that cluster patient groups and allocate appointment slots to these. A two-stage stochastic optimisation model was designed to simultaneously optimise patient group clustering and capacity allocation decisions. The study resulted in maintaining high-capacity utilisation and timely access for specific groups of patients. Davarian and Behnamian (2022) focused on optimising operating room scheduling and rescheduling to minimise patient waiting time, considering both emergency and elective patients, as well as uncertainties. The model outperforms the particle swarm optimisation algorithm regarding waiting time and tardiness using robust optimisation and a genetic algorithm. Hoffmans et al. (2024) developed a stochastic optimisation method using generic algorithms to optimise the scheduling of radiotherapy resources. The study of Zhou et al. (2022) integrated capacity planning and patient scheduling using a two-stage stochastic optimisation model. Their paper indicated that such integration enhances both planning and scheduling efficiency. Vali-Siar et al. (2018) focus on multi-period, multi-resource planning under uncertainty. A mixed integer linear programming model was developed to minimise tardiness, overtime and idle time while considering professionals, equipment, and bed availability.

Simulation model

Simulation models are also common for improving staff scheduling and resource allocation. In the obtained studies, it is also a tool to evaluate scheduling and allocation strategies. First, Al-Hawari et al. (2022) developed a framework using discrete event simulation (DES) and response surface methodology to evaluate and optimise healthcare systems. DES is a flexible tool for dealing with complex systems that consider details.

Berg et al. (2018) evaluated the effects of a flexible examination room policy with discrete-event simulation among specialities in an outpatient clinic of an academic medical centre, focussing on resource utilisation. Barros et al. (2021) used stochastic simulation to assess the performance of different configurations of facilities and resources within a hospital. The study provides hospital managers with a decision tool for determining the distribution of their medical resources. Similarly, Patel et al. (2020) evaluated resource allocation policies of shared resources in an outpatient speciality clinic using a simulation model. The model improved resource utilisation and a better understanding of the operational performance trade-offs. Berg and Vandenbrink (2019) also used simulation to evaluate healthcare provider scheduling heuristics, enhancing scheduling efficiency and healthcare provider utilisation. Using a simulation model, Sajadi et al. (2016) optimised nurse scheduling in emergency departments. A simulated annealing algorithm is applied to the model and shows a decrease in waiting time while fulfilling the hospitals' limitations and nurse preferences.

Queueing theory

One study applies queueing theory. Mtonga et al. (2022) assessed the relationship between staffing ratios and waiting times at a hospital. With queueing theory, a steady state has been determined to reduce waiting times and improve the delivered healthcare.

Game theory

Wu (2023) used two game-theoretic models to allocate physician appointments in outpatient clinics, realising the availability objectively assesses physician workload and provides a more equitable distribution of appointment availability.

Artificial intelligence

Eskandarani et al. (2024) developed AI-based annual medical training rotation schedules for emergency medicine residents to meet the educational guidelines and improve resident satisfaction.

G. PRISMA research information extraction table

Title	Authors	Year	Country	Objective	Population	Approach	Software	Input Data	Outcome Measures	Results	Validation	Conclusion	Discussion
A Framework for Multi-response Optimization of Healthcare Systems Using Discrete Event Simulation and Response Surface Methodology	Al-Hawari, T., et al.	2022	Jordan	Optimize healthcare systems	Healthcare systems	Simulation & Response Surface Methodology	Not specified	System data from healthcare settings	Optimization metrics, response surface analysis	Improved system efficiency and response times	Discrete Event Simulation	Framework improves efficiency and response time.	AI models improve scheduling, enhance resident wellness.
A robust optimization model for tactical capacity planning in an outpatient setting	Aslani, N., et al.	2021	USA	Improve capacity planning for outpatient services	Outpatient facilities	Robust optimization model	IBM CPLEX	Patient arrival data, demand forecasts	Capacity utilization, scheduling efficiency	Enhanced capacity planning and reduced waiting times	Monte-Carlo simulation	Model effectively improves capacity planning.	Multi-response optimization integrates DES, RSM for healthcare systems.
Partially partitioned templating strategies for outpatient specialty practices	Bai, M., et al.	2023	USA	Improve scheduling in specialty outpatient practices	Specialty practices	Stochastic optimization model	Not specified	Historical scheduling data, patient flow data	Scheduling metrics, patient throughput	Improved scheduling efficiency and reduced wait times	Case-study	Templating strategies enhance scheduling efficiency.	Robust models manage outpatient capacity amid uncertainties.
Dynamic resource allocation for efficient patient scheduling: A data-driven approach	Bakker, M., Tsui, K.-L.	2017	Netherlands	Optimize patient scheduling	Healthcare facilities	Optimization model: Generic algorithm	Matlab	Patient scheduling data, resource availability	Resource utilization, scheduling efficiency	Improved scheduling efficiency and resource utilization	Discrete Event Simulation	Approach enhances scheduling and resource use.	Templating strategies balance specialization, flexibility in outpatient practices.
Demand analysis and capacity management for hospital emergencies using advanced forecasting models and stochastic simulation	Barros, O., et al.	2021	Brazil	Manage emergency room capacity and demand	Hospital emergency rooms	Stochastic simulation	Arena	Historical demand data, emergency room capacity	Demand forecasts, capacity utilization	Improved management of emergency room capacity and demand	Validated by staff	Forecasting models improve emergency capacity management.	Data-driven methods optimize patient scheduling, resource allocation.
Use of simulation to evaluate resource assignment policies in a multidisciplinary outpatient clinic	Berg, B., et al.	2018	USA	Evaluate resource assignment policies	Outpatient clinics	Simulation model	Arena	Clinic resource data, patient flow data	Resource utilization, patient wait times	Improved resource assignment policies and reduced wait times	Discrete event simulation	Simulation improves resource assignment and reduces wait times.	Stochastic simulations forecast demand, manage emergency capacities.
Using Simulation to Evaluate Provider Scheduling Heuristics in Specialty Outpatient Clinics	Berg, B., Vandenbrink, A.	2019	USA	Evaluate provider scheduling heuristics	Specialty outpatient clinics	Discrete Event Simulation and Scheduling heuristics	Arena	Provider scheduling data, clinic operations data	Scheduling efficiency, provider utilization	Enhanced provider scheduling and utilization	Simulation	Simulation improves provider scheduling and utilization.	Simulations evaluate outpatient clinic resource policies.
Reducing access times for radiation treatment by aligning the doctor's schemes	Bikker, I. A., et al.	2015	Netherlands	Reduce access times for radiation treatment	Radiation treatment centres	Optimization model: Integer Linear Programming	AIMMS using CPLEX	Doctor scheduling data, patient treatment data	Access times, scheduling efficiency	Reduced access times and improved scheduling	Simulation	Aligning doctor schedules improves access times.	Heuristics assessed via simulations for provider scheduling.
Optimizing a Dynamic Outpatient Facility System with Multiple Servers	Bolsi, B., et al.	2022	Italy	Optimize outpatient facility with multiple servers	Outpatient facilities	Optimization model: Local Search Heuristic	C++	Facility operations data, patient flow data	Server utilization, wait times	Improved server utilization and reduced wait times	Computational experiments	Optimization improves server utilization and wait times.	Aligning schedules cuts radiation treatment access times.
Integrated master surgery and outpatient clinic scheduling	Bovim, T. R., et al.	2022	Norway	Integrate surgery and outpatient clinic scheduling	Hospitals	Optimization model	IVE Xpress 8.6	Surgery and clinic scheduling data	Scheduling efficiency, resource utilization	Improved integration of surgery and outpatient scheduling	Simulation	Integration improves scheduling efficiency.	Dynamic outpatient systems optimized with multi-server models.
Robust finite-horizon scheduling/rescheduling of operating rooms with elective and emergency surgeries under resource constraints	Davarian, F., Behnamian, J.	2022	USA	Optimize scheduling of operating rooms with constraints	Hospitals	Robust optimization model: Bertsimas and Sim model	GAMS with CPLEX	Operating room scheduling data, surgery data	Scheduling efficiency, resource utilization	Improved scheduling and resource management under constraints	Stochastic modeling	Robust scheduling improves efficiency under constraints.	Integrated scheduling enhances surgery and clinic efficiency.
A simulation-optimization approach for the surgery scheduling problem: Case research considering stochastic surgical times	Díaz-López, D. M., et al.	2018	Colombia	Optimize surgery scheduling with stochastic times	Hospitals	Optimization model: MILP with GRASP	GAMS with CPLEX	Surgical times data, scheduling data	Scheduling efficiency, stochastic time management	Improved scheduling efficiency considering stochastic times	Monte Carlo Simulation	Simulation-optimization improves scheduling under stochastic conditions.	Robust scheduling balances electives and emergency surgeries.
Creating a master training rotation schedule for emergency medicine residents and challenges in using artificial intelligence	Eskandarani, R., et al.	2024	USA	Develop training rotation schedules for residents	Emergency medicine residents	Artificial intelligence	Not specified	Training data, resident preferences	Scheduling efficiency, resident satisfaction	Improved scheduling and satisfaction among residents	AI-based tools	AI-based scheduling improves training effectiveness.	Stochastic times modeled in surgery scheduling optimization.

Staffing for many-server systems facing non-standard arrival processes	Heemskerk, M., et al.	2022	Netherlands	Optimize staffing for many-server systems	Many-server systems	Queueing	Not specified	Arrival data, staffing data	Staffing efficiency, system performance	Improved staffing efficiency and system performance	Simulation	Staffing optimization improves system performance.	AI addresses training schedule challenges for residents.
Robust optimisation of a radiotherapy pretreatment preparation workflow	Hoffmans-Holtzer, N., et al.	2024	Netherlands	Optimise radiotherapy pretreatment preparation	Radiotherapy centres	Optimisation model: Stochastic Integer Programming	AIMMS with CPLEX	Pretreatment preparation data	Workflow efficiency, preparation times	Improved pretreatment preparation workflow	Case-study	Optimisation improves pretreatment preparation efficiency.	Staffing models adapt to non-standard patient arrivals.
Creating resident shift schedules under multiple objectives by generating and evaluating the Pareto frontier	Hong, Y.-C., et al.	2019	USA	Create shift schedules considering multiple objectives	Residents	Optimisation model: Integer Programming	Python and C++ using CPLEX	Shift scheduling data, resident preferences	Scheduling efficiency, objective balance	Enhanced shift scheduling considering multiple objectives	Computational experiments and case-study	Pareto analysis improves shift scheduling balance.	Optimisation robustifies radiotherapy prep workflows.
Fractured systems: A literature review of OR/MS methods applied to orthopaedic care settings and treatments	Howells, M., et al.	2023	UK	Review OR/MS methods for orthopaedic care settings	Orthopaedic care settings	Literature review	Not specified	Literature on OR/MS methods	Review of methods, treatment effectiveness	Identified effective OR/MS methods for orthopaedic care	Literature-based validation	Effective OR/MS methods are available for orthopaedic care.	Pareto Frontier optimizes resident shift schedules.
Research on outpatient capacity planning combining lean thinking and integer linear programming	Hua, L., et al.	2023	China	Improve outpatient capacity planning	Outpatient facilities	Optimisation model: Integer Linear Programming	IBM CPLEX	Capacity data, efficiency metrics	Capacity utilisation, planning efficiency	Enhanced capacity planning and efficiency	Not specified	Capacity planning improves with lean thinking and programming.	OR/MS methods applied to orthopedic care scheduling.
Case Research: Capacity Management in the General Hospital of ZGT, Almelo (NL)	Kats, M. M., Quik, J. H.	2021	Netherlands	Manage capacity in a general hospital	General Hospital	Case research approach	Not specified	Hospital capacity data	Capacity utilisation, resource management	Improved capacity management and resource utilization	Not specified	Capacity management strategies are effective in hospitals.	Lean ILP methods optimise outpatient capacity planning.
Capacity Allocation in Cancer Centers Considering Demand Uncertainty	Keshtzari, M., Norman, B. A.	2024	USA	Optimize capacity allocation in cancer centers	Cancer centres	Optimisation model: mixed-integer linear program	Not specified	Cancer centre capacity data, demand forecasts	Capacity utilisation, demand management	Improved capacity allocation considering demand uncertainty	Computational experiments	Capacity allocation improves under demand uncertainty.	Case research on hospital capacity management.
Development of a new personalized staff-scheduling method with a work-life balance perspective: Case of a hospital	Koruca, H. İ., et al.	2023	Türkiye	Develop personalized staff scheduling with work-life balance	Hospital staff	Optimization model: generic algorithms	C#	Staff scheduling data, work-life balance metrics	Scheduling efficiency, work-life balance	Improved staff scheduling with better work-life balance	Case-study	Personalised scheduling improves work-life balance.	Managing demand uncertainty in cancer centre capacities.
Physician scheduling for the outpatient department with nonhomogeneous patient arrival and priority queue	Li, N., et al.	2022	China	Optimize physician scheduling with nonhomogeneous arrivals	Outpatient departments	Optimisation model: Generic Algorithm	Not specified	Arrival data, priority data	Scheduling efficiency, patient wait times	Improved scheduling considering nonhomogeneous arrivals	Computational experiments	Scheduling improves with priority queue considerations.	Personalised scheduling considers work-life balance for staff.
Adaptive staff scheduling at Outpatient Department of Ntaja Health Center in Malawi-A queuing theory application	Mtonga, K., et al.	2022	Malawi	Improve staff scheduling using queuing theory	Outpatient department	Queuing theory	Not specified	Staff data, queuing metrics	Scheduling efficiency, staff utilisation	Improved scheduling and staff utilisation through queuing theory	Not specified	Scheduling improves with queuing theory application.	Q-learning enhances cloud healthcare scheduling.
Research on obstetric ward planning combining lean thinking and mixed-integer programming	Mu, D., et al.	2021	China	Optimise obstetric ward planning	Obstetric wards	Optimisation model: Mixed-integer programming	IBM CPLEX	Ward planning data, efficiency metrics	Planning efficiency, resource utilisation	Improved ward planning and efficiency with lean thinking	Regression model	Ward planning improves with lean thinking and programming.	Queuing theory adapts outpatient staff schedules.
A Robust Predictive Resource Planning under Demand Uncertainty to Improve Waiting Times in Outpatient Clinics	Munavalli, J. R., et al.	2017	India	Improve resource planning under demand uncertainty	Outpatient clinics	Optimization model: Integer Linear Programming	Not specified	Demand data, resource availability	Resource utilisation, waiting times	Improved resource planning and reduced waiting times	Discrete Event Simulation Model	Predictive planning improves resource allocation and waiting times.	Lean, mixed-integer programming applied to ward planning.
Using Simulation to Evaluate Operational Trade-Offs Associated with the use of Care Teams in Specialty Care Settings	Patel, K., Berg, B., & Vahdat, V.	2020	USA	Evaluate operational trade-offs of care teams	Specialty care settings	Simulation model	Not specified	Care team data, operational metrics	Operational efficiency, trade-offs	Improved understanding of trade-offs with care teams	Case study and computational experiments	Care teams impact operational efficiency.	Robust planning reduces outpatient clinic waiting times.
Optimal Scheduling of Doctors Outpatient Departments Based on Patients' Behavior	Ren, Z., Guo, H., Bai, S., & Li, P.	2016	China	Optimise doctor scheduling based on patient behavior	Outpatient departments	Optimisation model: PGSA	Matlab	Patient behaviour data, scheduling constraints	Scheduling efficiency, patient satisfaction	Improved scheduling efficiency considering patient behaviour	Simulation model	Scheduling efficiency improves with patient behavior consideration.	Simulations evaluate care team operational trade-offs.
Simulation optimisation for nurse scheduling in a hospital emergency department	Sajadi, S. M., Ghasemi, S., & Vahdani, H.	2016	Iran	Optimize nurse scheduling in	Hospital emergency department	A simulation model with	Not specified	Nurse scheduling data, emergency department metrics	Scheduling efficiency, nurse utilisation	Improved nurse scheduling and utilisation	Case-study	Nurse scheduling improves with optimization.	Patient behavior informs optimized doctor scheduling.

				emergency department		Simulated Annealing .							
Multi-period and multi-resource operating room scheduling under uncertainty: A case study	Vali-Sair, M.M, et al.	2018	Iran	Multi-resource OR planning and scheduling under uncertainty to minimize tardiness, overtime, and idle time	Operating theatre	Optimization model: Integer Linear Programming with a generic algorithm	GAMS with CPLEX	Surgical and recovery durations	Tardiness, overtime, and idle time	Minimization of tardiness, overtime, and idle time	Case-study	Significant reduction of overtime and idle time.	Assumptions can influence the solutions, such as independent resources.
Integrated scheduling of tasks and gynecologists to improve patient appointment scheduling; case research	van de Vrugt, N. M., et al.	2018	Netherlands	Improve patient appointment scheduling in gynecology	Gynaecology departments	Optimization model: Mixed Integer Linear Programming	AIMMS with Gurobi	Appointment data, gynaecologist schedules	Appointment scheduling efficiency	Enhanced patient appointment scheduling	Case-study	Scheduling improves with integrated methods.	Simulation-optimization improves nurse scheduling.
Operations research for resource planning and -use in radiotherapy: A literature review	Vieira, B., Hans, E. W., et al.	2016	Netherlands	Review resource planning and use in radiotherapy	Radiotherapy centres	Literature review	Not specified	Literature on radiotherapy resource planning	Review of strategies and effectiveness	Identified effective strategies for radiotherapy resource planning	Not specified	Effective strategies identified for radiotherapy resource planning.	Stochastic integer programming aids outpatient clinic planning.
Master scheduling of medical specialists	Vissers, J.	2022	Netherlands	Master scheduling for medical specialists	Medical specialists	Optimization model: Integer quadratic programming	Not specified	Specialist scheduling data, resource metrics	Scheduling efficiency, specialist utilization	Improved scheduling of medical specialists	Case-study	Master scheduling improves specialist efficiency.	Integrated scheduling improves gynecologist and task efficiency.
Short-term physician rescheduling model with feature-driven demand for mental disorders outpatients	Wang, F., Zhang, C., Zhang, H., & Xu, L.	2021	China	Reschedule physicians based on feature-driven demand	Mental disorders outpatients	Optimization model: Mixed-Integer Linear Programming	Not specified	Demand data, scheduling constraints	Rescheduling efficiency, physician utilization	Improved physician rescheduling based on demand features	Case-study	Rescheduling improves with demand features.	Review of OR methods for radiotherapy planning.
A Two-Stage Approach for Resource Allocation and Surgery Scheduling with Assistant Surgeons	Wang, J., Li, X., Chu, J., & Tsui, K.-L.	2020	China	Optimize resource allocation and surgery scheduling	Surgery centres	Optimization model: Mixed-Integer Programming	Python with Gurobi	Resource and scheduling data	Scheduling efficiency, resource utilization	Improved resource allocation and scheduling for surgeries	Computational experiments	Improved allocation and scheduling with two-stage approach.	Master scheduling enhances specialist availability.
Two-stage Game Theoretic Model for the Allocation of Physician Appointments in an Outpatient Clinic	Wu, C.-K.	2023	China	Allocate physician appointments using game theory	Outpatient clinics	Game-Theory model	Not specified	Appointment data, physician schedules	Appointment efficiency, physician utilization	Enhanced appointment allocation with game theory	Computational experiments	Game theory improves appointment allocation.	Feature-driven demand informs mental health rescheduling.
Ensemble meta-heuristics and Q-learning for staff dissatisfaction constrained surgery scheduling and rescheduling	Yu, H., Gao, K.-Z., Wu, N., & Suganthan, P. N.	2024	China	Optimize surgery scheduling with staff dissatisfaction constraints	Surgery centres	Optimization model: Heuristics	C++	Scheduling data, staff feedback	Scheduling efficiency, staff satisfaction	Improved scheduling with consideration for staff dissatisfaction	Computational experiments	Scheduling improves with meta-heuristics and Q-learning.	Two-stage approach for resource, surgery scheduling.
Outpatient Scheduling based on Bottleneck Analysis from the Perspective of Complex Network	Yuan, Y., Liu, Y., Li, X., & Rezibieke, J.	2019	China	Optimize outpatient scheduling using bottleneck analysis	Outpatient settings	Scheduling algorithm	Not specified	Scheduling data, network analysis	Scheduling efficiency, bottleneck reduction	Improved scheduling by identifying and addressing bottlenecks	Case-study	Bottleneck analysis improves scheduling.	Game theory allocates outpatient physician appointments.
Integrated Multisource Capacity Planning and Multitype Patient Scheduling	Zhou, L., Geng, N., Jiang, Z., & Jiang, S.	2022	China	Integrate capacity planning and patient scheduling	Healthcare facilities	Stochastic optimization model: Mixed-integer programming	C++ with CPLEX	Capacity and scheduling data	Capacity planning efficiency, scheduling effectiveness	Enhanced integration of capacity planning and scheduling	Computational experiments	Integration improves planning and scheduling.	Meta-heuristics, Q-learning optimize surgery scheduling.
Operating room planning and surgical case scheduling: A review of literature	Zhu, S., Fan, W., Yang, S., Pei, J., & Pardalos, P. M.	2019	USA	Review operating room planning and surgical case scheduling	Operating rooms	Literature review	Not specified	Literature on operating room scheduling	Review of techniques and effectiveness	Identified effective techniques for operating room planning	Not specified	Effective techniques for operating room planning identified.	Bottleneck analysis aids outpatient scheduling.
Optimising nurse schedules at a community health centre	Zimmerman, S. L., Bi, A., Dallow, T., Rutherford, A. R., Stephen, T., Bye, C., Hall, D., Day, A., Latham, N., & Vasarhelyi, K.	2021	Canada	Optimize nurse schedules	Community health centre	Optimization model: Mixed Integer Linear Programming	Gurobi	Nurse scheduling data, resource metrics	Scheduling		Discrete Event Simulation		Integrated planning aligns capacity, patient schedules.

Formal problem description

Sets

Set	Description
$p \in P = \{1, 2, 3, \ldots, 44\}$	Healthcare professionals
$s \in S = \{1, 2, 3, 4, 5\}$	Specialty of a healthcare professional
$d \in D = \{1, 2, 3, 4, 5\}$	Days in a week, where $d = 1$ represents Monday and $d = 5$ represents Friday
$h \in H = \{1, 2\}$	Periods in a day, where $h = 1$ represents morning and $h = 2$ represents afternoon
$w \in W = \{1, 2\}$	Weeks
$k \in K = \{1, 2, 3, \ldots, 13\}$	Rooms
$a \in A = \{1, 2, \ldots, 53\}$	Set of activities
$A_{\text{ca}} \subseteq A = \{1, 2, 3, \ldots, 51\}$	Care activities
$A_{\text{pa}} \subseteq A = \{1, 2\}$	Professional activities

Parameters

Parameter	Full Name	Index	Description
PT_{ca}	PatientsSeen	(ca)	Patients seen with activity ca
$NPR_{ca,s}$	NumProfessionalRequired	(ca, s)	Number of professionals of specialty s required for an activity ca
$PC_{p,w}$	ProfessionalCapacity	(p, w)	Total capacity of professional p in week w
RR_{ca}	RoomsRequired	(ca)	Number of rooms required for activity ca
$RA_{ca,w}$	RequiredAmountCareActivity	(ca, w)	Required number of blocks per week for activity ca in week w
$RPA_{p,pa,w}$	RequiredAmountProfessionalActivity	(p, pa, w)	Required number of blocks for activity pa for professional p in week w
$PA_{p,d,h,w}$	ProfessionalAvailability	(p, d, h, w)	1 if professional p is available on day $d,$ at period $h,$ in week w
$CP_{p,ca}$	CompetenceProfessionals	(p, ca)	1 if professional p is competent of providing activity ca
$ST_{ca,d,h,w}$	SpecificTimeSlot	(ca, d, h, w)	1 if activity ca needs to take place at day d and period h in week w
$SPS_{p,s}$	SpecialtyProfessional	(p, s)	1 if professional p belongs to specialty s
ED_p	EntireDay	(p)	1 if professional p can solely work an entire workday, and not solely a daypart

Decision Variables

Variable	Full name	Index	Description
$px_{p,ca,d,h,w}$	ProfessionalCareActivity	(p, ca, d, h, w)	1 if professional p provides care activity ca on day d at period h in week $w,$ else 0
$x_{ca,d,h,w}$	PlannedCareActivity	(ca, d, h, w)	1 if care activity ca is provided on day d at period h in week $w,$ else 0
$y_{p,pa,d,h,w}$	PlannedProfessionalActivity	(p, pa, d, h, w)	1 if professional p provides professional activity pa on day d at period h in week $w,$ else 0
Performance auxiliary			
$nx_{ca,w}$	CountNotPlannedCareActivity	(ca, w)	Number of blocks of demand for care activity ca that are not planned in week w
$ny_{p,pa,w}$	CountNotPlannedProfessionalActivity	(p, pa, w)	Number of blocks of demand for care activity pa that are not planned for professional p in week w
Remaining auxiliary			
ax	TotalNotPlannedCareActivity		Total demand of care activities that are not planned
ay	TotalNotPlannedProfessionalActivity		Total demand of professional activities that are not planned
an	SumNotPlannedActivity		Total demand of activities that are not planned
tp	TotalPatientsTreated		Total amount of patients seen with this blueprint schedule

Constraints

$$\sum_{ca} px_{p,ca,d,h,w} + \sum_{pa} y_{p,pa,d,h,w} \leq PA_{p,d,h,w} \qquad \forall p,d,h,w \tag{1}$$

$$\sum_{ca}\sum_{d}\sum_{h} px_{p,ca,d,h,w} + \sum_{pa}\sum_{d}\sum_{h} y_{p,pa,d,h,w} \leq PC_{p,w} \qquad \forall p,w \tag{2}$$

$$px_{p,ca,d,h,w} \leq CP_{p,ca} \qquad \forall p,ca,d,h,w \tag{3}$$

$$x_{'CHUvei',d,h,w} + x_{'CHMac',d,h,w} \leq 1 \qquad \forall d,h,w \tag{4}$$

$$\sum_{ca} px_{p,ca,d,'1',w} + \sum_{pa} y_{p,pa,d,'1',w} = \sum_{ca} px_{p,ca,d,'2',w} + \sum_{pa} y_{p,pa,d,'2',w} \qquad \forall p,d,w \mid ED_p = 1 \tag{5}$$

$$\sum_{p} SPS_{p,s} * px_{p,ca,d,h,w} = NPR_{ca,s} * x_{ca,d,h,w} \qquad \forall\ ca,d,h,w,s \tag{6}$$

$$\sum_{ca} x_{ca,d,h,w} * RR_{ca} \leq |k| \qquad \forall d,h,w \tag{7}$$

$$\sum_{d}\sum_{h} x_{ca,d,h,w} + nx_{ca,w} = RA_{ca,w} \qquad \forall ca,w \tag{8}$$

$$\sum_{d}\sum_{h} y_{p,pa,d,h,w} + ny_{p,pa,w} = RPA_{p,pa,w} \qquad \forall p,pa,w \tag{9}$$

$$x_{ca,d,h,w} \geq 1 \qquad \forall (ca,d,h,w) \mid ST_{ca,d,h,w} = 1 \tag{10}$$

$$\sum_{ca}\sum_{w} nx_{ca,w} = ax \tag{11}$$

$$\sum_{p}\sum_{pa}\sum_{w} ny_{p,pa,w} = ay \tag{12}$$

$$\sum_{ca}\sum_{d}\sum_{h}\sum_{w} x_{ca,d,h,w} * PT_{ca} = tp \tag{13}$$

Objective value function

$\min \quad \omega_1 ax + \omega_2 ay$

Formal problem description

Sets

Set	Description
$p \in P = \{1, 2, 3, \ldots, 44\}$	Healthcare professionals
$s \in S = \{1, 2, 3, 4, 5\}$	Specialty of a healthcare professional
$d \in D = \{1, 2, 3, 4, 5\}$	Days in a week, where $d = 1$ represents Monday and $d = 5$ represents Friday
$h \in H = \{1, 2\}$	Periods in a day, where $h = 1$ represents morning and $h = 2$ represents afternoon
$w \in W = \{1, 2\}$	Weeks
$k \in K = \{1, 2, 3, \ldots, 13\}$	Rooms
$a \in A = \{1, 2, \ldots, 53\}$	Set of activities
$A_{\text{ca}} \subseteq A = \{1, 2, 3, \ldots, 51\}$	Care activities
$A_{\text{pa}} \subseteq A = \{1, 2\}$	Professional activities

Parameters

Parameter	Full Name	Index	Description
PT_{ca}	PatientsSeen	(ca)	Patients seen with activity ca
$NPR_{ca,s}$	NumProfessionalRequired	(ca, s)	Number of professionals of specialty s required for an activity ca
$PC_{p,w}$	ProfessionalCapacity	(p, w)	Total capacity of professional p in week w
RR_{ca}	RoomsRequired	(ca)	Number of rooms required for activity ca
$RA_{ca,w}$	RequiredAmountCareActivity	(ca, w)	Required number of blocks per week for activity ca in week w
$RPA_{p,pa,w}$	RequiredAmountProfessionalActivity	(p, pa, w)	Number of blocks for activity pa for professional p in week w
$PA_{p,d,h,w}$	ProfessionalAvailability	(p, d, h, w)	1 if professional p is available on day $d,$ at period $h,$ in week w
$CP_{p,ca}$	CompetenceProfessionals	(p, ca)	1 if professional p is competent of providing activity ca
$ST_{ca,d,h,w}$	SpecificTimeSlot	(ca, d, h, w)	1 if activity ca needs to take place at day d and period h in week w
$SPS_{p,s}$	SpecialtyProfessional	(p, s)	1 if professional p belongs to specialty s
ED_p	EntireDay	(p)	1 if professional p can solely work an entire workday, and not solely a daypart
$PW_{ca,w}$	PatientsPerWeek	(ca, w)	Number of patients that needs to been seen in week w for activity ca

Decision Variables

Variable	Full name	Index	Description
$px_{p,ca,d,h,w}$	ProfessionalCareActivity	(p, ca, d, h, w)	1 if professional p provides care activity ca on day d at period h in week w, else 0
$x_{ca,d,h,w}$	PlannedCareActivity	(ca, d, h, w)	1 if care activity ca is provided on day d at period on day dh in week w, else 0
$y_{p,pa,d,h,w}$	PlannedProfessionalActivity	(p, pa, d, h, w)	1 if professional p provides professional activity pa on day d at period h in week w, else 0
Performance auxiliary			
$nx_{ca,w}$	CountNotPlannedCareActivity	(ca, w)	Number of blocks of demand for care activity ca that are not planned in week w
$ny_{p,pa,w}$	CountNotPlannedProfessionalActivity	(p, pa, w)	Number of blocks of demand for care activity pa that are not planned for professional p in week w
Remaining auxiliary			
ax	TotalNotPlannedCareActivity		Total demand of care activities that are not planned
ay	TotalNotPlannedProfessionalActivity		Total demand of professional activities that are not planned
an	SumNotPlannedActivity		Total demand of activities that are not planned
tp	TotalPatientsTreated		Total amount of patients seen with this blueprint schedule

Constraints

$$\sum_{ca} px_{p,ca,d,h,w} + \sum_{pa} y_{p,pa,d,h,w} \leq PA_{p,d,h,w} \qquad \forall p,d,h,w \qquad (1)$$

$$\sum_{ca}\sum_{d}\sum_{h} px_{p,ca,d,h,w} + \sum_{pa}\sum_{d}\sum_{h} y_{p,pa,d,h,w} \leq PC_{p,w} \qquad \forall p,w \qquad (2)$$

$$px_{p,ca,d,h,w} \leq CP_{p,ca} \qquad \forall p,ca,d,h,w \qquad (3)$$

$$\sum_{d}\sum_{h} x_{ca,d,h,w} + nx_{ca,w} = RA_{ca,w} \qquad \forall ca,w \qquad (4)$$

$$\sum_{d}\sum_{h} y_{p,pa,d,h,w} + ny_{p,pa,w} = RPA_{p,pa,w} \qquad \forall p,pa,w \qquad (5)$$

$$x_{'CHUvei',d,h,w} + x_{'CHUvei',d,h,w} \leq 1 \qquad \forall d,h,w \qquad (6)$$

$$\sum_{ca} px_{p,ca,d,'1',w} + \sum_{pa} y_{p,pa,d,'1',w} = \sum_{ca} px_{p,ca,d,'2',w} + \sum_{pa} y_{p,pa,d,'2',w} \qquad \forall p,d,w \mid ED_p = 1 \qquad (7)$$

$$\sum_{p} SPS_{p,s} * px_{p,ca,d,h,w} = NPR_{ca,s} * x_{ca,d,h,w} \qquad \forall\ ca,d,h,w,s \qquad (8)$$

$$\sum_{ca} x_{ca,d,h,w} * RR_{ca} \leq |k| \qquad \forall d,h,w \qquad (9)$$

$$\sum_{d}\sum_{h} x_{ca,d,h,w} + nx_{ca} = RA_{ca,w} \qquad \forall ca,w \qquad (10)$$

$$\sum_{d}\sum_{h} y_{p,pa,d,h,w} + ny_{p,pa} = RPA_{p,pa,w} \qquad \forall p,pa,w \qquad (11)$$

$$x_{ca,d,h,w} \geq 1 \qquad \forall (ca,d,h,w) \mid ST_{ca,d,h,w} = 1 \qquad (12)$$

$$\sum_{ca}\sum_{w} nx_{ca,w} = ax \qquad (13)$$

$$\sum_{p}\sum_{pa}\sum_{w} ny_{p,pa,w} = ay \qquad (14)$$

$$\sum_{ca}\sum_{d}\sum_{h}\sum_{w} x_{ca,d,h,w} * PT_{ca} = tp \qquad (15)$$

$$\sum_{d}\sum_{h} x_{'CHAnt1',d,h,w} * PT_{'CHAnt1'} + \sum_{d}\sum_{h} x_{'CH2Ant',d,h,w} * PT_{'CHVoorAnt2'} \geq PW_{'CHAnt',w} \qquad \forall w \qquad (16)$$

$$\sum_{d}\sum_{h} x_{'CHKPed1',d,h,w} * PT_{'CHPed1'} + \sum_{d}\sum_{h} x_{'CHPed2',d,h,w} * PT_{'CHPed2'} \geq PW_{'CHPed',w} \qquad \forall w \qquad (17)$$

$$\sum_{d}\sum_{h} x_{'CHOrb1',d,h,w} * PT_{'CHOrb1'} + \sum_{d}\sum_{h} x_{'CHOrb2',d,h,w} * PT_{'CHOrb2'} \geq PW_{'CHOrb',w} \qquad \forall w \qquad (18)$$

$$\sum_{d}\sum_{h} x_{'CHRet1',d,h,w} * PT_{'CHRet1'} + \sum_{d}\sum_{h} x_{'CHRetr2',d,h,w} * PT_{'CHRet2'} \geq PW_{'CHRet',w} \qquad \forall w \qquad (19)$$

$$\sum_{d}\sum_{h} x_{'CHUvei1',d,h,w} * PT_{'CHUvei1'} + \sum_{d}\sum_{h} x_{'CHUvei2',d,h,w} * PT_{'CHUvei2'} \geq PW_{'CHUvei',w} \qquad \forall w \qquad (20)$$

$$\sum_{d}\sum_{h} x_{'CHMac1',d,h,w} * PT_{'CHMAc1'} + \sum_{d}\sum_{h} x_{'CHMac2',d,h,w} * PT_{'CHMac2'} \geq PW_{'CHMac',w} \qquad \forall w \qquad (21)$$

Objective value function

min $\quad \omega_1 ax + \omega_2 ay$