SUSTAINABILITY OF THE HVAC SYSTEMS IN THE CLINICAL OPERATING ROOM DEPARTMENT

Bachelor thesis

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Executive summary

Problem definition

The Amsterdam UMC is a hospital located in Amsterdam, Netherlands. The healthcare industry is one of the largest polluters with an average share of 5.5% of the total national carbon footprint. In the Netherlands, this share was higher than 5.5% according to Pichler et al. (2019). The healthcare industry was responsible for 8.1% of the total national carbon footprint in the Netherlands (Pichler et al., 2019). This is the highest share compared to a sample of 36 countries affiliated with the Organization for Economic Co-operation and Development (OECD). Heating, Ventilation, and Air Conditioning (HVAC) systems are responsible for approximately 30%-50% of the total energy use in hospitals, which means HVAC systems emit large amounts of CO2. However, hospitals must obey guidelines concerning the air treatment of operating rooms (ORs) to prevent surgical site infections. This makes it complicated for hospitals to reduce the energy consumption of HVAC systems. Recent changes in the guideline for air treatment in ORs stimulate hospitals to implement changes in their HVAC system usage, reducing CO2 emissions. The Amsterdam UMC has not implemented changes since the revised air treatment guideline was published.

This research consists of a problem-solving approach containing 7 steps designed to answer the research question:

"How can the planning of the HVAC system usage and the scheduling of the surgeries in the ORs be optimized so that a reduction in energy consumption is realized without compromising the efficiency of the OR while obeying the guideline concerning air quality in the OR? "

Solely the clinical OR department of the Amsterdam UMC is within the scope of this study. The department consists of 20 ORs of class 1 performance level 1. This is the OR class with the strictest requirements. This means that all procedures can be executed at each OR. However, significant amounts of energy are consumed due to the strict requirements of the class 1 performance level 1 ORs. Figure 1 depicts the performance requirements of class 1 performance level 1 ORs and class 1 performance level 2 ORs.

Performance requirements	Performance level 1	Performance level 2
Degree of protection protective area	≥ 3.0 for the center of the protected area, ≥2.0 for the extreme edge of the protected area	-
Recovery time	≤ 3 minutes (center of the protected area)	≤ 20 minutes (entire OR)
ISO class (for particles ≥ 0,5 µm	Class 5 or better (≤ 3,520 particles/m3)	Class 7 or better (≤ 352,000 particles/m3)

Figure 1: Performance requirements class 1 ORs "At rest"

The recently published revised guideline introduced a new classification of class 1 ORs. Class 1 ORs are now distinguished by class 1 ORs and class 1+ ORs, replacing the performance level 1 and performance level 2 classification. The performance level requirements of class 1+ and class 1 ORs are similar to the requirements of performance level 1 and performance level 2 ORs, respectively. The revised guideline abandons the recommendation of unidirectional flow HVAC systems because there is no evidence that these systems prevent surgical site infections more effectively than turbulent HVAC systems. Major joint replacements are recommended to be executed in class 1+ ORs, while class 1 ORs suffice for all other surgeries. All surgeries can be executed in class 1+ ORs.

Since 2018, 15 of the ORs are in nighttime operation between 21:00 and 6:30 on Monday to Friday and between 00:00 and 23:59 during weekends and holidays. The remaining five ORs are functional 24/7. This resulted in an estimated reduction in energy consumption of approximately 33%.

Research methods

A problem identification and motivation are performed to gain insights into the problem. An action- and a core problem is selected during this stage, and the intended deliverables, key constructs and variables, the theoretical perspective, and the research design are identified. Then, a literature review is performed to solve the knowledge problems. By analyzing the current situation at the Amsterdam UMC afterward, all knowledge problems must be solved. Improvement measures can be generated, selected, and elaborated on as soon as all knowledge problems are solved. The research is concluded after having determined the conclusion and recommendations. The deliverables consist of an effective heuristic for efficient surgery scheduling, insights into the energy consumption before and after the implementation of the proposed heuristic, and potentially other recommendations concerning the sustainability of the hospital. A Monte Carlo simulation is used to assess the effectiveness of the proposed heuristic. The goal of the heuristic is to effectively schedule surgeries for the two types of ORs: Class 1 ORs and class 1+ ORs. Data concerning all executed surgeries in 2019 is used for this research, as this is the most recent year unaffected by the COVID-19 pandemic.

Results

All executed distinct procedures in 2019 have been classified as either class 1 or class 1+ surgeries. We conclude from the data of all executed surgeries in 2019 that two class 1+ ORs suffice. The remaining 18 ORs will be class 1 ORs. The data from 2019 suggested that five 24/7 ORs were rarely occupied outside operating hours and if this was the case, the ORs were not used simultaneously. Decreasing the number of 24/7 ORs to four 24/7 ORs is viable, and this should be implemented as this reduces energy consumption. In 2019, only 19 surgeries classified as class 1+ surgeries started outside operating hours (6:30 – 21:00). None of these surgeries occurred on the same day and not even in the same week. We conclude that it would suffice if one class 1+ OR is appointed as a 24/7 OR. Two ORs should also be appointed as emergency ORs. No surgeries are scheduled for these ORs, but they are solely used for emergencies. The emergency ORs should be classified as class 1 ORs, as joint replacements are generally not urgent.

Two heuristics proposed by Arnaout & Kulbashian (2008) for scheduling the surgeries while minimizing the makespan are evaluated during this research: Longest Expected Processing Time (LEPT) and Longest Expected Processing Time with setup times (LEPST). The LEPT heuristic first schedules the job with the longest expected processing time, while the LEPST heuristic first schedules the job with the highest value of the expected processing time plus the corresponding setup time multiplied by the control parameter α. The control parameter α determines the relative importance of the setup time as opposed to the processing time. The optimal value of control parameter α is researched using the Monte Carlo simulation and it equals $\alpha = 0.65$. The proposed heuristics LEPT and LEPST are designed for assigning jobs to identical machines. We want to distinguish between class 1 ORs and class 1+ ORs. Therefore, some changes are made to the heuristic. We denote the adjusted LEPT and LEPST heuristics as LEPT* and LEPST*, respectively.

The Monte Carlo simulation is used to assess the effectiveness of the LEPT* and LEPST* heuristics. The objective of the heuristics is to minimize the maximum completion time, which is also referred to as the makespan. A completion time is defined as the point in time at which a job is finished. Minimizing the makespan allows the ORs to switch to nighttime operation as soon as possible, which decreases the energy consumption of the clinical OR department. In the simulation, the same number as the average number of executed elective surgeries per week in 2019 is generated according to the empirical distributions of the processing times and the setup times of both class 1 and class 1+. These generated surgeries are then scheduled according to the LEPT* and LEPST* heuristics. The average maximum completion time of every day ($\bar{C}_{max}$) is used as the output parameter, as this reflects the extent to which the two heuristics effectively achieve the objective of minimizing the maximum completion time. Figure 2 depicts the output of the Monte Carlo simulation using 1000 iterations. This means that a week is generated repeatedly 1000 times to acquire the most accurate estimate of $\bar{C}_{max}$. We conclude from Figure 2 that the LEPST* heuristic outperforms the LEPT* heuristic as the value of $\bar{C}_{max}$ for the LEPST* heuristic is less than the value of $\bar{C}_{max}$ for the LEPT* heuristic.

Output	
LEPT	
Average Cmax (1000 iterations)	**463**
LEPST	
Average Cmax (1000 iterations)	**456**

Figure 2: Monte Carlo simulation output

Data from 2019 showed that the OR department attained a $\bar{C}_{max}$ of 812 minutes. The LEPST* heuristic attains a $\bar{C}_{max}$ of 456 minutes, which is a reduction of the makespan of approximately 44%. After implementing the proposed HVAC system changes, the LEPST* heuristic, and the proposed OR classification, the hospital is expected to save 791,820.73 kWh annually compared to the energy consumption in 2019, corresponding to a reduction of approximately 48% relative to 2019. Using a CO2e emission intensity of 0.390 kg CO2e per kWh, $791{,}820.73 * 0.390 = 308{,}810.085$ kg CO2e can be saved compared to 2019. This conversion factor for the Netherlands was determined by the European Environmental Agency (2019).

Acknowledgments

Dear reader,

You are about to read the thesis that concluded my Bachelor of Industrial Engineering and Management. The research “Sustainability of the HVAC systems in the clinical operating room department” was conducted at the Amsterdam UMC from April 2022 until August 2022. This thesis aims to reduce the energy consumption of the Amsterdam UMC hospital while obeying the most recent guidelines concerning air treatment of ORs.

I am grateful to all the people who contributed to this thesis. I would like to thank some in particular. I would like to express my deepest gratitude to my first supervisor Amin Asadi for guiding me throughout this research. I am also thankful to Shiva Faeghinezhad, who provided knowledge and expertise. This endeavor would also not have been possible without Erwin Hans, who is my second supervisor.

I would like to thank everyone who contributed to my thesis at the Amsterdam UMC. Special thanks go to Niek Sperna Weiland and Anne Timmermans, my supervisors from the Amsterdam UMC hospital. Both supervisors were supportive and consistently provided me with helpful feedback. The atmosphere at the hospital was very pleasant, as everyone was willing to help.

Finally, I also wish to thank my family and friends for their love and support. They always provided moral support when things got difficult.

Matthijs de Groot

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Contents

List of acronyms

ACRONYM	DEFINITION
AMC	Academic Medical Center
Amsterdam UMC	Amsterdam University Medical Center
BPMN	Business Process Model Notation
CDF	Cumulative Distribution Function
CF	Carbon Footprint
CFU(s)	Colony-Forming Unit(s)
EDD	Earliest due date
FCFS	First come, first served
GHG	Greenhouse Gas
HVAC	Heating, Ventilation, and Air Conditioning
IAQ	Indoor Air Quality
KPI(s)	Key performance indicator(s)
L(E)PT	Longest (expected) processing time
LEPST	Longest expected processing time with setup times
MC	Monte Carlo
MPSM	Managerial Problem-Solving Method
NVMM	Nederlandse Vereniging voor Medische Microbiologie
NVVH	Nederlandse Vereniging voor Heelkunde
OR(s)	Operating room(s)
RH	Relative Humidity
RQ(s)	Research Question(s)
S(E)PT	Shortest (expected) processing time
SLR	Systematic Literature Review
SSI(s)	Surgical Site Infection(s)
UDF	Unidirectional Flow
VUmc	VU University Medical Centers
WIP	Werkgroep Infectie Preventie

Reader's guide

The reader's guide briefly explains the general relevance and content of each chapter. It contains a brief, general overview of the thesis.

1 Introduction

The first chapter introduces the research by describing the problem. This is done by performing a problem identification, elaborating on the problem owner, selecting an action- and core problem, and by dividing the research into research questions designed to be able to conclude the research.

2 Methodology

The "Methodology" chapter describes the methodology implemented in this research. The problem-solving approach is described, and the intended deliverables, research design, and the validity and reliability of measurement are stated.

3 Literature review

After introducing the research and describing the methodology, a literature review is performed. Literature related to this research is studied in this chapter concerning the previous and revised guideline concerning air quality in operating rooms and scheduling problems. The scheduling problem of this research is formulated using optimal job scheduling. The literature review is therefore focused on this topic specifically after having researched the guidelines.

4 Evaluation of the Amsterdam UMC

Relevant information concerning the Amsterdam UMC is described in this chapter. This chapter is divided into the sections: "Scheduling", "HVAC system", and "Energy consumption of the clinical OR department" as these are the relevant topics for this research.

5 Conceptual design

Chapter 5 describes a conceptual design that is proposed to the Amsterdam UMC. This conceptual design proposes a (near-optimal) solution to the Amsterdam UMC. This solution obeys the guideline and uses optimal job scheduling researched in the literature review. The conceptual design proposes a classification concerning ORs and surgeries, the type of HVAC systems, and two heuristics that will be compared using the Monte Carlo simulation.

6 Monte Carlo simulation

The effectiveness of the two proposed heuristics must be compared using the Monte Carlo simulation. This chapter elaborates on the Monte Carlo simulation by elaborating on the data preparation and simulation programming. Additionally, it depicts and explains the interface of the Monte Carlo simulation. It does not elaborate on the most effective heuristic, as that will be done in Chapter 7: "Results".

7 Results

This chapter formulates the results of the research by describing the optimal value of control parameter α for the LEPST* heuristic, a selection of the proposed heuristics, and the expected energy consumption reduction while using the proposed optimal heuristic.

1 Introduction

Before describing the research methodology, we will start by giving elaboration on the problem owner and by performing a problem identification in this chapter. The process of performing a problem identification is described by Heerkens & Winden (2017) in *Solving Managerial Problems Systematically,* where the seven steps of the Managerial Problem-Solving Method (MPSM) are illustrated. It entails the selection of an action problem – defined as a discrepancy between the norm and reality as defined by the problem owner - after which an inventory of potential causes of this problem is made. Finally, a single core problem – defined as the problems which have no direct causes themselves - is selected. Therefore, core problems can be found at the very beginning of a problem cluster. Because core problems are at the beginning of a problem cluster, solving these problems has the most impact when evaluating an action problem. This chapter also formulates the knowledge problems – defined as knowledge gaps that need to be resolved to be able to solve the core problem - which can be considered interchangeably with the term "research questions (RQs)" for the remainder of this report, as the research questions currently cannot be answered because of a knowledge gap. A knowledge gap can be defined as a discrepancy between the desired level of expertise and the current expertise concerning a particular topic. RQs must be answered to solve the knowledge problems. This research aims to solve the core problem after solving the knowledge problems.

1.1 Problem owner description

To get an understanding of the context of this research, a description concerning the problem owner is given in this section. The problem owner is an academic hospital in Amsterdam called Amsterdam University Medical Centers (Amsterdam UMC). "Together we discover the healthcare of tomorrow" is what Amsterdam UMC stands for (Amsterdam UMC, 2022). Amsterdam UMC is one of the eight Dutch academic hospitals. The hospital strives to provide the best patient treatment by continuously conducting innovative research and educating future professionals in healthcare.

A merger in 2018 between the Academic Medical Center (AMC) and the VU UMC (VUmc) resulted in the Amsterdam UMC. The merger is often referred to as an administrative merger, as the locations of the original separate hospitals remain the same. The AMC and VUmc are nowadays referred to as Amsterdam UMC location AMC and Amsterdam UMC location VUmc, respectively. Amsterdam UMC consists of medical faculties from the University of Amsterdam and the Vrije Universiteit Amsterdam. The two locations employ over 16.000 people in total (Amsterdam UMC, 2022). The scope of this research is the Amsterdam UMC location AMC. The Amsterdam UMC location AMC is for simplicity reasons referred to as Amsterdam UMC for the remainder of this research. This hospital consists of two operating room (OR) departments: The day center and the clinical OR department. These OR departments consist of five and 20 ORs, respectively. The OR departments consist of different OR classes; The five ORs in the day center are classified as class 1 performance level 2 ORs, while the 20 ORs in the clinical OR department are class 1 performance level 1 ORs. Class 1 performance level 1 is the OR class with the strictest requirements. The clinical OR department is located in departments D1 and E1, while the ORs of the day center can be found in department D0. See Appendix A for a map of the hospital.

Niek Sperna Weiland and Anne Timmermans guided me during this research. They are anesthetist and gynecologist at the Amsterdam UMC, respectively. Additionally, Niek Sperna Weiland founded the Green Team OR, and they are both active members of the Green Team OR. This team consists of ambitious medical specialists and healthcare professionals aiming to decrease CO_2 emissions in the OR. The Green team OR aspires to achieve a more sustainable OR by focusing on air treatment, waste disposal, and anesthetic gases.

1.2 Problem identification

In this problem identification, the effect and the significance of the problem are described. A brief literature review is executed to research the problem's significance. An action- and a core problem is selected as a result of the problem identification. Section 1.3: "Selection of the action- and the core problem" concludes the description given in this section. The goal of this section is to identify and describe the underlying problem as perceived by the problem owner.

The healthcare industry is among the largest CO2 polluters in the industrialized world, as its share of the total national carbon footprint (CF) was 5.5% on average back in 2014 and is therefore partially responsible for climate change. Pichler et al. (2019) concluded that the Netherlands had the highest share compared to a sample of 36 Organization for Economic Co-operation and Development (OECD) countries with 8.1% of its total CF. The healthcare industry is responsible for a substantial amount of greenhouse gas (GHG) emissions and to prevent climate change, these GHG emissions need to be reduced. A gap between norm and reality can be identified where the norm entails a world without climate changes due to GHG emissions. This gap between norm and reality cannot be resolved during this research. However, a reduction in GHG emissions caused by Heating, ventilation, and air conditioning (HVAC) systems is feasible. The large amounts of GHG emissions caused by hospitals are partly because they operate continuously, which requires substantial amounts of energy. HVAC is generally responsible for approximately 30%-50% of the total energy use in hospitals (Cubí Montanyà, 2014). Additionally, Guidelines for the internal air quality (IAQ) of ORs must be obeyed, which makes it difficult for hospitals to decrease their HVAC system's CF. However, recently published changes in the Dutch guidelines for air treatment inside ORs enable hospitals to implement changes in their HVAC usage to realize a decrease in their HVAC system's CF. The Amsterdam UMC hospital did not implement changes made possible by the latest air treatment guidelines thus far.

1.3 Selection of the action- and the core problem

Section 1.2: "Problem identification" elaborated on the problem as perceived by the problem owners of the Amsterdam UMC. As a result of the problem identification, we can define the action problem as follows:

- "Earth experiences climate change due to human activities."

The core problem, found at the very start of the problem cluster, can be defined as:

- "The Amsterdam UMC hospital did not implement changes made possible by the latest air treatment guidelines thus far."

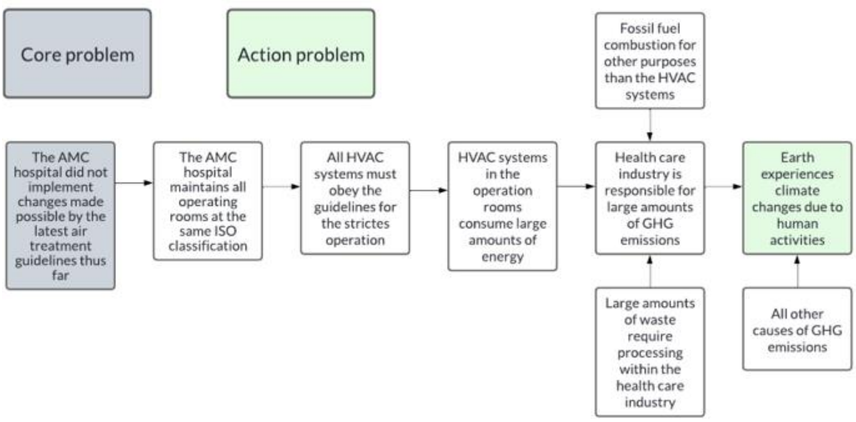


Figure 1-1: Problem cluster

Figure 1-1 gives a clear overview of the causes and effects of the problems that can be identified concerning the sustainability of the healthcare industry. It starts with the action problem that needs to be tackled. This action problem concerns climate change due to human activities. This action problem is caused by many polluters and the healthcare industry is not solely responsible for this problem. However, they are responsible for large amounts of GHG emissions, and they are therefore within the scope of this research. The causes of climate change within the healthcare industry are visualized in Figure 1-1 afterward. This research also specifically focussed on the emissions regarding the HVAC systems of the Amsterdam UMC because these systems are responsible for the largest part of the emissions within ORs. This is caused by the fact that the ORs must obey guidelines concerning their IAQ. Because of this, the Amsterdam UMC hospital retains all HVAC systems in the 20 ORs switched on during the day to simplify the scheduling of surgeries. However, recent changes in the guidelines make it possible to implement changes in the ORs potentially leading to a reduction in energy consumption. These changes in the guidelines are currently not implemented in the scheduling of surgeries at the Amsterdam UMC. This problem has no other causes, and it is the cause of all other problems. It is therefore the core problem.

1.4 Research questions

This section elaborates on the knowledge problems related to the research. To solve the core problem as defined in section 1.3: "Selection of the action- and the core problem", research questions are formulated that must be answered during this research. The knowledge gaps will be solved by answering the research questions that are formulated in this section.

- **RQ1: What were the previous guidelines concerning the air treatment of operating rooms in Dutch hospitals?**
  To understand the impact of the previous guidelines on the current scheduling processes, research should be conducted concerning the contents of the previous guidelines. Solving this knowledge problem provides a better understanding of the current situation in the Amsterdam UMC hospital concerning surgery planning and HVAC usage. This research question is answered using a literature review, as documents of the Dutch organization responsible for the guidelines provide information regarding the guidelines. Additionally, a semi-structured interview with Ingrid Spijkerman is performed for additional information. Ingrid Spijkerman is responsible for infection prevention and medical microbiology within the Amsterdam UMC. Additionally, she was a member of the expert group "Luchtbehandeling op de OK", which can be translated as "Air treatment in the OR". This expert group was involved in writing the new guideline.

- **RQ2: What are the most important changes in the latest guidelines concerning the air treatment of operating rooms in Dutch hospitals compared to the previous guidelines?**
  The changes in the guidelines of 2022 compared to the previous guidelines should be understood as these changes are why the problem owners believe there is room for improvement. Solving this knowledge problem, therefore, simplifies idea generation. Hence, it contributes to solving the core problem. The new guidelines might also form the basis of the constraints when developing a new scheduling heuristic. This research question is solely answered using a literature review, as documents of the Dutch organization responsible for the guidelines provide all information regarding the guidelines. The semi-structured interview with Ingrid Spijkerman is useful for this knowledge problem.

- **RQ3: What are the HVAC systems in ORs used for, which type of HVAC systems are used in the Amsterdam UMC, and how are they operated?**
  The processes concerned with the HVAC systems need to be understood. To devise changes in the processes, a clear understanding of the current processes is required. Clear knowledge concerning the processes is crucial during this research. Obtaining that knowledge is the main purpose while solving this knowledge problem. This RQ determines which specific guidelines apply to the ORs in the Amsterdam UMC as the HVAC systems used in the hospital are identified here. Observations and a literature study are used here as information can be extracted during guides around the OR department for example, but data can also be found in the air management plan *Luchttechnischbeheersplan* (Amsterdam UMC, 2018) of the Amsterdam UMC hospital.

- **RQ4: How are the planning of the HVAC system usage and the scheduling of the surgeries in the ORs of the Amsterdam UMC currently executed?**
  The surgery scheduling processes and planning of the HVAC system usage in the hospital need to be understood, as a change concerned with these processes is sought during this research. To devise a change in the current processes, the current processes need to be understood. Solving this knowledge problem simplifies the optimization of the OR as it provides a more specific gap between norm and reality. Interviews, observations, and literature reviews are used to answer this research question. Interviews concerning this knowledge problem are held with Karin de Vlaming. Karin de Vlaming is the manager of the OR department. Observing the current scheduling process is also effective when answering this research question. Finally, the criteria for appointing a certain specialty to an OR will be researched as this is crucial when developing the scheduling heuristic. This is researched by performing a literature review using the air management plan of the Amsterdam UMC hospital.

- **RQ5: What is the total energy consumption of the HVAC systems in the OR department of the Amsterdam UMC hospital before and after implementation of the proposed heuristic?**
  This RQ makes the gap between norm and reality measurable. Data concerning this knowledge problem is acquired by performing semi-structured interviews with Jelle Koeman, Anne Brouwer, and Wilco van Nieuwenhuyzen. Jelle Koeman is responsible for housing and technology within the Amsterdam UMC. Anne Brouwer and Wilco van Nieuwenhuyzen work at the external companies Royal HaskoningDHV and Interflow, respectively. Both companies have experience in the engineering of HVAC systems in hospitals. By predicting the energy consumption after implementation using a Monte Carlo (MC) simulation, a difference can be made quantifiable by comparing this to historical energy consumption. An MC simulation is chosen as this is easy to implement. It can provide an approximately optimal solution to a mathematical model. Additionally, stochastic data is included as the duration of surgeries for example is probabilistic. An MC simulation can deal with uncertainty, and it has therefore been chosen as the simulation method. This knowledge problem also underlines the relevance of this research as it quantifies the problem. The distribution of the processing times of surgeries is made as input for the MC simulation. This is done by using historical data concerning surgery scheduling provided by “EVA stuurinformatie” from the AMC hospital. Historical data concerning the year 2019 is selected as this year is pre-COVID-19. The scheduling of the surgeries in this year was not affected by COVID-19 regulations.

- **RQ6: How can the scheduling problem be formulated, and which heuristics should be used for reducing carbon emissions while not hurting the efficiency of the OR?**
  This RQ supports RQ7 by researching which heuristics can be used when solving the scheduling problem. The most effective heuristics are found using a literature review. Two heuristics will be selected after having researched all models. "Loosely speaking, heuristic means to find or to discover by trial and error (Yang, 2011). Examples of potential heuristics are "Earliest Due Date" and "Shortest Processing Time". A literature review is used when answering this research question using databases such as Scopus, Google Scholar, and PubMed. The heuristics will be applied to the OR scheduling problem of the Amsterdam UMC.

- **RQ7: How can the planning of the HVAC system usage and the scheduling of the surgeries in the ORs be optimally changed using a heuristic so that a reduction in energy consumption is realized without compromising the efficiency of the OR while obeying the guideline concerning air quality in the OR?**
  This is the main RQ, it concludes the research as solutions are generated. Afterward, possible solutions are analyzed, and the best option is selected. The core problem is solved while solving this knowledge problem, while all other knowledge problems support solving this knowledge problem. After describing the scheduling problem using optimal job scheduling, two heuristics will be used for the scheduling problem. These heuristics will be compared, and the most effective heuristic will be selected. The solution will then be validated by comparing it with the current situation.

2 Methodology

This chapter explains the research methodology by describing the contextual framework used in this research. It consists of a problem-solving approach, a description of the intended deliverables, a research design, and an assessment of the validity and reliability of the research.

2.1 Problem-solving approach

This section describes the problem-solving approach implemented during this research. The problem-solving approach consists of 7 steps that are designed to answer the RQ. Each step is described and explained in this section.

1. *<u>Problem identification and motivation</u>*

During this first stage, a clear overview of the problem is made. The most important aspect of this phase is formulating the assignment. Knowing what the problem of the research is and why the research should be conducted is crucial during research. A problem cluster is generated, and the action problem, core problem, and knowledge problems are identified. The intended deliverables, key constructs and variables, the theoretical perspective, and the research design are also identified. Performing semi-structured interviews and making observations are the main activities at this stage.

2. *<u>Literature review</u>*

The second stage of the problem-solving approach concerns the execution of the literature review. This stage is done according to the systematic literature review (SLR) protocol. The goal of the literature review is to answer some knowledge problems. The knowledge problems can be found in section 1.4: **"**Research questions**"**. RQ1 and RQ2 are answered entirely using a literature review and these knowledge problems will therefore be solved during this stage. The knowledge problems RQ1 and RQ2 are solved using documents including previous guidelines and current guidelines. RQ3, RQ4, RQ5, and RQ6 will require some literature review and these knowledge problems will therefore also be assessed. For RQ3, some general information regarding the purpose and functionalities of HVAC systems is acquired using a literature review. RQ4 uses some information extracted from the literature review regarding the allocation of surgeries to OR types. RQ5 includes calculations and some assumptions might have to be made for this. A literature review is used for that. RQ6 requires the use of documents where types of scheduling problems are explained. The OR scheduling problem of the Amsterdam UMC has to be identified. Therefore, RQ6 cannot be answered completely using a literature review.

This stage does not necessarily have to take place at the Amsterdam UMC because it relies on a literature search. Databases such as Scopus, Google Scholar, and PubMed are used. However, internal files from the Amsterdam UMC are also extracted and used for the literature review. The air management plan is an example of an internal document from the hospital. Internal files are found in the management software of the Amsterdam UMC called “Zenya”. Additionally, “EVA stuurinformatie” should be able to provide data concerning for example all executed surgeries in 2019.

3. *Analyze the current situation*

During this stage, research is executed at the Amsterdam UMC hospital using observations and interviews. For the remainder of RQ3, RQ5, and RQ6 both semi-structured interviews and observations are executed at the hospital. RQ4 is answered during this stage entirely as the scheduling methods are hospital-specific. Data is therefore acquired by both semi-structured interviews and observations as well. The interviews are executed with the people introduced in section 1.4: “Research questions**”**.

4. *Generate improvement measures*

The remainder of RQ6 will be considered during this stage. Ideas are generated that potentially realize a reduction in energy consumption while not hurting the efficiency of the clinical OR department. All knowledge acquired using the previous RQs is considered during the generation of ideas in this stage. Heuristics that can be used to solve the OR scheduling problem are selected using a literature review.

5. *Analysis and selection of improvements*

All the heuristics listed in the previous phase concerning RQ6 are analyzed. A literature review is performed to analyze the performance of each of the proposed heuristics. After evaluating the heuristics, the two best heuristics must be selected. The heuristics that are selected must apply to the OR scheduling problem of the Amsterdam UMC.

6. *Elaboration on improvement measure*

This stage is also part of RQ6, and it concerns the elaboration of the selected heuristic in stage 5. A detailed explanation of the selected solution is written during this stage.

7. *Write conclusion and recommendations*

A concise conclusion is written at this stage, where the most important findings resulting from the research are stated. A summary of the core problem, the action problem, and each knowledge problem are given. Recommendations for the Amsterdam UMC hospital are given concerning the planning of the HVAC systems usage and the scheduling of surgeries. RQ7 is answered at this stage.

2.2 Intended deliverables

The problem owner Amsterdam UMC aims to make the clinical OR department more sustainable by decreasing the energy consumption of the HVAC systems in the ORs. To realize a reduction in energy consumption, potential improvements regarding the scheduling of the surgeries are researched. This research is intended to result in the following deliverables:

- A heuristic that can be implemented for surgery scheduling
- Insights into energy consumption before and after implementation of the heuristic using an MC simulation
- Other recommendations regarding the organization of surgery scheduling and sustainability of the clinical OR department

An effective heuristic is delivered to the Amsterdam UMC. This heuristic should be ready for implementation in the clinical OR department of the hospital. Heuristics that cannot be applied to the Amsterdam UMC hospital are therefore outside the scope of this research. Insights into the current energy consumption of the HVAC systems in the clinical OR department and the expected impact of the proposed heuristic on the energy consumption are delivered to the problem owner. The current energy consumption and the impact on the energy consumption are estimated using an MC simulation. Other recommendations regarding the sustainability of the clinical OR department and surgery scheduling are also delivered, as well as potential further improvements to the heuristic. A comprehensive thesis describes all the intended deliverables.

2.3 Research design

This research was started by executing exploratory research to get a full understanding of the topic. The exploratory phase contained interviews, observations, and a literature review. The observations were performed by receiving guides around the ORs and by spending time in the Amsterdam UMC hospital. The interviews were semi-structured, which means that important elements that should be elaborated on will be structured but the rest of the interview will not have a particular structure. After having obtained a clear understanding of the processes at the Amsterdam UMC hospital, descriptive research was performed as the current processes, guidelines, and emissions were analyzed and described. In this phase, the topic was described in detail using academic theory. For the prediction of the environmental impact of the ORs after implementation of the proposed heuristic, an MC simulation is made. This MC simulation can deal with the uncertainty of implementing the recommended solution. Interviews were also performed in the descriptive research phase.

2.3.1 Data collection

This research combined qualitative and quantitative research by answering both qualitative and quantitative research questions. The method of combining these two data gathering and analysis methods is called “triangulation”. Knowledge problems concerned with energy consumption are quantitative as the consumption is quantified in these elements of the research. The rest of the research is qualitative, as nonnumerical research is done there. Qualitative research was done by performing interviews and literature reviews, while the quantitative elements are researched by modeling the MC simulation. Data is therefore analyzed both qualitatively and quantitatively. Both methods are necessary during this research as it is important to understand the processes and guidelines to be able to recommend a solution. However, energy consumption also had to be calculated to predict the reduction in energy consumption and compare this to the current situation. That is, the solution should be verified by performing quantitative research.

2.3.2 Limitations

Every research design, including this research design, contains some limitations. These limitations must be identified to limit their impact on the study. This research design consists of both qualitative and quantitative elements which might make the study too broad. It is therefore important to formulate the scope of this research to narrow down the research. Additionally, the qualitative element in this research requires numerical data. A potential limitation is that this data is unavailable for the specific situation at the Amsterdam UMC hospital. This data should in that case be acquired by observing and researching the ORs. Finally, this research has a period of ten weeks. This potentially limits the scope of the research to finish in time. The scope of the research is narrowed down to still provide added value. Data that is studied was data from a maximum of one year and solutions that are not related to optimizing the scheduling of surgeries will not be assessed.

2.4 Validity and reliability of measurement

2.4.1 Validity

"Validity is the extent to which a test measures what we actually wish to measure (Cooper & Schindler, 2014). Additionally, validity can be divided into two forms: External- and internal validity. External validity concerns whether data generalization is justifiable. This means that data that is acquired during this research should apply to the research sufficiently. Internal validity assesses the extent to which the research instruments are fit to measure what they are used for. In this section, the validity is divided into three different forms: content validity, criterion-related validity, and construct validity.

Content validity

"The content validity of a measuring instrument is the extent to which it provides adequate coverage of the investigative questions guiding the study" (Cooper & Schindler, 2014). This means that all elements of the research questions should be covered, with sufficient elaboration concerning the topic. Each knowledge problem should therefore be researched extensively, making sure all elements are elaborated on. For each knowledge problem, elements that should be researched should be determined before researching so that no elements are missed. To ensure content validity, this research provides background information for every knowledge problem. After this, the research will contain specific information regarding the research question.

Criterion-related validity

This type of validity "reflects the success of measures used for prediction or estimation" (Cooper & Schindler, 2014). In this research a simulation will be made, predicting the energy consumption after implementing a solution. This research has predictive validity if this simulation correctly predicts energy consumption after implementation. Modeling should therefore be performed correctly and considerate to ensure criterion-related validity.

Construct validity

Construct validity is the extent to which a test measures the construct it claims to measure. This means that constructs should be clearly defined to prevent confusion. This will ensure construct validity for this research. Valid calculations must be made during this research, and correct distribution must be used as input for the MC simulation.

2.4.2 Reliability

"Reliability has to do with the accuracy and precision of a measurement procedure" (Cooper & Schindler, 2014). It contributes to the validity of research; however, it does not ensure validity. During this research, important experiments are performed multiple times to ensure stability.

3 Literature review

A literature review is conducted using databases such as Scopus, Google Scholar, Pubmed, and Zenya. Zenya is a database containing documents originating from the Amsterdam UMC. The literature review elaborates on the previous guideline on air treatment of ORs, the most recent guideline on air treatment of ORs, and optimal job scheduling.

3.1 Previous guidelines concerning the air treatment of operating rooms in Dutch hospitals

We currently have a knowledge problem as the previous guidelines of 2014 are unknown and it should therefore be researched. The previous guidelines should be compared to the most recent guidelines to obtain insight into the processes concerned with OR planning at the Amsterdam UMC. The guidelines concerned with internal air quality (IAQ) are to be identified for different OR types and surgeries, and only Dutch guidelines are within the scope of this RQ. Two guidelines concerning air treatment apply to the air management of the clinical OR department of the hospital, as described in *Luchttechnischbeheersplan OK* (Amsterdam UMC, 2018). These guidelines are the Werkgroep Infecite Preventie (WIP) guidelines *Luchtbehandeling in operatiekamer en opdekruimte in operatieafdeling klasse 1* (WIP, 2014) and *Omstandigheden (kleine) chirurgische en invasieve ingrepen* (WIP, 2011).

3.1.1 Introduction

An OR's state is distinguished into three states. These three states are labeled: “As-built”, “At rest”, and “Operational”. “As-built” is referred to as the OR as delivered including the fixed equipment but excluding medical equipment and persons present in the room. “At rest” is the OR with a set-up ready for use with all equipment present, but without people in the OR. Finally, “Operational” is the situation where the OR is used, with the prescribed number of people present in the OR. Additionally, a distinction is made between class 1 and 2 ORs. Next to the ORs of classes 1 and 2, independent treatment rooms also exist. However, only class 1 ORs are within the scope of this research as the scheduling of the clinical OR department will be optimized. Within class 1, a distinction is made between performance levels 1 and 2. These performance levels do not strictly correspond to the two types of HVAC systems to prevent potential obstacles when striving for innovation concerning the HVAC systems. As SSIs are largely caused by contaminated particles carrying micro-organisms, SSI prevention mainly contains the minimization of particles in the OR (Chauveaux, 2015). ISO levels classify the number of particles per m^3.

There are currently two types of HVAC systems: A unidirectional Flow (UDF) and a turbulent HVAC system. A UDF HVAC system vertically ventilates the protected area, causing the micro-organisms to flow horizontally across the floor towards the walls, where suction is applied. A turbulent HVAC system does not have a protected area. Here, the IAQ is the same in the entire OR. For the performance of UDF HVAC systems, the degree of protection within the protected area and the recovery time of the protected area are performance measures. The degree of protection depends on the difference between the number of particles per m^3 within the protected area and the number of particles per m^3 outside the protected area. For turbulent HVAC systems, the degree of protection is not applicable as there is no protected area. The performance of turbulent HVAC systems is therefore singularly assessed by using the recovery time of the entire OR. The recovery time is defined as: “The time it takes after an increase in the concentration of particles with a size equal to or greater than 0.5 µm, to lower the concentration by a factor of 100 compared to the 'at rest' situation (WIP, 2014). Additionally, the degree of protection is calculated using equation 1 (Traversari et al., 2019):

$$DP_x = -log(\frac{C_x}{C_{ref}}) \quad (1)$$

, where:

DP_x = Degree of protection at place x
C_x = Concentration of particles at place x (within protected area) [particles/m^3]
C_{ref} = Reference concentration of particles (outside protected area) [particles/m^3]

Additionally, both the ISO class and the air permeability are performance requirements for ORs. ISO 5 means that a maximum of 3,520 particles/m^3 with a size equal to or greater than 0.5 µm may be found 'at rest' in the protected area. ISO 7 corresponds to a maximum of 352,000 particles/m^3 with a size equal to or greater than 0.5 µm may be found 'at rest' in the protected area (WIP, 2014). Air permeability is defined as the "air leakage rate per envelope area at the test reference pressure differential across the building envelope" (NEN, Stichting Koninklijk Nederlands Normalisatie Instituut, 2015).

3.1.2 Performance, construction, and other guidelines HVAC system of class 1 ORs

Performance requirements HVAC system

Table 3-1: Performance requirements class 1 ORs "At rest" summarizes the performance requirements of ORs "At rest" (WIP, 2014). As can be seen, the degree of protection only applies to performance level 1. In the table, UDF HVAC systems are not necessarily referred to as "performance level 1", while turbulent HVAC systems are also not strictly referred to as "performance level 2".

Performance requirements	Performance level 1	Performance level 2
Degree of protection protective area	≥ 3.0 for the center of the protected area, ≥2.0 for the extreme edge of the protected area	-
Recovery time	≤ 3 minutes (in the center of the protected area)	≤ 20 minutes (for the entire OR)
ISO class (for particles ≥ 0,5 µm)	Class 5 or better (≤ 3,520 particles/m3)	Class 7 or better (≤ 352,000 particles/m3)
Air permeability	Maximum $q_{v;10}$ value of 1.5 times the OR's volume in m3/hour	Maximum $q_{v;10}$ value of 1.5 times the OR's volume in m3/hour

Table 3-1: Performance requirements class 1 ORs "At rest"

ORs with performance level 1 must have a degree of protection of at least 3.0 at the center of the protected area, while the extreme edges of the protected area must have a degree of protection of 2.0 or more. The recovery time should be under minutes in the center of the protected area, and the OR should have ISO 5 or better. ORs classified as performance level 2 should have a recovery time of maximum 20 minutes while maintaining an ISO class of 7 or better. Both ORs with performance levels 1 and 2 should have a maximum air permeability of 1.5 times the OR's volume.

Construction guidelines

The OR should be provided with an HVAC system that should not depend on the hospital's ventilation system to provide clean air. This minimizes the chances of system failure. The ORs department needs to be separated from the rest of the hospital using airlocks. The airlocks consist of an area between two doors. These two doors cannot be opened at the same time to make differences in air pressure possible. This is important as the airflow should be directed towards the zone with the lowest air quality. Figure 3-1 provides a schematic overview of the clinical OR department (WIP, 2014). The airflow direction is controlled by maintaining increasing pressure levels from zone D toward zone A. Appendix B depicts an overview of the pressure levels in the clinical OR department of the Amsterdam UMC (Amsterdam UMC, 2018). The walls around the OR department are also not allowed to have any openings in them to prevent unwanted outside air from entering the clinical OR department. An exception is made for emergency exits.

The air that is provided to zone A, B, and C of the OR department should have an air quality of at least F9 filtered air. An F9 air filter is designed for HVAC usage and provides a high level of air filtration. The air that is provided to the OR itself should be filtered using an H13 filter. Additionally, the air coming from zone A may only be circulated within zone A. This is important as the circulation of air cause a risk of surgical site infection (SSI) occurrence. By excluding recirculation of air between different ORs in zone A, the air from different ORs cannot mix and the risk of SSI occurrences caused by the air via the HVAC system is reduced. Additionally, the temperature of the airflow in zone A originating from the HVAC systems preferably is controlled using an automized central system. The reason for this is that changing the temperature of this airflow might temporarily affect the performance of the HVAC system.

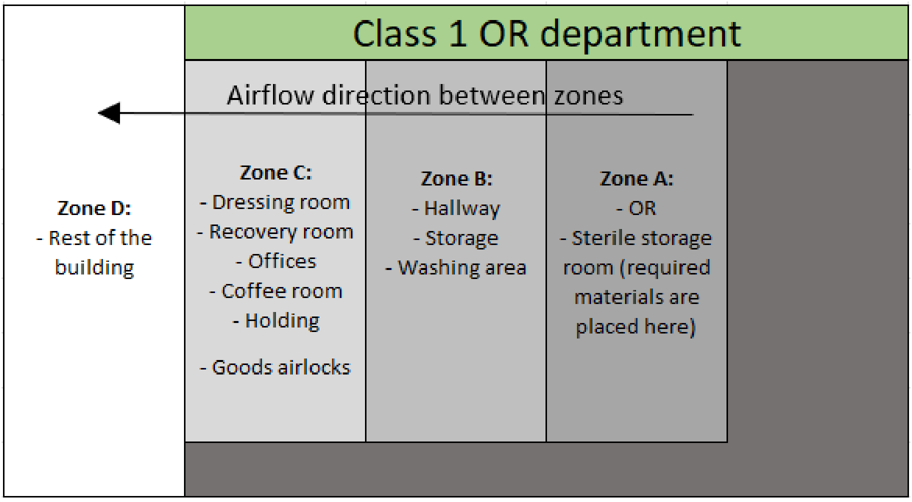


Figure 3-1: Schematic overview of the OR department with class 1 ORs

The floor, walls, and ceilings should be smooth, seamless, and closed off to prevent dirt accumulation and to make effective cleaning possible. Zone A is only allowed to have openings that are connected to zone B. Additionally, prevent particles (dust) from entering Zone A from the ceiling. This can preferably be prevented by implementing a box-in-box construction for Zone A.

Other guidelines

Provide Zone A within a class 1 OR department with a dashboard that monitors and indicates whether the HVAC system is functioning properly. Some key performance indicators (KPIs) such as room temperature and relative humidity (RH) are shown here. This dashboard prevents the execution of surgeries at times when the HVAC system does not function properly causing some KPIs to exceed their limit values. Additionally, equipment should be used that does not unnecessarily interfere with the airflow of the UDF HVAC system. Equipment used in the OR might produce heat causing upward airflow. This upward airflow results in clean air mixing with the polluted air. Air quality in ORs using a turbulent HVAC system is not affected heavily by equipment as these ORs' air quality does not depend on the direction of the airflow to the extent of UDF HVAC systems. Finally, the protected area in an

OR using a UDF HVAC system should be marked on the floor. This area in the OR should be at least large enough so that the operating table, the instrument tables, and the operating team can be placed within the protected area during a procedure. The OR should also preferably have a minimum distance of 1.5 meters between the walls of the OR and the extreme edges of the protected area. Dutch hospitals should have an air management plan, describing the HVAC system, the quality management system related to air quality at the ORs, the maintenance procedures, limit values of the KPIs, etc. A document indicating which interventions may be performed under which conditions and indicating a classification of surgeries are also mandatory (Inspectie voor de Gezondheidszorg, 2016).

HVAC system usage guidelines

The display in the OR should indicate whether important KPIs are within their limit values. These values should be established using the documentation of the HVAC system. Continuous monitoring of the KPIs should be executed automatically. The OR should only be used when all these values are within their limit values. Clear procedures on how to act if the KPI values are outside their limit values should also be established. Additionally, procedures should be established concerning the release of the OR at the start of the working day. Here, the system should be checked for any errors and functionality. However, procedures should also be made concerning OR usage outside regular working times.

The patient must be placed so that the operating area, surgical team, tables, and sterile instrument tables are in the protected area of the OR. The operating lamp should not be placed horizontally below the HVAC system, disrupting the airflow. Additionally, the air temperature of the air provided by the UDF HVAC system should only be altered by strict necessity. Air temperature is a crucial KPI for the effective functioning of the HVAC system. Changing the temperature has a temporary negative effect on the air quality, as a new balance needs to be formed. Finally, the patient's body temperature should be between 36 degrees Celsius and 38 degrees Celsius, as this reduces the chances of SSI occurrence. Heating blankets or mattresses can be used for the preservation of patients' body temperature. These products do not have a proven negative effect on air quality within the OR (WIP, 2014).

The number of people present in the OR should be limited. People radiate heat and micro-organisms, and they negatively influence the airflows in the OR. Only OR clothing should be worn in the OR, as clothing plays an essential role in the emissions of micro-organisms. During surgery, the door of the OR should not be opened if this is not necessary. It is advised to preferably provide each OR with a separate restroom with at least comparable performance requirements for the air treatment as for the associated OR (WIP, 2014). It must be prevented that instruments that must be sterile become contaminated, which could increase the risk of SSI occurrences.

HVAC type recommendation

Factors that influence the selection of a vertical UDF HVAC system or a turbulent HVAC system include the number of SSIs; the number of bacteria in the air and above the wound while the OR is in use; the degree of contamination of the wound; the cost, the patient's body temperature and the effect of heating blankets on both systems (WIP, 2014).

Table 3-2 shows the recommendations as proposed by WIP (2014) concerning the performance level. Arthroplasty surgery and procedures with implantation of (endo)prostheses are recommended to be performed in an OR with performance level 1 and not in an OR with performance level 2. All other surgeries do not have a pronounced recommendation concerning a performance level 1 or 2 (WIP, 2014). These recommendations result in the hypothesis that an OR equipped with a UDF HVAC system generally has fewer bacteria in the air as opposed to an OR equipped with a turbulent HVAC system, as UDF HVAC systems are more frequently used for performance level 1 ORs compared to turbulent HVAC systems.

The hypothesis that an OR equipped with a UDF HVAC system generally has fewer bacteria in the air as opposed to an OR equipped with a turbulent HVAC system is confirmed by R.J. Knudsen et al. (2021). Their research counted colony-forming units (CFUs) during live surgery in ORs with a UDF HVAC system and ORs with a turbulent HVAC system. These units are used to estimate the number of bacteria in the air.

Surgery type	Performance level 1	Performance level 2
Joint replacement surgery	X	
Procedures with implantation of (endo)prostheses	X	
Procedures without implantation of (endo)prostheses	X	X

Table 3-2: Performance level recommendations

They concluded that ORs equipped with a UDF HVAC system had lower CFU counts compared to ORs equipped with a turbulent HVAC system. ORs with a UDF HVAC system were able to provide ultra-clean air, while turbulent HVAC systems failed to provide ultra-clean air (Knudsen et al., 2021). This fact is also confirmed by WIP (2014), who stated: "The scientific research shows that when a UDF HVAC system is used in the OR, fewer micro-organisms are present in the air and there is less contamination of instruments than with a turbulent HVAC system. This is not only "At rest" but also when the OR is in operation." However, this research limits itself to surgeries concerning knee and hip prostheses. The researchers add: "We conclude that there is unambiguous support in the literature for the fact that UDF leads to less contaminated air above the surgical site and less contamination of instruments during procedures and that there is inconclusive evidence for a decrease in the number of SSIs in the application of UDF." By this, they mean that UDF HVAC systems lead to better air quality. However, there is no clear evidence found that these systems also lead to fewer SSIs.

However, we conclude that a UDF HVAC system protects the protected area in an OR better against micro-organisms than a turbulent HVAC system and is therefore superior. Using a UDF HVAC system also makes it easy to indicate a clear protected area. Some potential disadvantages of a UDF HVAC system compared to a turbulent HVAC system are listed below (WIP, 2014):

- the technical complexity of the design, installation, maintenance, and management;
- the impediment to the functionality of the HVAC system caused by objects that are placed in the airflow such as the operating lamp and screens;
- effect of operating and user errors when the temperature in the OR changes – the airflows have to stabilize again. If one starts operating immediately after the temperature change, the air in the OR usually does not meet the requirements for the protected area;
- overestimation of the importance of the UDF, with underestimation of the other measures.

These potential theoretical disadvantages have been considered. However, they do not compensate for the advantages of UDF HVAC systems as opposed to turbulent HVAC systems according to WIP (2014). Dutch hospitals should therefore have at least one OR equipped with a UDF HVAC system, or they should have advanced plans to implement it.

3.1.3 Guidelines of class 2 ORs compared to class 1 ORs

During the remainder of this section, guidelines concerning class 2 ORs are briefly compared to the guidelines concerning class 1 ORs. As the Amsterdam UMC does not have class 2 ORs, this comparison will not be detailed. Table 3-3 gives an overview of some general differences between the guidelines (WIP, 2011).

Guideline differences	Class 1	Class 2
Layout	3 zones	2 zones
Airlocks	4 types	Airlock for personel
HVAC system recommendation	UDF	Standard ventilation system
Air changes/hour	20x	6x
Air pressure	overpressure zone A vs B vs C	overpressure zone A vs B
Recovery room	In OR department	Close to OR department
Air quality	ISO 5/7[1]	ISO 7

Table 3-3: Overview of general differences in the guidelines between class 1 ORs and class 2 ORs[1]

The layout of class 2 ORs is different, as different zones and airlocks can be identified. An OR with class 2 requires only two separate zones. The connections between these zones are not as strict in class 2 ORs, as only personnel airlocks are required. Zone B does not need to have overpressure compared to zone C for class 2 ORs. Zone B of the OR department with class 2 ORs integrates zone B and C of the class 1 OR department (WIP, 2011). Check Figure 3-2 for a schematic overview of an OR department with ORs of class 2.

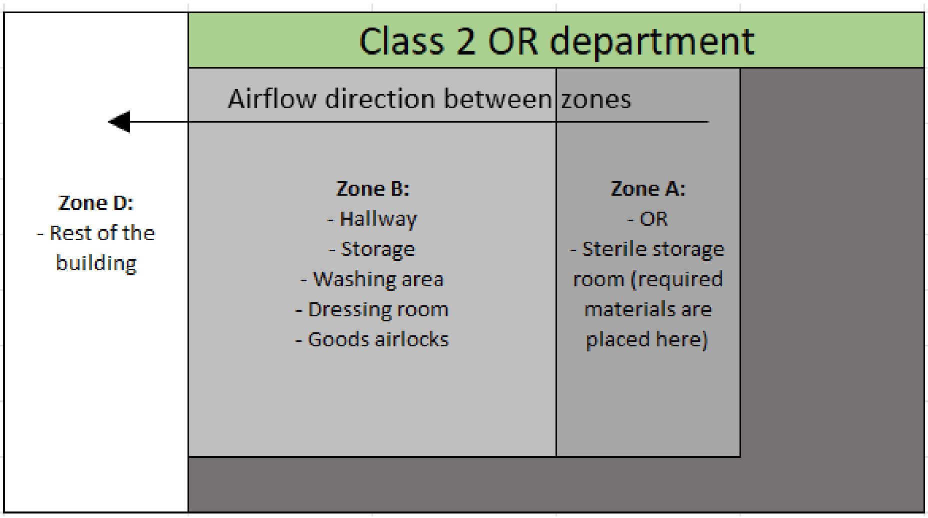


Figure 3-2: Schematic overview of the OR department with class 2 ORs

Commissie kwaliteitsdocumenten NVOG (2020) concludes that class 2 ORs emit significantly smaller amounts of CO_2 compared to class 1 ORs mainly because standard ventilation systems consume a smaller amount of energy compared to UDF HVAC systems or turbulent HVAC systems. The energy consumption of an OR can be reduced by 70% if the ventilation rate is reduced from 30 to six times per hour. Additionally, six air changes per hour are sufficient to maintain ISO 7, even in class 2 ORs. Figure 3-3 verifies this (Commissie kwaliteitsdocumenten NVOG, 2020).

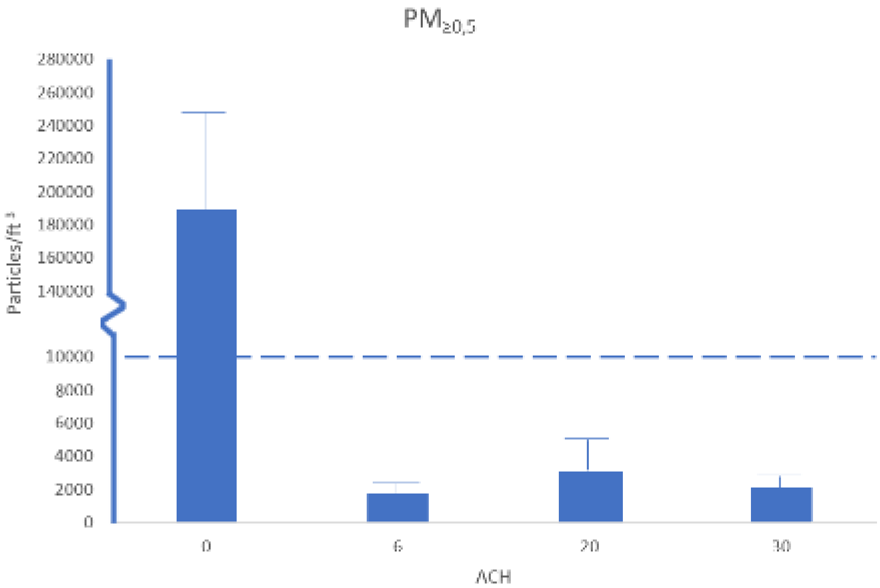


Figure 3-3: The influence of the number of air changes on the number of particles found. The blue dotted line corresponds to the ISO 7 standard

3.2 Changes in the revised guidelines concerning the air treatment of operating rooms in Dutch hospitals compared to the previous guidelines

Recently published changes in the guidelines have been published initiated by Nederlandse Vereniging voor Medische Microbiologie (NVMM). The guideline generally remains the same. However, some crucial changes have been made. This section elaborates on the most important changes between the revised guidelines and the previous guidelines described in the previous section. The newest guideline *Richtlijn Luchtbehandeling in operatiekamers en behandelkamers* (NVMM, 2022) aims to reduce the discrepancy and confusion around the guideline (I. Spijkerman, personal communication, June 22, 2022) (See Appendix C.1: Interview with Ingrid Spijkerman (Amsterdam UMC) for the interview). To achieve this, a new guideline is composed and for example, the recommendations regarding the HVAC system selection have been altered.

3.2.1 Recommendations regarding HVAC system

As explained in the previous section, UDF HVAC systems are more effective at limiting the number of micro-organisms in the OR as opposed to turbulent HVAC systems. However, no evidence is found that these systems also lead to fewer SSI occurrences. The international guidelines World Health Organization (2016), Centers for Disease Control and Prevention (2017), and National Institute for Health and Care Excellence (2020) also state that research in this area has serious shortcomings and that this low to very low level of evidence suggests a choice for equipping an OR with a UDF HVAC system or a turbulent HVAC system is not supported by research (NVMM, 2022). More, but especially qualitatively better research into the effect of different HVAC systems on SSIs is urgently needed. The guidelines in for example the UK, the USA, Germany, and Belgium do not recommend a specific HVAC system an OR should be equipped with (NVMM, 2022). The revised guideline in the Netherlands abandons the recommendation of UDF HVAC systems because there is no evidence that these systems prevent SSIs more effectively as opposed to turbulent HVAC systems.

3.2.2 Revised classification

The revised guideline proposes a new system to classify HVAC systems in ORs as class 1+, class 1, or class 2. The classifications “performance level 1” and “performance level 2” have been removed. To prevent SSIs as effectively as possible, ORs should be equipped with an HVAC system that (regardless of the type of HVAC system) at least meet the minimum criteria stated in Table 3-4. Additionally, for elective major joint replacement operations (knee, hip, shoulder), an OR with ultra-clean air is preferred. Notice that this was already the case in the previous guideline, as we see in Table 3-2. That is, an OR that meets the criteria of an OR class 1+ described in Table 3-4 is prescribed (NVMM, 2022).

New guidelines	OR class 1+	OR class 1	OR class 2
Air changes/hour	At least 20x	At least 20x	At least 6x
Air quality	ISO 5	ISO 7	ISO 7
Recovery time	≤ 3 min	≤ 20 min	N.A.
Temperature	18 °C - 23 °C	18 °C - 23 °C	18 °C - 23 °C
Relative humidity	< 65%	< 65%	< 65%

Table 3-4: Minimum criteria for ORs in the revised guideline

NVMM (2022) also provides a classification of surgeries in accordance with every specialism in the revised guideline. The table for classification of interventions was completed by the scientific associations of the accompanying specialism. This extensive surgery classification can be seen in Appendix D: Surgery classification as proposed in the revised guideline.

3.3 Optimal job scheduling

To formulate the surgery scheduling problem, we use optimal job scheduling. We view the surgeries as independent jobs that must be scheduled on one of the machines. In this case, ORs are referred to as machines in optimal job scheduling. After having formulated the scheduling problem using optimal job scheduling, we can search for effective heuristics to optimize surgery scheduling.

Optimal job scheduling is an optimization problem related to scheduling processes using one or several machines. It refers to a set of tasks that must be performed under different configurations of production resources, such as a single machine or multiple machines (Azimpoor & Taghipour, 2020). A typical optimal job scheduling problem aims to find a schedule that optimizes an objective function using a list of jobs and machines. A scheduling problem might be either a single-stage or a multi-stage schedule problem. In a single-stage optimal job scheduling problem, each job requires only a singular phase. Each job in a multi-stage optimal job scheduling problem requires multiple phases before completion. These phases can be carried out either in sequence or in parallel. The types of job scheduling problems will now be discussed (Graham et al., 1979).

3.3.1 Single-stage job scheduling problems

- **1: Single-machine scheduling**
  Single-machine scheduling is an optimization problem where n jobs $J_1, J_2, \dots, J_n$ with different processing durations that need to be scheduled on a single machine.

- **P: Identical-machines scheduling**
  This optimization problem concerns where n jobs $J_1, J_2, \dots, J_n$ with different processing durations that need to be planned on m identical machines. Job j has a processing duration denoted by p_j on any of the machines.

- **Q: Uniform-machines scheduling**
  The uniform-machines scheduling problem concerns n jobs $J_1, J_2, \dots, J_n$ with different processing times that need to be scheduled on m machines. Each machine i has a factor representing its relative speed s_i and every job j has an individual processing duration on a specific machine i of $p_{i,j}$. $p_{i,j}$ is calculated by: $p_{i,j} = \frac{p_j}{s_i}$.

- **R: Unrelated-machines scheduling**
  n jobs $J_1, J_2, \dots, J_n$ need to be scheduled on m different machines. The time that machine i needs for job j is denoted $p_{i,j}$. There is no relation between the values of $p_{i,j}$ for the different jobs and machines.

3.3.2 Multi-stage job scheduling problems

- **J: Job-shop scheduling**
  This optimization problem concerns n jobs $J_1, J_2, \dots, J_n$ with different processing durations that need to be planned on m machines with varying processing speeds. Every job consists of different operations $O_1, O_2, \dots, O_n$. These operations need to be processed in a specific order in a job-shop scheduling problem. Additionally, every operation can only be handled by a dedicated machine, and no more than one operation in a job can be executed simultaneously.

- **F: Flow-shop scheduling**
  In this case, there are n jobs $J_1, J_2, \dots, J_n$ with different processing durations that need to be planned on m machines with varying processing speeds. Every job consists of different operations $O_1, O_2, \dots, O_n$. These operations also need to be processed in a specific order. Also, only a single operation can be performed by each machine simultaneously and the next operation can only be started before the previous operation is finished. There is not one dedicated machine for a specific operation.

- **O: Open-shop scheduling is a similar problem but also without the order constraint**
  The open-shop scheduling problem concerns n jobs $J_1, J_2, \dots, J_n$ with different processing durations that need to be planned on m machines with varying processing speeds. Every job consists of different operations $O_1, O_2, \dots, O_n$. These operations can be scheduled in any order and on any machine for this specific scheduling problem.

3.3.3 Job data

The following data concerning optimal job scheduling problems can be identified for each job J_j:

- The completion time C_j is the point in time at which a job J_j is finished;
- The processing time p_j or p_{ij} is the duration of completing job J_j on machine m_i, either machine-independent or machine-dependent, respectively;
- The release date r_j is the moment job J_j becomes available for processing;
- The due date d_j is the moment at which job J_j must be finished;
- The setup time s_j is the duration required for machine preparation before job J_j can start.

3.3.4 Optimality criteria

When solving a scheduling problem, a particular objective must be achieved. Several objectives can be discovered when performing a literature review. These objectives, or optimality criteria, can for example be the following:

- C_{max}: The maximum completion time, or makespan, can be minimized;
- $\bar{C}$: The average completion time can be minimized;
- L_{max}: The maximum lateness can be minimized. $L_j = C_j - d_j$;
- $\sum T_j$: The tardiness represented by the sum of $T_j \ \forall\ j$ can be minimized. $T_j = \max\{0;\ C_j - d_j\}$;
- $\sum F_j$: The total flow time represented by the sum of $F_j \ \forall\ j$ can be minimized. $F_j = C_j - r_j$;
- $\sum U_j$: The number of jobs that are completed before their deadline represented by the sum of $U_j \ \forall\ j$ can be maximized. This is called the throughput;
- E_{min}: Maximize the minimum earliness. The earliness is calculated using $E_j = \max\{0;\ d_j - C_j\}$.

3.3.5 Notation for optimal job scheduling problems

This research uses the three-field problem classification notation as described by Graham et al (1979). This notation describes a scheduling problem using a three-field notation denoted α|β|γ, where:

- α is used to describe the type of scheduling problem;
- β is used to describe the job characteristics;
- γ is used to describe the optimality criteria.

For example, $1|d_j|L_{max}$ is a single-machine scheduling problem with given due dates for each job where the aim is to minimize the maximum lateness.

4 Evaluation of the Amsterdam UMC

This chapter elaborates on the case study. The data collected in this chapter originates mainly from observations and interviews but also using a literature review found in the "Zenya" database from the Amsterdam UMC. Topics such as scheduling, HVAC systems, and energy consumption are discussed in this chapter. As the Amsterdam UMC has not implemented the new guideline thus far, we will use the old OR classification (e.g., class 1 performance level 1) in the evaluation of the Amsterdam UMC.

4.1 Scheduling

Each surgery is classified and scheduled in either a class 1 OR or in an independent treatment room. Another classification is made regarding the urgency of surgeries. This requires systematic planning strategies. This section elaborates on the surgery process and classifications of surgeries used by the Amsterdam UMC. Additionally, their current planning is explained.

4.1.1 Surgery process description

The process of carrying out surgery on one patient is depicted in Figure 4-1 using a Business Process Model Notation (BPMN) model. The BPMN model consists of four pools representing the corresponding department. These departments are the nursing department, holding, OR, and the recovery room. Every activity depicted in the BPMN model represents a stage to be registered in the information system EPIC.

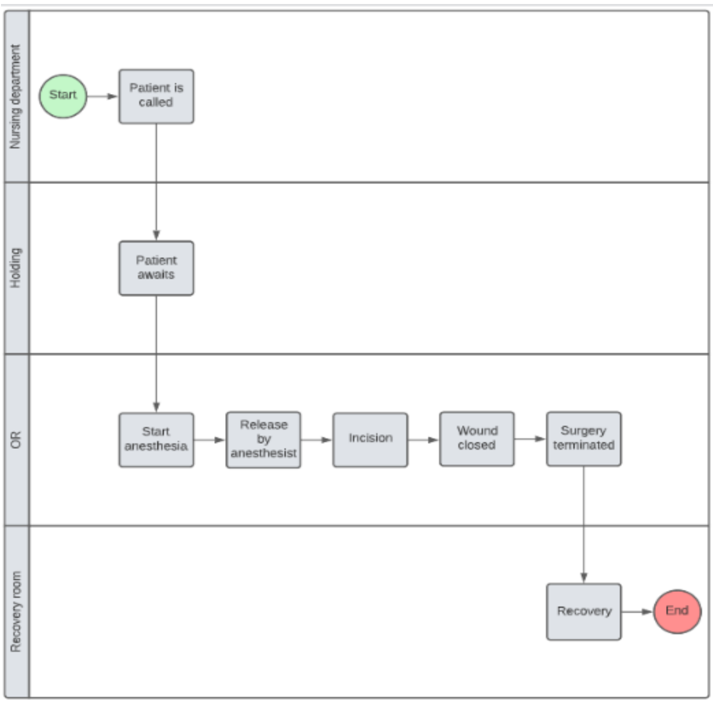


Figure 4-1: BPMN model of an individual surgery process

The process starts in the nursing department, where the patient is called. The patient is then taken to the waiting room in the holding. After this, the patient is brought to the OR. The surgery then generally consists of five stages: Start anesthesia, release by the anesthetist, incision, wound closed, and the termination or end of the surgery. The surgeon can start preparing for the surgery as soon as the patient is released by the anesthetist. This can occur before the anesthetist has finished the anesthesia. Preparing the patient consists of positioning the patient, applying iodine compounds, and covering the patient. The incision is then started, and the wound is closed afterward. The surgery is then finished, and the patient is brought to the recovery room. After having recovered, the patient is taken to the nursing department or intensive care. These stages are not registered in EPIC and are thus not depicted in the BPMN model. Two points in time where the patient arrives and departs the OR must also be registered in EPIC. This sequence of steps is executed repeatedly in all 20 ORs.

We define the processing time as the duration between the points in time where the patient arrives at the OR and leaves the OR. The time difference between the point in time where a patient leaves the OR and where the next patient arrives at the OR is the setup time. However, in this definition, we assume that the idle time is equal to zero. Figure 4-2 visualizes the processing time and setup time if we assume the idle time to be equal to zero.

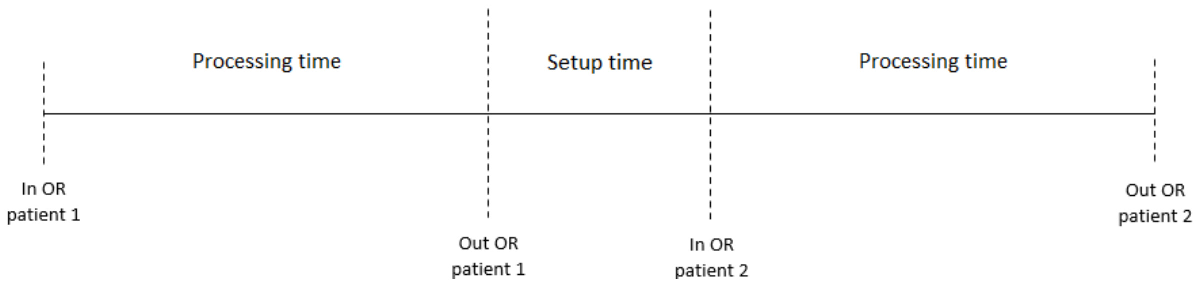


Figure 4-2: Processing time and setup time

4.1.2 Current OR classification of surgeries

The guidelines do not prescribe the type of OR that should be used for each type of surgery, because it is not possible to give a strict classification of interventions according to the circumstances under which they must be performed based on the literature. Only an example of surgery classification and allocation is given in the guideline (Check Appendix E for the example that is provided) (WIP, 2011). Note that this is solely an example and that it is not used in practice. However, an institution that has several OR types as described in the guideline where interventions can be performed, must explicitly describe which interventions may be performed at which OR(s). That is, each hospital should make a classification of surgeries and which ORs can be used for the type of surgery individually. The following criteria must be considered when deciding where to perform which interventions:

- the size of the incision;
- the depth of the incision;
- the duration of the procedure;
- implantation of a foreign material;
- opening sterile cavities, bones, or large joints;
- the consequences of an SSI for the patient.

As mentioned in 3.1.2: “Performance, construction, and other guidelines HVAC system of class 1 ORs”, every hospital is obliged to compose an air management plan, a document indicating the requirements for surgery allocation, and a classification of surgeries. Van der Steen – de Vlaming (2022) composed a document for the Amsterdam UMC indicating a classification of surgeries and which interventions may be performed under which conditions (treatment room, OR class 1 performance level 1, OR class 1 performance level 2). Notice that class 2 ORs are not included in the classification because there are no class 2 ORs in the Amsterdam UMC hospital, as mentioned in 1.1: “Problem owner description”. The following classification and allocation are described by Van der Steen – de Vlaming (2022):

- **OR class 1 performance level 1**
  The following surgical procedures may take place in the ORs class 1 performance level 1:
  - All surgical procedures may be performed in the clinical ORs, which are all class 1 performance level 1.

- **OR class 1 performance level 2**
  The following surgical procedures may take place in the ORs class 1 performance level 2:
  - Intraocular procedures.

  The following surgical procedures may <u>not</u> take place in the ORs class 1 performance level 2:
  - Total hip- and knee arthroplasty;
  - Breast implants;
  - Central vascular prostheses;
  - Surgical procedures in which an endoprosthesis or implant is inserted, which in terms of SSI risk and consequences are comparable to a joint replacement.

- **Treatment room**
  - No surgical procedures may take place in a treatment room.

We conclude that the Amsterdam UMC hospital adheres to the performance level recommendations in the guidelines composed by WIP (2014) (Table 3-2), as surgeries concerning joint replacement or procedures with implantation of (endo)prostheses must be performed in clinical ORs classified as class 1 performance level 1. This was also prescribed in the guideline discussed in 3.1.2: "Performance, construction, and other guidelines HVAC system of class 1 ORs". However, all surgeries are currently executed in class 1 performance level 1 ORs in the clinical OR department. This is not necessary. ORs are also equipped with different equipment, which complicates the scheduling of surgeries.

4.1.3 Urgency classification of surgeries

Some surgeries are prioritized over other surgeries in the Amsterdam UMC. Acute and emergency surgeries for example have more urgency than elective surgeries. Prioritizing a surgery over another surgery means scheduling the prioritized surgery earlier. An urgency classification is made to determine the priority of every surgery. The Amsterdam UMC uses urgency classes S1, S2, S3, and S4 (Steen - de Vlaming & Hamersveld, 2021). We define the urgency classes as:

- S1: Acute, patient must be on the operating table within one hour at the latest.
- S2: Urgent, patient must be on the operating table within six hours at the latest.
- S3: Semi-urgent, patient must be on the operating table within 24 hours at the latest.
- S4: (Semi-)elective, patient must be on the operating table within between 24 and 72 hours. Surgery is not scheduled outside business hours.

There is no nationally used classification system, but local systems are used per hospital or region. The Amsterdam UMC applies the surgery urgency classification as proposed by Werkgroep Nederlandse Vereniging voor Heelkunde (NVVH) (2017). An extensive urgency classification over every surgery can be found on their website. This classification is formulated and clustered by the following specialisms:

- Surgery
- Pediatric surgery
- Otolaryngology surgery
- Oral and maxillofacial surgery

- Neurosurgery
- Obstetrics and gynecology
- Ophthalmology
- Plastic surgery
- Radiology
- Thorax surgery
- Traumatology & orthopedic surgery
- Urology
- Vascular surgery

4.1.4 Currently implemented scheduling

The planning must be within the established (financial) budget of the OR department and the specialisms. The OR planning and control at the Amsterdam UMC is done at a strategic level, tactical level, and operational level (Steen - de Vlaming & Hamersveld, 2021). The management levels are distinguished by different planning horizons, different frequencies, and differences in the detail level. The strategic level is involved with monitoring and controlling the organization. Long-term decisions are made which are often annually. The decisions made on a strategic level impact the decisions on a tactical level. The tactical level consists of monthly or weekly decisions and this level must implement the decisions on a strategic level. The operational level concerns controlling daily operations. The management at the tactical level is informed about potential problems (Kaplan Financial Limited, 2020).

Strategic level

The annual planning is determined by the management at a strategic level of the Amsterdam UMC. The annual planning includes the planning of the budgeted OR capacity for each specialism for that year (K. de Vlaming, personal communication, June 30, 2022) (See Appendix C.3: Interview with Karin de Vlaming (Amsterdam UMC). The annual plan is released no later than two months before the start of the new year. Approximately 30% of this planning consists of stochastic OR-hours. These stochastic hours are allocated two months in advance in the monthly planning. This allocation depends on available personnel and unforeseen circumstances (Steen - de Vlaming & Hamersveld, 2021).

Tactical level

On the tactical level, the monthly planning and the weekly planning are formulated. The monthly planning includes the final planning of the OR capacity concerning the corresponding month. The stochastic OR-hours and the reserved OR-hours as described in the annual planning are definitively assigned depending on available personnel and unforeseen circumstances. This planning must be released at least two months in advance. The weekly planning for the next week is determined each Thursday at 12:00. Each specialism is responsible for scheduling surgeries within the released OR capacity in the weekly planning. Before the weekly planning on Thursday, all specialisms have a multidisciplinary meeting. During this meeting, the past week is reflected on and the planning for the next week is discussed. The reflection aims to identify potential medical and logistical bottlenecks. The planning of surgeries is executed in the system Optime by EPIC, and the weekly planning is based on historical data concerning the processing time of surgeries per operator, procedure, and anesthesia type. The concept of the weekly planning of every specialism must be available in EPIC Optime on Wednesday at 17:00 at the latest.

Operational level

The daily OR planning on the operational level is determined at 10:30 one working day before the day of surgery. To make this possible, the planning per specialism must be uploaded to EPIC Optime at 10:00 at the latest (Steen - de Vlaming & Hamersveld, 2021). Appendix F depicts an example of the planning of a random day in a Gantt chart. The appendix shows the planning, as executed on 4-3-2019.

4.2 HVAC system

The guidelines concerning HVAC systems are explained in previous sections. However, it is not clear what HVAC systems are generally used for thus far. Additionally, there remains a knowledge problem as it is unknown how HVAC systems are implemented in the Amsterdam UMC hospital. Different types of HVAC systems are available, so the type(s) of HVAC systems used, and the operation of the systems should be identified. This section elaborates on the importance of HVAC systems and on which type(s) of HVAC systems are implemented in the Amsterdam UMC.

4.2.1 Importance of HVAC systems

The HVAC system in ORs ensures comfortable climate conditions within the OR by heating, cooling, and ventilating. The HVAC system ensures the RH can be controlled and an environment free of micro-organisms is created. Microorganisms such as bacteria are released into the air via, among others, human skin, dust, and hair. Therefore, people present in the OR are the main source of the spread of micro-organisms into the air. The air treatment in ORs via the use of HVAC systems aims to minimize micro-organisms to prevent SSIs. This minimizes the chances of SSI or any other type of contamination occurrences.

4.2.2 Operation of the HVAC systems

The HVAC system is set to daytime operation via a clock program that is adjustable at the reception of the hospital, but it can also be set to daytime operation via a software switch. The clock program automizes the operation of the HVAC systems by automatically switching to the daytime operation or nighttime operation. Currently, the daytime operation is switched on between 6:30 a.m. and 9:00 p.m., from Monday to Friday. When switching an HVAC system from nighttime operation to daytime operation, approximately 30 minutes are required before the system optimally operates. Out of the 20 class 1 performance level 1 ORs, 15 ORs are in nighttime operation between 9:00 p.m. and 6:30 a.m., from Monday to Friday. These ORs are continuously in nighttime operation on weekends and during holidays. OR 4, 5, 8, 12, and 14 are exceptions to the clock program operation, as they are operational 24 hours a day, seven days a week. This means that the HVAC systems in these ORs are always in daytime operation. These ORs are preferably used for emergency procedures. The HVAC systems are 100% operational during daytime operation, while the airflow rate of the HVAC systems is a maximum of 50% compared to daytime operation during nighttime operation.

Each OR is equipped with the signaling and operating panel depicted in Figure 4-4. This is referred to as a “Bender panel” in the hospital, as it is produced by the company Bender. This is a display visualizing some KPIs. Color coding is used for visualizing whether the KPIs are within their limit values, and both visual and audible notifications can be given in case of an alarm. Additionally, the panel can be used for the operation of the HVAC system. All values of the KPIs on the dashboard can be changed by using the interface of the panel. The panel overrides the central operating system. Limit values of all KPIs related to the OR are described by Amsterdam UMC (2018) in their air management plan. Check Appendix G for the requirements for critical parameters in class 1 performance level 1 ORs of the Amsterdam UMC. The plenum is divided into two zones T1 and T2. The air in the downflow zone T1 is approximately 1.5 °C lower than the downflow zone (T2). These temperature differences are necessary to ensure downflow stabilization. As can be seen in this table, all clinical ORs currently satisfy ISO 5 standards.

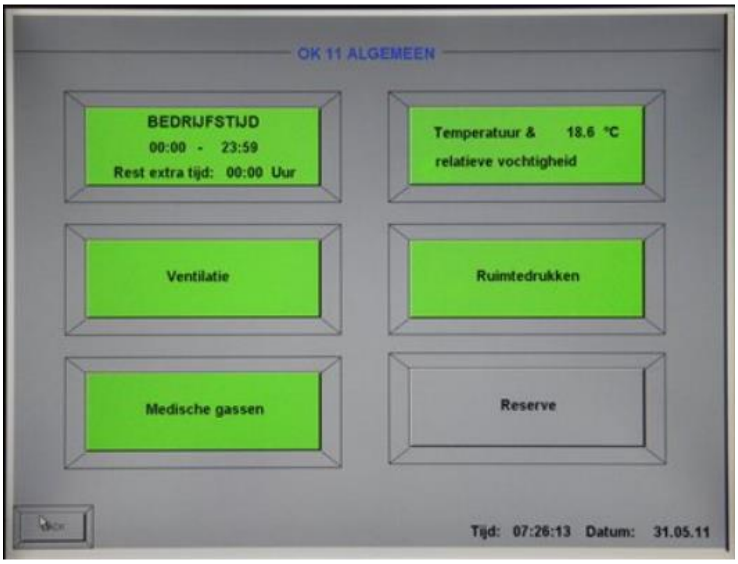


Figure 4-4: Bender panel in OR 11

If surgery is still in progress outside daytime operation hours, the temperature and RH cannot be kept within the set limits if no action is taken. This can be done by interacting with the panel in the OR. This panel visualizes the daytime operation time window and some other relevant parameters for that specific OR. By interacting with the "Bedrijfstijd" tab of the "Bender panel" of Figure 4-4, the switch to nighttime operation can be postponed (Check Figure 4-3) (van der Steen - de Vlaming, 2022). The screen will be green when the HVAC system of the corresponding OR is in daytime operation. If the switch to nighttime operation is planned in an hour or less or five minutes or less, the screen will be orange or red, respectively.

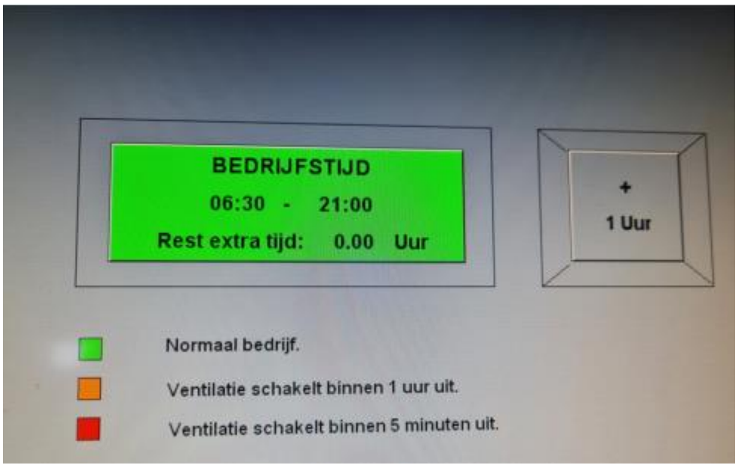


Figure 4-3: Bender panel displaying an OR in daytime operation

4.2.3 HVAC systems at the Amsterdam UMC

As described in section 1.1: "Problem owner description", the clinical OR department consists of 20 clinical ORs. In accordance with the guideline, the air treatment in the ORs was measured. It appears that the clinical ORs meet the requirements for OR class 1 performance level 1 (van der Steen- de Vlaming, 2022). The 20 ORs in the OR department of the Amsterdam UMC are equipped with UDF HVAC systems. UDF HVAC systems can both have horizontal or vertical airflow, both of which can meet ISO 5 standards. Figure 4-5 depicts the airflow patterns of horizontal and vertical UDF HVAC systems. This airflow is often referred to as laminar. Laminar airflow is defined as airflow taking place along constant streamlines, without turbulence (Oxford languages, 2022). However, in practice airflow provided by UDF HVAC systems is never without turbulence as fixed equipment, medical equipment, or even the surgeon redirect airflow. This causes some degree of turbulence. Horizontal UDF HVAC systems provide an airflow of clean, filtered air from a plenum in one of the walls of the OR horizontally. The wall in the opposite direction will remove the polluted air. In building construction, a plenum is defined as a separate space provided for air circulation for HVAC (C2G, 2021). Horizontal UDF in an OR as built causes less turbulence as opposed to vertical UDF, as turbulence is not the result of airflow being redirected by a perpendicular surface. Because less turbulence is occurring with horizontal UDF, better protection against contamination can be achieved. However, large materials upstream can obstruct the operating area and contaminate the area.

Vertical UDF or downflow HVAC systems are implemented in every OR of the Amsterdam UMC hospital. This type of HVAC system provides a protected area in an OR of filtered air originating from a plenum in the ceiling. Polluted air is afterward removed by applying suction from every wall. A vertical UDF system does not need as much floor space as a horizontal UDF. Additionally, the airflow is not parallel to the operating area, which means that cross-contamination occurs less frequently compared with a horizontal UDF HVAC system. The motivation to include only vertical UDF HVAC systems stem from the fact that horizontal UDF HVAC systems are in practice found to be more sensitive to airflow disruption caused by the positioning of personnel, material, and equipment. This susceptibility to airflow disturbance was also observed under experimental conditions.

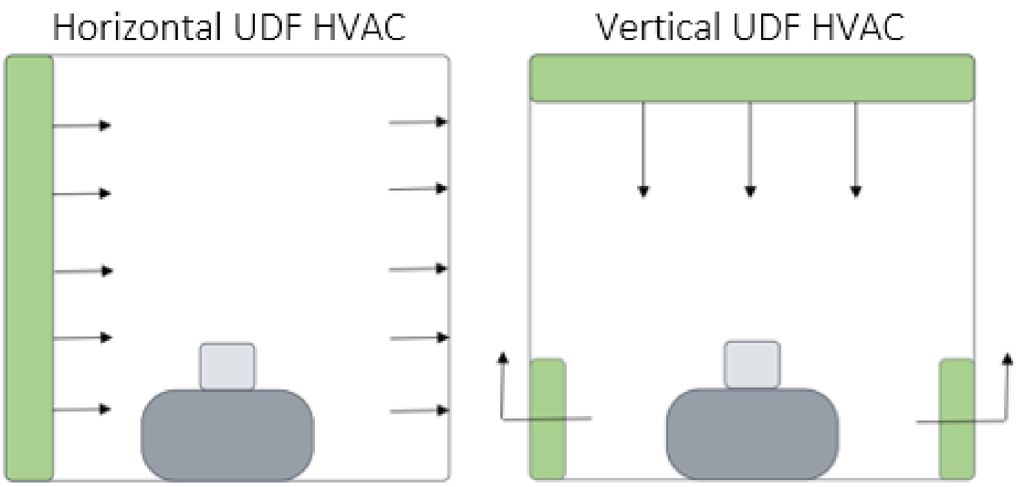


Figure 4-5: Airflow patterns of horizontal and vertical UDF HVAC systems

4.2.4 HVAC system design

Different configurations of HVAC system elements are applied in hospitals. These configurations consist of different applications of the clean air system, recirculation system, plenum, and swirl diffusers. NVMM (2022) stated: "Of the two most commonly used HVAC systems, UDF and turbulent, there seem to be advantages in terms of sustainability for using a turbulent HVAC system. Exact data on this cannot be given because the environmental impact depends on more factors than just the type of HVAC system. However, the use of a turbulent HVAC system generally leads to less energy consumption because less air is transported". We conclude that generally, vertical UDF HVAC systems should be used for ORs with class 1 performance level 1 and turbulent HVAC systems for class 1 performance 2 ORs as turbulent HVAC systems consume less energy compared to UDF HVAC systems, and class 1 performance 2 requirements can be met using turbulent HVAC systems. Figure 4-6 depicts the configurations that are applied frequently by hospitals.

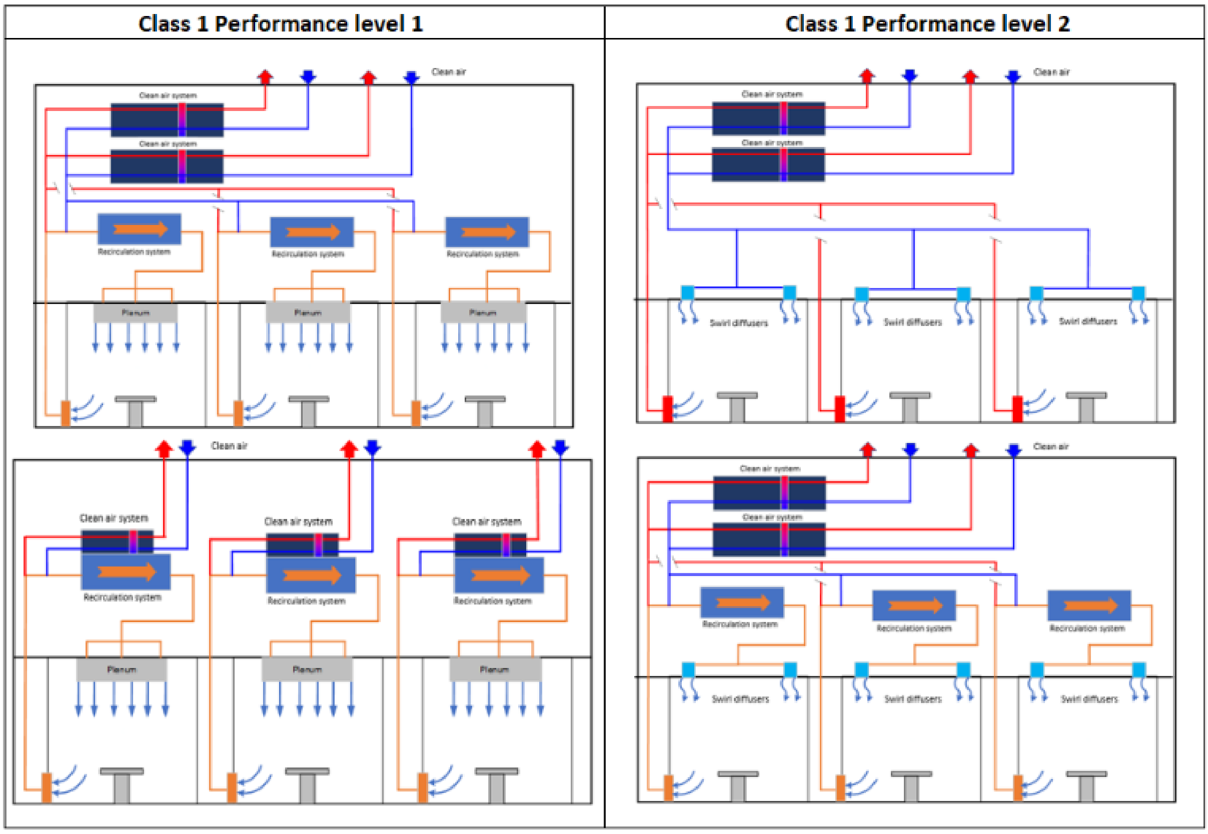


Figure 4-6: HVAC system configurations

UDF HVAC systems that are applied to class 1 performance level 1 generally have two potential configurations, as the clean air system can be centralized or decentralized. Decentralized clean air systems feature a clean air unit for every OR, while centralized clean air systems consist of central clean air units providing clean air to the plenums of every OR. Recirculation systems are decentralized, recirculating air for every corresponding OR individually. ORs classified as class 1 performance level 2 are often equipped with turbulent HVAC systems. These HVAC systems distribute air to the OR using swirl diffusers instead of plenums. A decentralized recirculation system is optional in the turbulent HVAC system. Clean air units are centralized.

Enlarged figures of the configurations are depicted in Appendix H. Figure H-2 visualizes the configuration applied in the clinical ORs of the Amsterdam UMC hospital. The UDF HVAC systems consist of a decentralized clean air system. This means that every OR is equipped with a clean air system that provides clean air, instead of a central clean air system that provides clean air to all ORs. Decentralized recirculation systems are installed for every individual OR. These systems filter the polluted air originating from the OR to provide clean air. The laminar airflow providing clean air is distributed via a plenum installed in the structural ceiling of the OR. Polluted air is removed as depicted in the vertical UDF HVAC system illustrated in Figure 4-5.

4.3 Energy consumption of the clinical OR department

The goal of this research is to decrease the CF in the clinical OR department of the Amsterdam UMC. Insights into the current energy consumption are crucial to verify the effectiveness of the potential recommendations.

4.3.1 Current energy consumption

As can be read in 4.2.3: "HVAC systems at the Amsterdam UMC", the clinical OR department consists of 20 class 1 performance level 1 ORs using UDF HVAC systems. Since 2018, 15 of these systems are in nighttime operation between 21:00 and 6:30 on Monday to Friday and between 00:00 and 23:59 during weekends and holidays. This measure dramatically decreased the energy consumption of the OR department. During the COVID-19 pandemic, the measure was temporarily not in effect. It was introduced again in March 2021. Figure 4-7 depicts the energy consumption of the OR department during a week in April 2019 (J. Koeman, personal communication, June 16, 2022). The blue graph represents the energy consumption before the measure, while the red graph depicts the energy consumption of the OR department after the implementation of the day- and nighttime operation measure. When assessing the local extrema of the two graphs, we conclude that the local maxima of the red graph are not notably decreased, while the local minima of the graph are significantly decreased as opposed to the blue graph. The decreases in the local minima are caused by the ORs in nighttime operation.

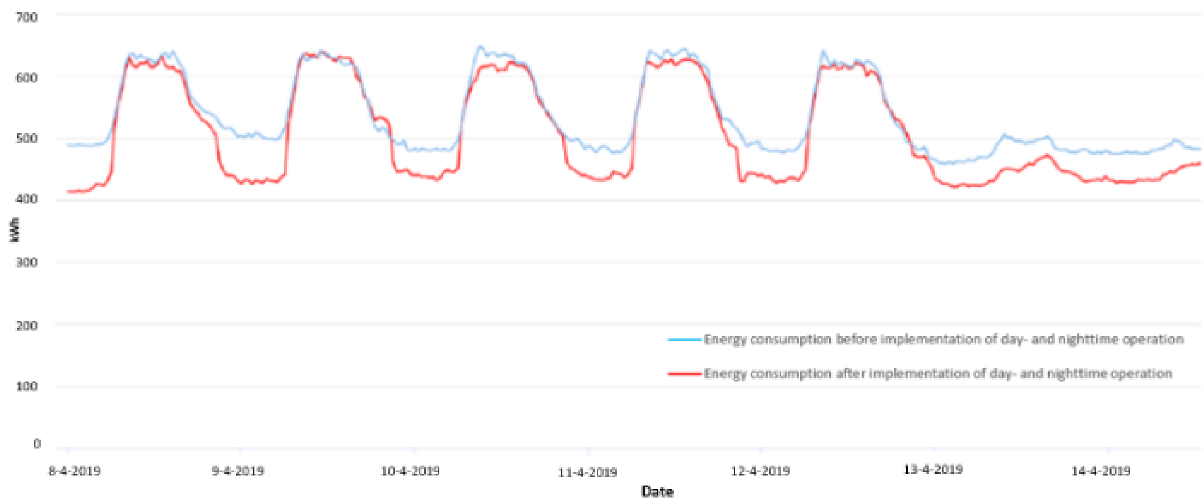


Figure 4-7: Energy consumption of the clinical OR department

The clinical OR department is in departments D and E of the Amsterdam UMC. These two departments consumed a total of 9.2 GWh in 2018 (J. Koeman, personal communication, June 16, 2022). To estimate the energy consumption of the ORs in the clinical OR department of the Amsterdam UMC, a tool is used provided by W. Nieuwenhuyzen (personal communication, June 21, 2022). This tool generates the annual energy consumption and energy costs as output using input parameters such as the square meter of OR, operating hours, percentage of energy reduction due to airflow rate reduction, and energy costs per kWh. All assumptions related to the input of this tool can be seen in Appendix I. The tool is not depicted directly as it contains confidential information.

Figure 4-8 depicts the output of the tool. It is an estimate of the total annual energy consumption before and after implementation of the nighttime operation measure under the assumptions of Appendix I. To acquire an estimate of the energy consumption before implementation, 20 ORs with a total cleanroom surface of $18 * 50 + 2 * 70 = 1{,}040\ m^2$ is assumed. Two separate calculations must be made for an estimation of the current total energy consumption: The total annual energy consumption of the 24/7 ORs and the total annual energy consumption of the elective ORs. We assume a cleanroom surface of $4 * 50 + 70 = 270\ m^2$ for the calculation of the energy consumption of the 24/7 ORs, as 24/7 OR 8 has a cleanroom surface of 70 m^2, while the other four 24/7 ORs have a cleanroom surface of 50 m^2. For the calculation of the total annual energy consumption of all elective ORs, $17 * 50 + 70 = 770\ m^2$ of cleanroom surface is assumed. The current total annual energy consumption of the clinical OR department is then estimated to be approximately 1.65 GWh, while the total annual energy consumption before implementation of the nighttime operation measure is estimated to be approximately 2.46 GWh. The measure resulted in a reduction of the total energy consumption of 33%. Currently, one OR is estimated to consume $\frac{1{,}654{,}175}{20} \approx 82{,}709$ kWh on average annually. This total assumes $8{,}760 * 5 + 3{,}654 * 15 = 98{,}610$ operating hours in total. This implies an average of $\frac{98{,}610}{20} = 4930.5$ operating hours per OR, which results in $\frac{82{,}709}{4930.5} \approx 16.77$ kWh per operating hour for one OR classified as class 1 performance level 1.

Energy consumption 24/7 ORs	627.891	kWh / jr
Energy consumption regular ORs	1.026.284	kWh / jr
Current total energy consumption	**1.654.175**	**kWh / jr**
Total energy consumption before implementation of nighttime operation measure	**2.464.758**	**kWh / jr**

Total energy consumption reduction	**-33%**

Figure 4-8: Energy consumption according to tool output

5 Conceptual design

This chapter elaborates on the proposed conceptual design. The conceptual design describes the most notable changes by elaborating on the proposed classifications, HVAC systems, and heuristics. As opposed to Chapter 4: "Evaluation of the Amsterdam UMC", we implement the classification of the revised guideline (e.g., class 1+).

5.1 OR classification and classification of surgeries

The proposed classification of surgeries is described in this section. This classification is achieved by classifying all surgeries concerning major joint replacements as class 1+. The remaining surgeries are then classified as class 1 surgeries. This classification of surgeries adheres to the most recent guideline concerning air treatment in ORs.

5.1.1 Proposed classifications of surgeries

The revised guideline proposed a new system to classify ORs as class 1+, class 1, or class 2. The current classification of OR surgeries does not consider these new classifications. Additionally, only elective major joint replacements are advised to be executed in a class 1+ OR (See Table D-1). Check Appendix J for an elaborate list of all surgical procedures that are considered elective major joint replacements. This comprehensive list is composed in cooperation with Niek Sperna Weiland, an anesthetist at the Amsterdam UMC and organization supervisor of this project. A class 1 OR suffices for all other surgeries. The current urgency classification does not require any changes. Assigning remaining surgeries to ORs class 1, class 2, and individual treatment rooms can be executed in further research.

5.1.2 Proposed OR classification

According to historical data from 2019, 7.36% of all procedures in that year included a major joint replacement. That is, 7.36% of all surgeries must be executed in an OR of class 1+. This results in $\lceil 20 * 0.0736 \rceil = 2$ class 1+ ORs. 18 ORs will then be classified as class 1.

In 2019, there were some days (for example 3-2-2019) on which five ORs were occupied outside business hours (6:30 – 21:00). However, none of the ORs were occupied simultaneously on this day. From the data, we conclude that four 24/7 ORs instead of five 24/7 ORs would suffice. This saves energy as a reduction of the operating hours will be realized. In 2019, only 19 surgeries classified as class 1+ surgeries (Check Appendix J for these surgeries) have started outside business hours. None of these surgeries occurred on the same day and not even in the same week. We conclude that it would suffice if one class 1+ OR should be appointed as a 24/7 OR. The other class 1+ OR will be appointed as an elective OR. Three class 1 ORs will then be appointed as 24/7 ORs and the remaining 15 class 1 ORs will be elective ORs. Check Figure 5-1 for a visual representation of the proposed OR classification.

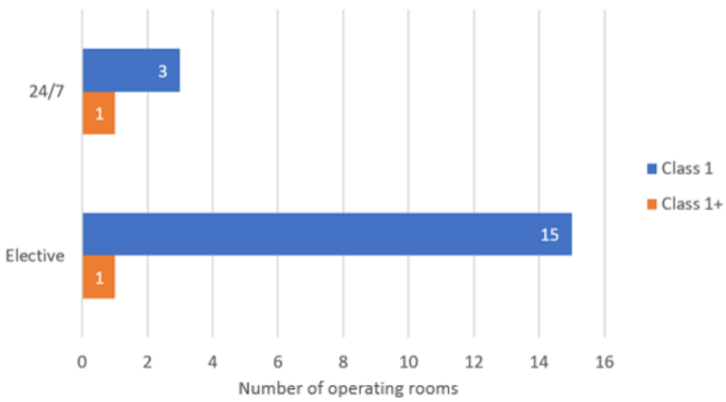


Figure 5-1: Proposed OR classification

5.2 HVAC system

This section elaborates on the proposed HVAC systems in the conceptual design. The expected energy consumption is also determined in this section. Data that is collected for this section originates mainly from the interview with A. Brouwer depicted in Appendix C.5.

5.2.1 Proposed HVAC systems

The proposed OR classes are class 1 and class 1+. This means that the class 1 ORs and class 1+ ORs in the Amsterdam UMC will need to have a minimum air quality of ISO 7 and ISO 5 and a minimum recovery time of 20 minutes and three minutes, respectively. The minimum number of air changes is 20 per hour for both classes (See Table 3-4). ISO 5 can be reached by turbulent HVAC systems, but it takes a long time before this is reached. Therefore, turbulent HVAC systems cannot meet the requirement for the recovery time of class 1+ ORs. UDF HVAC systems can meet this requirement and should therefore be used in the class 1+ ORs, even though these systems consume more energy. Turbulent HVAC systems can meet all requirements for class 1 ORs while consuming relatively small amounts of energy compared to UDF HVAC systems.

The current ORs are equipped with UDF HVAC systems with decentralized clean air systems as depicted in Figure H-2. The class 1+ ORs do not require changes as these ORs currently meet the criteria for class 1+ ORs. However, energy might be saved by switching to a UDF HVAC system with a centralized clean air system. Table 5-1 depicts the costs associated with each system according to Braam (2022). The table uses general estimations of an average system. However, they do not necessarily apply to the Amsterdam UMC.

	Investment (Excl. taxes)	Maintenance costs (10 years)	Energy costs (10 years)	CO2 emissions (10 years)	Number of trees necessary to compensate	Hectares of forest
Class 1 - P1: Decentralized clean air system	€ 272.000,00	€ 56.900,00	€ 32.200,00	170,7 tonne	6.600	16,4
Class 1 - P1: Centralized clean air system	€ 236.000,00	€ 49.300,00	€ 31.600,00	167,4 tonne	6.400	16,1
Class 1 - P2: Without recirculation system	€ 87.000,00	€ 18.200,00	€ 29.900,00	158,2 tonne	6.100	15,2
Class 1 - P2: With recirculation system	€ 129.000,00	€ 26.900,00	€ 22.300,00	117,8 tonne	4.500	11,3

Table 5-1: Costs of the HVAC system configurations

ORs "at-rest" with UDF HVAC systems with a laminar airflow will always maintain ISO 5 and a recovery time of three minutes. However, this is not necessary for the class 1 ORs. The ORs classified as class 1 should be equipped with turbulent HVAC systems with decentralized recirculation systems, as can be seen in Figure H-4. This configuration consumes the smallest amount of energy. The investment as depicted in Table 5-1 will not be necessary, as the current UDF HVAC systems can be maintained. Control technology can be built in with which the airflow rate can be reduced from high (laminar) to low (turbulent) (A. Brouwer, personal communication, June 14, 2022) (Check Appendix C.5). If the airflow rate is reduced, the plenum will function as a large diffuser of turbulent ventilation. It is required that the fans in the HVAC system are adjustable and additional control technology must therefore be installed. The "Bender panel" of the OR can then provide the interface for switching the airflow rate. It needs to be validated that the OR meets the requirements of the intended OR class after having switched from one class to another. Another aspect that needs to be validated is whether the control system incorporates the switch to nighttime operation for the elective ORs.

5.2.2 Energy consumption of proposed HVAC systems

As concluded in 4.3.1: "Current energy consumption", ORs of class 1 performance level 1 consume 16,77 kWh per operating hour on average. We assume ORs of class 1+ and class 1 ORs to have similar energy consumptions as ORs of class 1 performance level 1 and class 1 performance level 2, respectively as the classes have similar characteristics. This means that we assume one class 1+ OR to consume 16,77 kWh per operating hour.

Table 5-1 displays the costs and CO2 emissions of every HVAC configuration (Braam, 2022). Here, both class 1 performance level 1 configurations use UDF HVAC systems, while both class 1 performance level 2 ORs are equipped with turbulent HVAC systems. Check Figure 4-6 for a reminder of the configurations. In Table 5-1, we see that the configuration that is currently implemented in the Amsterdam UMC has the highest energy consumption. The color coding depicts this with the red color. ORs with HVAC systems with a centralized clean air system as depicted in Figure H-1 can be used for class 1+ ORs, and it could result in a reduction of $\frac{32{,}200-31{,}600}{32{,}200} \approx 1.86\%$ of energy costs. We assume energy costs per kWh to be constant. Therefore, the energy consumption is reduced by approximately $1{,}86\%$ as opposed to the current situation with decentralized clean air systems. Each class 1+ OR will then consume $16.77 * (1 - 0.0186) \approx 16.46$ kWh per operating hour. Class 1 ORs should be equipped with turbulent HVAC systems with recirculation systems as visualized in Figure H-4, as this HVAC system configuration has the smallest energy consumption while meeting class 1 standards according to Braam (2022). The configuration for class 1 ORs consumes $\frac{32{,}200-22{,}300}{32{,}300} \approx 30.75\%$ less energy as opposed to the current ORs. This corresponds to an energy consumption of $16.77 * (1 - 0.3075) \approx 11.61$ kWh per operating hour of one class 1 OR.

The four 24/7 ORs will then consume a total of $8{,}760 * (11.61 * 3 + 16.46) = 449{,}300.40$ kWh, while the 16 elective ORs are expected to consume $3{,}654 * (11.61 * 15 + 16.46) = 696{,}488.94$ kWh annually if we assume the same number of operating hours as in 2019. This results in total energy consumption of $449{,}300.40 + 696{,}488.94 = 1{,}145{,}789.34$ kWh for the clinical OR department. In total, 508,385.66 kWh is then saved annually. This corresponds to a reduction of the energy consumption in the clinical OR department of approximately 31% as opposed to 2019.

5.3 Heuristics

This section describes the OR scheduling problem of the Amsterdam UMC, and it elaborates on appropriate heuristics for assigning surgeries with the same urgency class to an OR. Data collection for this section is executed using literature review and observations. The heuristics are designed for management at a tactical level.

5.3.1 The OR scheduling problem

The Amsterdam UMC aims to reduce the maximum completion time of their surgeries to reduce the energy consumption of the OR department. Minimizing the maximum completion time maximizes the OR utilization and minimizes the duration that the machines, or ORs, must be operational. A reduction of the maximum completion time enables the hospital to reduce the duration of the ORs in daytime operation. Therefore, a reduction in the energy consumption of the HVAC systems can be realized. Minimizing C_{max} will be the objective of the heuristic. However, the throughput rate of the OR department cannot suffer from the new planning heuristic. The maximum completion time C_{max} defined as $max\{C_1, C_2, \ldots, C_n\}$, is referred to as the makespan. This OR scheduling problem is a single-stage schedule problem, as each job is finished after a singular execution phase, and each machine, or OR, is identical in terms of processing speed as all the ORs have the same processing speed. However, the scheduling heuristic will allocate surgeries to two types of machines which are class 1 and class 1+

ORs. All surgeries can be performed in class 1+ ORs, while a subset of all surgeries can be performed at the class 1 ORs. Therefore, this non-preemptive scheduling problem requires a variant of identical-machine scheduling for the formulation of the scheduling problem. It is labeled non-preemptive as we assume that surgeries cannot be interrupted and finished in a different OR. Additionally, sequence-dependent setup times are required for each surgery. These setup times are, among other things, caused by cleaning the OR, personnel preparation, and equipment preparation. We assume that the setup time before a job depends on the previous job executed at a machine, regardless of the machine. The problem is NP-hard. Here NP means "non-deterministic polynomial time". An NP-hard problem is considered the most difficult problem to find an optimal solution. We, therefore, use a heuristic to find a near-optimal solution.

The clinical OR department consists of 20 ORs, which can be classified as either class 1 or class 1+ ORs. We define $V_{p,q}$ to be the scheduling variant applicable to the OR scheduling problem, where p denotes the number of class 1 ORs and q denotes the number of class 1+ ORs at the clinical OR department. We assume $M \in \{M_1, M_2, \dots, M_m\}$ to be the set of machines, while $J \in \{J_1, J_2, \dots, J_n\}$ denotes the set of independent jobs. Using the three-field notation, this scheduling problem is then described as $V_{18,2}\ |s_{k,j}|C_{max}$ if the clinical OR department consists of 18 class 1 ORs and two class 1+ ORs as explained in 5.1.2: "Proposed OR classification".

5.3.2 Proposed heuristics

"Loosely speaking, heuristic means to find or to discover by trial and error (Yang, 2011). It consists of various consequent steps to perform to approach an optimal solution. Well-known heuristics that are implemented in many scheduling problems are First Come, First Served (FCFS), Earliest Due Date (EDD) first, Shortest Processing Time (SPT) first, and Longest Processing Time (LPT) first. The EDD rule generally minimizes the maximum job lateness for scheduling problems with a single machine including job due dates, while the SPT rule generally minimizes the flow time of a job. These heuristics solve relatively easy problems that are solvable in polynomial time. It can be shown that the OR scheduling problem of the Amsterdam UMC is a complex problem that cannot be solved in polynomial time. It is NP-hard (Pinedo & Hadavi, 1995). We are interested in minimizing the makespan.

Arnaout & Kulbashian (2008) evaluated five heuristics intending to minimize the makespan of an OR scheduling problem in a Lebanese hospital. The following heuristics were considered:

- Longest Processing Time (LPT) and Shortest Processing Time (SPT)
- Longest Expected Processing Time (LEPT) and Shortest Expected Processing Time (SEPT)
- Longest Expected Processing Time with Setup Time (LEPST)

LEPT and SEPT are extensions of LPT and SPT, respectively. In contradiction to LPT and SPT, LEPT and SEPT consider the average processing times of jobs, which is the only aspect in which the heuristics differ. This enables the heuristic to approach an optimal solution for stochastic problems. LEPT and SEPT selects the job with the maximum or minimum expected processing time $E(p_j)$, respectively. The selected job is then assigned to the machine with the minimum completion time.

LPT generally minimizes the makespan relatively effectively. However, several heuristics outperform the LPT heuristic. Arnaout & Kulbashian (2008) showed that Longest Expected Processing Time (LEPT) is a heuristic that outperforms LPT. Additionally, the authors claimed Longest Expected Processing Time with Setup Time (LEPST) to be the best heuristic to maximize utilization and minimize the makespan. The study by Arnaout & Kulbashian (2008) showed that LEPST outperforms LPT, SPT, LEPT, and SEPT. LEPT performed the second best out of all the heuristics. Therefore, we will elaborate on the proposed heuristics LEPST and LEPT in the remainder of this research.

LEPT

LPT selects the job j with the longest processing time p_j first and allocates this job to machine i. LEPT is an extension of LPT, which select the job j with the longest expected processing time $E(p_j)$, and allocates this job to machine i. Priority is therefore given to jobs with the maximum value of expected processing time.

Let S be the set consisting of all unscheduled jobs. We assume j to be an element of the set of unscheduled jobs S: $j \in S$. Additionally, we define $C_{k,i}$ as the completion time of the previous job k on machine i. A sequence of three steps can be formulated to define the LEPT heuristic (Arnaout & Kulbashian, 2008):

1. Find and select the job j and machine i in the set S with the maximum value of 2:

$$[min\{C_{k,i}\} + E(p_j)] \qquad \textbf{(2)}$$

2. Assign the selected job j to the selected machine i. Remove job j from the set S.
3. If $S = \emptyset$, then STOP. Else, return to step 1.

To implement the LEPT heuristic to the OR scheduling problem of the Amsterdam UMC, some adjustments have to be made to the heuristic because we want to distinguish between class 1 and class 1+ ORs. For this purpose, let S remain the set of unscheduled jobs. A subset S_B of S contains all unscheduled jobs of type B: $S_B \subseteq S$. To specify the type of machine, we define M_B to be a subset of M, which is the set containing all machines: $M_B \subseteq M$. Let M_B denote the set of machines of type B. For the remainder of this chapter, we will define type A jobs as surgeries that can be executed in ORs of class 1 and class 1+, excluding jobs that can only be executed in class 1+ ORs. A job of type B is defined as a job that must be executed in ORs class 1+. This includes surgeries concerning elective major joint replacements. ORs class 1 are machines of type A, while ORs class 1+ are machines of type B. Jobs of type A can be executed using any machine, while jobs of type B can only be executed at dedicated machines. These dedicated machines are ORs of class 1+. The following sequence of steps can then be implemented by the Amsterdam UMC denoted by LEPT*:

1. Find and select the job j in the subset S_B and machine i in the subset M_B with the maximum value of 2:

$$[min\{C_{k,i}\} + E(p_j)] \qquad \textbf{(2)}$$

2. Assign the selected job j to the selected machine i. Remove job j from the set S and subset S_B.
3. If $S_B = \emptyset$, then proceed to step 4. Else, return to step 1.
4. Find and select the job j in the set S and machine i in the set M with the maximum value of 2:

$$[min\{C_{k,i}\} + E(p_j)] \qquad \textbf{(2)}$$

5. Assign the selected job j to the selected machine i. Remove job j from the set S.
6. If $S = \emptyset$, then STOP. Else, return to step 4.

LEPST

LEPST is an extension of both LPT and LEPT, considering setup times in contradiction to LPT and LEPT. It is introduced by Arnaout & Kulbashian (2008), and it is used for strongly NP-hard problems with sequence-dependent setup times (Pinedo & Hadavi, 1995). The idea of LEPST is to give priority to jobs with relatively long setup times, minimizing the makespan.

Let S be the set consisting of all unscheduled jobs and let $s_{i,k,j}$ denote the sequence-dependent setup time between the previous job k and the next job j on machine i. We assume j to be an element of the set of unscheduled jobs S: $j \in S$. Additionally, we define $C_{k,i}$ as the completion time of the previous job k on machine i. The control parameter α is a variable with a value between 0 and 1, which indicates the importance of processing times when selecting a job. A value of 0 means that only the setup times are considered while ignoring the processing times. A control parameter α with a value of one is used to assign equal weights to setup times and processing times when selecting a job. The LEPST heuristic can then be described as a sequence of three steps (Arnaout & Kulbashian, 2008):

1. Find and select the job j and machine i in the set S with the maximum value of 3:

$$[min\,\{C_{k,i}\} + E(p_j) * \alpha + s_{i,k,j}] \quad \textbf{\textit{(3)}}$$

1. Assign the selected job j to the selected machine i. Remove job j from the set S.
2. If $S = \emptyset$, then STOP. Else, return to step 1.

To implement the LEPST heuristic to the OR scheduling problem of the Amsterdam UMC, some adjustments must be made to the heuristic because we want to distinguish between class 1 and class 1+ ORs again. This is done in the same way as for the LEPT* heuristic. For this purpose, let S remain the set of unscheduled jobs. A subset S_B of S contains all unscheduled jobs of type B: $S_B \subseteq S$. To specify the type of machine, we define M_B to be a subset of M, which is the set containing all machines: $M_B \subseteq M$. Let M_B denote the set of machines of type B. The following sequence of steps can then be implemented by the Amsterdam UMC denoted by LEPST*:

1. Find and select the job j in the subset S_B and machine i in the subset M_B with the maximum value of 3:

$$[min\,\{C_{k,i}\} + E(p_j) * \alpha + s_{i,k,j}] \quad \textbf{\textit{(3)}}$$

2. Assign the selected job j to the selected machine i. Remove job j from the set S and subset S_B.
3. If $S_B = \emptyset$, then proceed to step 4. Else, return to step 1.
4. Find and select the job j in the set S and machine i in the set M with the maximum value of 3:

$$[min\,\{C_{k,i}\} + E(p_j) * \alpha + s_{i,k,j}] \quad (3)$$

5. Assign the selected job j to the selected machine i. Remove job j from the set S.
6. If $S = \emptyset$, then STOP. Else, return to step 4.

6 Monte Carlo simulation

An MC simulation is made to verify the effectiveness of the LEPT* heuristic and the LEPST* heuristic. This chapter describes the MC simulation by first explaining how the data of all surgeries from 2019 is prepared for the MC simulation. After this, this chapter describes how the MC simulation is made and how it should be used.

6.1 Data preparation

Historical data of 2019 is used in this research, as this is the most recent year that was not affected by COVID-19. The data depicted all surgeries as executed in that year in an Excel file. Appendix L depicts a fraction of the original Excel file as delivered by the Amsterdam UMC. The OR, date, start time and end time, duration, procedure, procedure number, and log number of every surgery was included. No indication of surgery urgency was provided. Therefore, the assumption was made that all surgeries that started between 7:30 and 17:00 on Monday to Friday were elective, while all surgeries executed at other times were emergency surgeries. All elective surgeries were extracted from the data in one new table using a filter in the IN_OR and day column. The column with the day of the week was added by using the Excel function depicted in Appendix K.1. Then, the procedure classification as depicted in Appendix J was compiled. Every distinct elective surgery in the table was classified as either “class 1” or “class 1+” by adding a column including the Excel function of Appendix K.2 in every row of this column. Appendix M depicts a fraction of the resulting table of the data of elective procedures.

6.1.1 Setup times

The processing times were already included in the data. However, setup times were not. The data of the elective procedures were used to determine the setup times of surgeries. Appendix K.3 depicts the Excel function that was used to determine the setup times. The function checks if the day and the OR are the same and subtracts the end time of the previous surgery from the start time of a new surgery if this is true. If an error occurs, the function returns a blank cell. The column with setup times is then filtered, as we assume the setup time to be greater than 0 minutes and less than or equal to 90 minutes. Check Figure 4-2 for a schematic overview of setup times.

6.1.2 Data analysis

The distribution of both the setup times and the processing times was analyzed. This was executed separately for class 1 and class 1+ procedures. Descriptive statistics were made for the class 1 processing times, class 1 setup times, class 1+ processing times, and class 1+ processing times using the Excel Data Analysis Tool. Four histograms were then made by implementing the rule of thumb of assigning $\sqrt{n}$ bins, where n represents the number of observations. Bins with less than five observations were merged with other bins. Figure 6-1 depicts the resulting histograms.

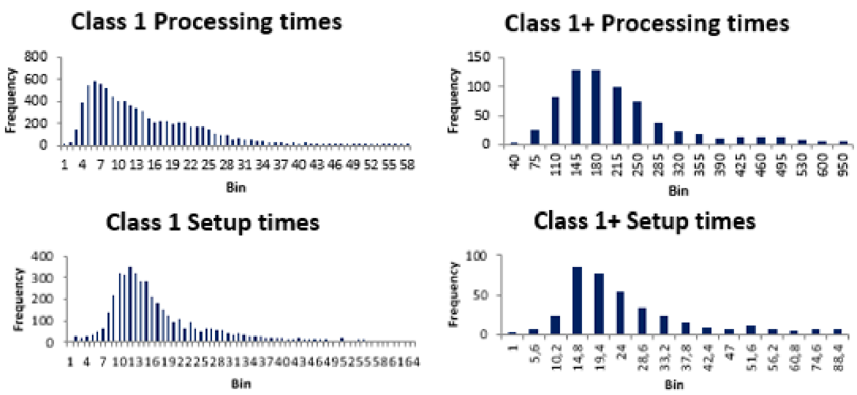


Figure 6-1: Histograms of 2019 data

The Chi-square goodness of fit test was applied to each dataset to test whether the datasets fit a particular theoretical distribution. This was done by computing the Cumulative Distribution Function (CDF) for every bin using the Excel functions of the corresponding theoretical distributions that were tested. The following theoretical distributions were considered: Gamma, Normal, Lognormal, Exponential, and Weibull. Check Appendix K.4: CDF for the Excel functions that were implemented to calculate the values of the CDF. The CDF values were then multiplied by the total number of observations. Now, we can compute the expected number of observations per bin by subtracting the individual values. Then, the test statistic was determined by adding the errors for each bin using the following formula:

$$\chi 2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i} \tag{4}$$

, where:

- $O_i =$ The number of observed observations $(i = 1, 2, \dots, k)$
- $E_i =$ The number of expected observations $(i = 1, 2, \dots, k)$

The test statistic was computed by adding the errors, and the critical value c was determined by the right-tailed probability of the Chi-squared distribution using the Excel function in Appendix K.5. This function requires the significance level and the degrees of freedom as input parameters. The degrees of freedom were equal to the number of bins subtracted by 1, with a significance level $\alpha = 0.05$. We can conclude whether a theoretical distribution fits the dataset by comparing the values of $\chi 2$ and c. We rejected the two null hypotheses that any of the evaluated theoretical distributions fit one of the datasets, as $\chi 2 > c$ for every Chi-square goodness of fit test.

As we could not show convincingly that any of the evaluated theoretical distributions fit the datasets, we conclude that all four datasets must be evaluated using empirical distributions. Empirical distributions are unlike the Gamma distribution, Weibull distribution, Normal distribution, Lognormal distribution, and Exponential distribution, not theoretical distributions. However, the distribution is based on observation as opposed to logic or mathematical functions.

6.2 MC simulation

The processing times and the setup times are input parameters for the MC simulation. Therefore, data must be generated according to their empirical distributions. For every input parameter (Class 1 processing times, class 1 setup times, class 1+ processing times, and class 1+ setup times) the probability that the input parameter is in a bin was computed for every bin by dividing the observed number of observations by the total number of observations. Then, the cumulative probabilities were calculated. This resulted in cumulative probabilities between 0 and 1. By generating a random variable $X \sim U[0, 1]$, the bin for which holds that the random variable X is greater than the lower bound of the cumulative probability of the bin but less than the upper bound of the cumulative probability of the bin is selected according to the empirical distribution. Then, a random number within the selected bin is selected. This is done repeatedly to generate data according to the corresponding empirical distributions of every input parameter. Appendix N.1 depicts the code implemented in Visual Basic for the generation of processing times of class 1+. Similar codes have been used for the generation of the other input parameters. The green letters represent pseudo codes: These codes are comments to clarify the written codes. The number of observations that are generated is equal to the number of observed observations in the data concerning elective procedures of 2019. The generated data is printed on a separate sheet. This means that this data will solely be used as input for the MC simulation, but it is not directly visible in the MC simulation.

6.2.1 Generating jobs

The MC simulation will simulate one working week. Therefore, 171 jobs must be generated as this was the average number of elective surgeries in one working week in 2019 if we assume 261 working days. 92.32% of these surgeries were class 1 surgeries, while the rest of the surgeries are classified as class 1+ surgeries. This was determined by implementing the Excel functions depicted in Appendix K.6. The MC simulation will randomly select a processing time and setup time from the input parameters which have empirical distributions. The processing time and setup time will be selected from either the class 1 or the class 1+ input parameters with the corresponding probability. Appendix N.2 depicts the code implemented in Visual Basic for the generation of jobs. Emergency surgeries are not generated as these surgeries are not simulated. However, at least two ORs must always remain available for emergency surgeries. Therefore, 18 of the 20 ORs can be used for elective surgeries in the simulation.

6.2.2 Scheduling jobs

The proposed heuristics must be applied to the generated jobs to verify the effectiveness of the individual heuristics. Therefore, the two heuristics must be programmed in Visual Basic. Check section 5.3: "Heuristics" for a reminder of the proposed heuristics. The LEPT* heuristic first schedules jobs with the longest expected processing time. Therefore, the jobs are sorted automatically decreasingly by processing time after generating jobs. The LEPST* first schedules jobs with the highest LEPST value. The column with these values is therefore sorted decreasingly in the LEPST* code. The Visual Basic code then schedules the class 1+ surgeries first, as these surgeries can only be assigned to dedicated class 1+ ORs. Class 1 surgeries are then scheduled for all the ORs. A surgery is assigned to the OR with the minimum completion time. Surgeries are only assigned to an OR if the surgery can start after 7:30 and before 17:00. As a working day generally starts at 7:30, surgeries can be started during the first 570 minutes. This means that the previous completion time of an OR plus the setup time of the scheduled surgery must be less than 570 minutes. Surgeries that cannot be scheduled within these 570 minutes must be planned for the next day. Appendix N.3 depicts the code implemented in Visual Basic for the application of the proposed scheduling heuristics. Pseudo-codes are provided for more elaboration on the written code.

6.2.3 Iteration

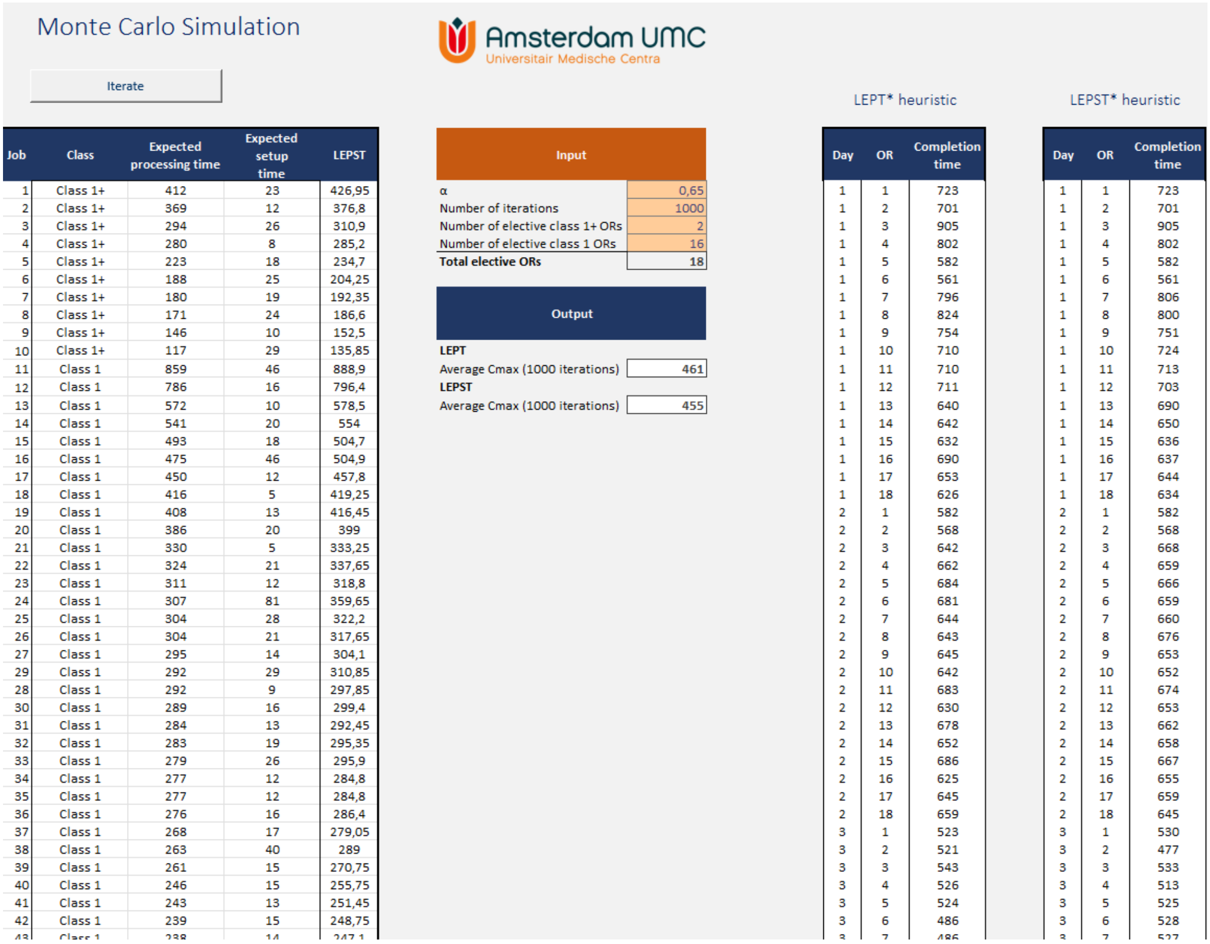
MC simulations estimate the result of stochastic events by iteratively predicting outcomes. The generation and scheduling of jobs must be performed iteratively to acquire more accurate results. This is done by running the codes repeatedly using a for loop in Visual Basic. A large number of iterations should be applied for accurate results. The MC simulation assesses the effectiveness of the heuristics using the KPI "Average maximum completion time ($\bar{C}_{max}$)". This is the average of each working day's maximum completion time over one working week. This average is calculated iteratively. Check Appendix N.4 for the implemented Visual Basic code for the iteration and calculation of the output of the MC simulation.

6.2.4 Interface

Figure 6-2 depicts the interface of the MC simulation. The MC simulation consists of three tables. Note that these tables are not depicted entirely in Figure 6-2, as the tables consist of many rows. The table at the left depicts the generated jobs that must be planned. These jobs consist of a corresponding class, expected processing time, and expected setup time. The LEPST value resulting from equation 3 is also included in this table. The two tables at the right visualize the schedule resulting from the LEPT* heuristic and the LEPST* heuristic by showing the completion time in minutes for every OR during each day. The MC simulation will run after clicking on the "Iterate button".

The input table in the middle of the interface allows the user to interact with the simulation by changing the input variables. α is currently set to 0.65, but this value can be changed if needed. The optimal value for α is researched in chapter 7: “Results”. 1000 iterations are used for the simulation to ensure accurate output. More iterations will not result in a significant increase in stability, as we already obtain stable results. The number of iterations can be changed to reduce the duration of the MC simulation or to increase the accuracy of the MC simulation. Finally, the number of both class 1 and class 1+ elective ORs can be altered to research the effect on the completion times. 18 of the 20 ORs are to be used for elective surgeries. 5.1.2: “Proposed OR classification” explains that two class 1+ ORs suffice. Therefore, the MC simulation uses two class 1+ ORs and 16 class 1 ORs as input values. The two remaining ORs are used for emergency procedures. Both ORs are class 1 ORs as orthopedic procedures are generally classified as urgency class S3. This means that surgery is semi-urgent. The patient then needs to be on the operating table within 24 hours.

The MC simulation also consists of an output table displaying the results of the previous simulation. The output depicts the KPI “Average maximum completion time” as explained in 6.2.3: Iteration for both the LEPT* heuristic and the LEPST* heuristic.



Job	Class	Expected processing time	Expected setup time	LEPST
1	Class 1+	412	23	426,95
2	Class 1+	369	12	376,8
3	Class 1+	294	26	310,9
4	Class 1+	280	8	285,2
5	Class 1+	223	18	234,7
6	Class 1+	188	25	204,25
7	Class 1+	180	19	192,35
8	Class 1+	171	24	186,6
9	Class 1+	146	10	152,5
10	Class 1+	117	29	135,85
11	Class 1	859	46	888,9
12	Class 1	786	16	796,4
13	Class 1	572	10	578,5
14	Class 1	541	20	554
15	Class 1	493	18	504,7
16	Class 1	475	46	504,9
17	Class 1	450	12	457,8
18	Class 1	416	5	419,25
19	Class 1	408	13	416,45
20	Class 1	386	20	399
21	Class 1	330	5	333,25
22	Class 1	324	21	337,65
23	Class 1	311	12	318,8
24	Class 1	307	81	359,65
25	Class 1	304	28	322,2
26	Class 1	304	21	317,65
27	Class 1	295	14	304,1
29	Class 1	292	29	310,85
28	Class 1	292	9	297,85
30	Class 1	289	16	299,4
31	Class 1	284	13	292,45
32	Class 1	283	19	295,35
33	Class 1	279	26	295,9
34	Class 1	277	12	284,8
35	Class 1	277	12	284,8
36	Class 1	276	16	286,4
37	Class 1	268	17	279,05
38	Class 1	263	40	289
39	Class 1	261	15	270,75
40	Class 1	246	15	255,75
41	Class 1	243	13	251,45
42	Class 1	239	15	248,75
43	Class 1	238	14	247,1

Input	
α	0,65
Number of iterations	1000
Number of elective class 1+ ORs	2
Number of elective class 1 ORs	16
Total elective ORs	18

Output	
LEPT	
Average Cmax (1000 iterations)	461
LEPST	
Average Cmax (1000 iterations)	455

LEPT* heuristic

Day	OR	Completion time
1	1	723
1	2	701
1	3	905
1	4	802
1	5	582
1	6	561
1	7	796
1	8	824
1	9	754
1	10	710
1	11	710
1	12	711
1	13	640
1	14	642
1	15	632
1	16	690
1	17	653
1	18	626
2	1	582
2	2	568
2	3	642
2	4	662
2	5	684
2	6	681
2	7	644
2	8	643
2	9	645
2	10	642
2	11	683
2	12	630
2	13	678
2	14	652
2	15	686
2	16	625
2	17	645
2	18	659
3	1	523
3	2	521
3	3	543
3	4	526
3	5	524
3	6	486
3	7	486

LEPST* heuristic

Day	OR	Completion time
1	1	723
1	2	701
1	3	905
1	4	802
1	5	582
1	6	561
1	7	806
1	8	800
1	9	751
1	10	724
1	11	713
1	12	703
1	13	690
1	14	650
1	15	636
1	16	637
1	17	644
1	18	634
2	1	582
2	2	568
2	3	668
2	4	659
2	5	666
2	6	659
2	7	660
2	8	676
2	9	653
2	10	652
2	11	674
2	12	653
2	13	662
2	14	658
2	15	667
2	16	655
2	17	659
2	18	645
3	1	530
3	2	477
3	3	533
3	4	513
3	5	525
3	6	528
3	7	527

Figure 6-2: MC simulation interface

7 Results

This chapter elaborates on the results of this research. The optimal value of control parameter α is researched. Additionally, the impact of the proposed OR classification and the proposed heuristic on energy consumption is assessed. The output of the MC simulation is used for this chapter. A selection is also made concerning the most effective heuristic.

7.1 Control parameter α

The effect of the value of α on C_{max} in the scheduling problem $V_i\,|s_{p,q}|\,C_{max}$ is researched by Arnaout & Kulbashian (2008). The minimum makespan was achieved by implementing a value of α equal to 0.63 (Arnaout & Kulbashian, 2008). The scheduling problem in that study is different because a single type of machine is involved. Therefore, we do not assume the optimum value of α to be the same in the OR scheduling problem of the Amsterdam UMC. The MC simulation is used to assess the impact of the value of α, and to determine the optimum value of α. This is done by running the MC simulation for different values of α using 100 iterations. The average maximum completion time $\bar{C}_{max}$ using the LEPST* heuristic is noted for every value of α. Figure 7-1 depicts the graph of the experiment. We conclude that 0.65 is the optimum value for α with 100 iterations, as this value resulted in the lowest value of $\bar{C}_{max}$. The corresponding value of $\bar{C}_{max}$ was 455 minutes in this experiment. For the remainder of this research, the value of α is equal to 0.65 as this is optimal.

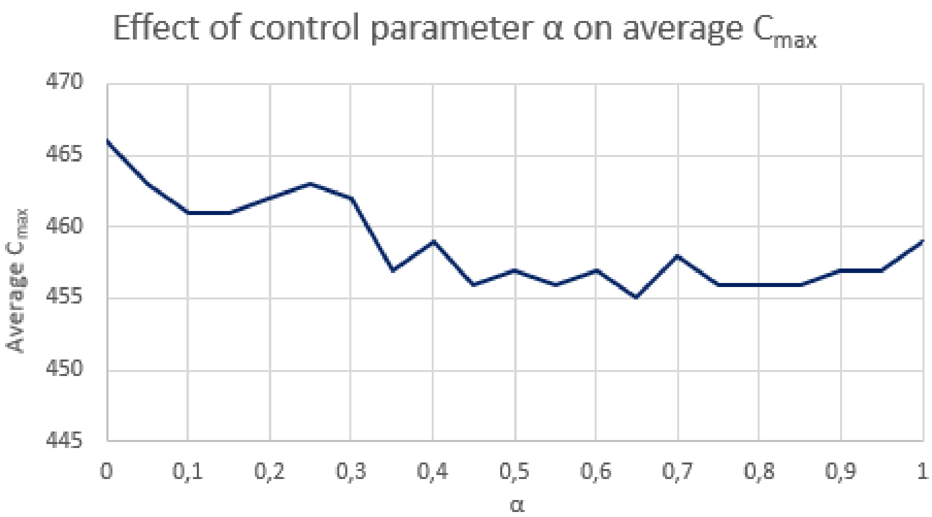


Figure 7-1: Control parameter α

7.2 Heuristic selection

In section 7.1: "Control parameter α", we observed a $\bar{C}_{max}$ of 455 minutes. To research the stability of the MC simulation, we will run the simulation several times with the same values for the input parameters. We can then gain insights into the stability of the MC simulation, and we can provide a more accurate estimate of $\bar{C}_{max}$.

Figure 7-2 denotes the results of 6 runs. All of these runs have the same values for the input parameters: $\alpha = 0.65$, 1000 iterations, 2 elective class 1+ ORs, and 16 elective class 1 ORs. The graph verifies that the LEPST* heuristic consistently outperforms the LEPT* heuristic. The lowest value of $\bar{C}_{max}$ for the LEPST* heuristic is 455 minutes, while the highest value of $\bar{C}_{max}$ attains a value of 458 minutes. This interval of 3 minutes is relatively small. Hence, we conclude that the output of the MC simulation is relatively stable. Over these experiments, the LEPST* heuristic attains an average $\bar{C}_{max}$ of 456 minutes and the LEPT* heuristic an average $\bar{C}_{max}$ of 462 minutes.

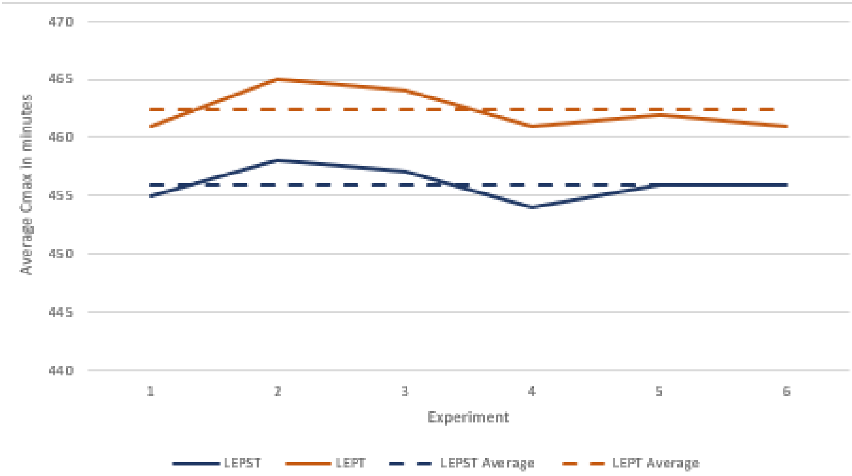


Figure 7-2: MC simulation output stability

The LEPST* heuristic consistently outperforms the LEPT* heuristic with $\alpha = 0.65$. The heuristic is approximately 1.3% more effective compared to the LEPT* heuristic when using 1000 iterations and $\alpha = 0.65$, as the LEPT* heuristic attains a $\bar{C}_{max}$ of 462 minutes as opposed to a $\bar{C}_{max}$ of 456 minutes for the LEPST heuristic. This results from the MC simulation, check Figure 7-3 for the output of one experiment in the simulation.

Output	
LEPT	
Average Cmax (1000 iterations)	**463**
LEPST	
Average Cmax (1000 iterations)	**456**

Figure 7-3: Output of the Monte Carlo simulation

7.3 Expected impact on sustainability

Currently, the elective ORs are operational between 6:30 and 21:00, which results in 14.5 operational hours daily. However, the operational hours can be increased if surgeries exceed the end of the scheduled operational hours in practice. The data showed that on average 14.53 operational hours were required to complete the elective surgeries in practice in 2019. If we assume that the surgeries generally start at 7:30 like in the MC simulation, the $\bar{C}_{max}$ of the OR department was 13.53 hours. This is equal to 811,8 $\approx$ 812 minutes. The LEPST* heuristic attains a $\bar{C}_{max}$ of 456 minutes. The heuristic saves 355.8 minutes or approximately 5.93 hours on average daily. As the ORs are operational from 6:30 and the surgeries start at 7:30, the ORs will be operational for $456 + 60 = 516$ minutes ≈ 8.6 hours per day. This results in approximately 2167 operational hours annually.

7.3.1 Validation of number of class 1+ ORs

Section 5.1.2: "Proposed OR classification" states that two elective class 1+ ORs suffice for the clinical OR department of the Amsterdam UMC. This section validates this statement by researching the effect of increasing and decreasing the number of elective class 1+ ORs. This is done by changing the input parameters of the MC simulation and observing the output repeatedly. Figure 7-4 depicts a graph of the results of this experiment. Decreasing the number of class 1+ ORs to one returns an error as the

MC simulation simulates only one week. With one class 1+ OR, the surgeries for class 1+ ORs cannot be finished within that week. It is, therefore, not viable to assign one elective class 1+ OR. Figure 7-4 depicts the graph resulting from this experiment. We conclude that $\bar{C}_{max}$ decreases if the number of elective class 1+ ORs increases from two to ten ORs. With ten elective class 1+ ORs, a $\bar{C}_{max}$ of 444 minutes is achieved by the LEPST* heuristic. We conclude that with every class 1+ OR that is added, approximately 1.5 minutes are saved. We assume that every class 1+ OR that is added switches to nighttime operation at night and on weekends. Then, $\frac{1.5}{60} * 5 * 52 = 6.5$ hours are saved annually with every additional elective class 1+ OR. This results in energy consumption of $(2167 - 6.5) * 16.46 = 35{,}561.83$ kWh per class 1+ OR annually, while every class 1 OR consumes $2167 * 11.61 = 25{,}158.87$ kWh annually. Adding more elective class 1+ ORs is not justified as this consumes more energy despite the smaller value of $\bar{C}_{max}$. Hence, sufficient ORs should be implemented to ensure enough capacity. However, not more than necessary.

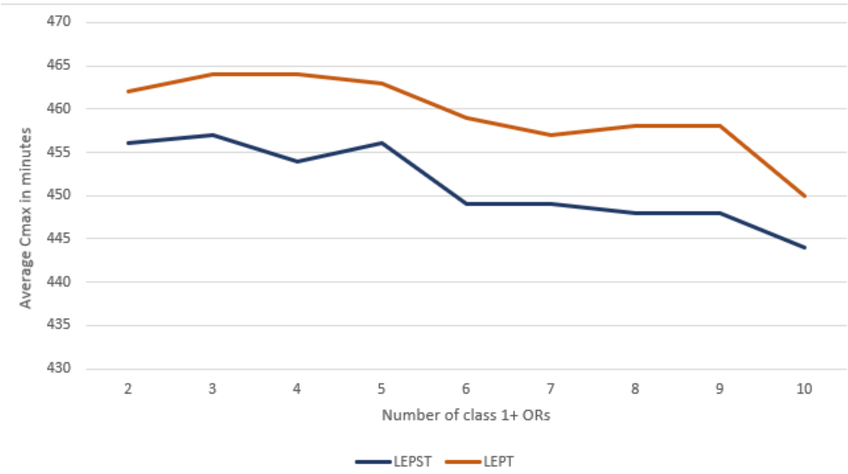


Figure 7-4: Validation of number of elective class 1+ operating rooms

7.3.2 Energy consumption

Section 5.2.2.: "Energy consumption of proposed HVAC systems" describes the energy consumption of the proposed HVAC systems by calculating the energy consumption of the 24/7 ORs and the energy consumption of the elective ORs separately. As a result of the proposed heuristic, the operational hours of the elective ORs will be decreased. This realizes a decrease in energy consumption. The energy consumption of the 24/7 ORs will not be affected by the proposed heuristic. Therefore, the four 24/7 ORs are expected to consume $449{,}300.40$ kWh after the implementation of the proposed OR classification and heuristic. The elective ORs are affected by the proposed heuristic. The expected energy consumption after implementation of the proposed OR classification and heuristic of the elective ORs equals $2167 * (11.61 * 15 + 16.46) = 413{,}051.87$ kWh. After implementing the proposed changes, the clinical OR department is expected to consume $449{,}300.40 + 413{,}051.87 = 862{,}352.27$ kWh. This results in a total expected reduction in energy consumption of $791{,}820.73$ kWh compared to the energy consumption in 2019, corresponding to a reduction of approximately 48% relative to 2019.

7.3.3 Sustainability

The conversion factor in the Netherlands was 0.390 kg CO2e per kWh in 2019. We define CO2e as carbon dioxide equivalents, which also takes other polluting gases besides CO2 into account. The European Environment Agency (2019) based this conversion factor on the ratio of CO2 emissions from public electricity production. We conclude using the CO2e emission intensity that $791{,}820.73 * 0.390 = 308{,}810.085$ kg CO2e can be saved compared to 2019.

Conclusions and recommendations

In this research, the objective is to decrease the energy consumption of the Amsterdam UMC hospital by optimally changing the HVAC planning and surgery scheduling without compromising the efficiency of the OR department while obeying the guideline concerning air quality in the OR. This chapter concludes the research by summarizing the answers to the research questions and by answering the research question of this research. Recommendations to the hospital are also given in this chapter. The research question is formulated as:

"How can the planning of the HVAC system usage and the scheduling of the surgeries in the ORs be optimized so that a reduction in energy consumption is realized without compromising the efficiency of the OR while obeying the guideline concerning air quality in the OR? "

Conclusions

This section concludes the research by summarizing the answers to each research question. The main research question is answered at the end of this section.

Guidelines

The previous guideline recommended that hospitals should be equipped with or have advanced plans to implement UDF HVAC systems in their OR department. UDF HVAC systems outperform turbulent HVAC systems when minimizing the number of micro-organisms in the OR. However, Nederlandse Vereniging voor Medische Microbiologie (NVMM) has not found any evidence that UDF HVAC systems also prevent SSIs more effectively relative to turbulent HVAC systems. Therefore, the revised guideline abandons the recommendation of implementing UDF HVAC systems in ORs. ORs should now be equipped with an HVAC system that (regardless of the type of HVAC system) at least meet the minimum criteria stated in Table 3-4. ORs of class 1+ use UDF HVAC systems and they are solely recommended for major joint replacements. Class 1 ORs with turbulent HVAC systems consume less energy and these ORs suffice for all procedures except major joint replacements according to the revised guideline.

HVAC systems

Besides ensuring comfortable climate conditions in the OR, the air treatment via the use of HVAC systems minimizes micro-organisms to prevent SSIs. This minimizes the chances of SSI or any other type of contamination occurrences. The ORs in the clinical OR department of the Amsterdam UMC currently consists of vertical UDF HVAC systems with decentralized clean air systems and recirculation systems. These HVAC systems use a clean laminar airflow to minimize micro-organisms in the protected area of the OR. The HVAC systems use a clock program that switches the systems on at 6:30 and switches the systems into nighttime operation at 21:00. A maximum of 50% of the airflow rate is applied by the HVAC systems when operating in nighttime operation. Exceptions to the clock program are the systems in OR 4, 5, 8, 12, and 14, as these ORs operate 24/7 for potential emergencies. Each OR is equipped with the "Bender" panel depicted in figure 4-4**,** displaying the operational hours of the OR, the temperature, RH, and other KPIs. The operational hours can be extended here, procrastinating the switch to nighttime operation. The current energy consumption of the clinical OR department was estimated using a tool for calculating the energy consumption of HVAC systems. The output of this tool can be found in Figure 4-8. 1,654,175 kWh are currently estimated to be consumed annually.

Scheduling

All ORs have the same HVAC systems, which means that all surgeries can be executed at each OR. However, ORs are equipped with different equipment, which complicates the scheduling of surgeries. The scheduling of the surgeries occurs at a strategic level, tactical level, and operational level. On a strategic level, the annual planning is determined, while the monthly and weekly planning are determined on a tactical level. The daily planning is determined on the operational level by every specialism. Urgency classifications are assigned to surgeries to determine the maximum duration before a patient must be on the operating table.

2 class 1+ suffice when assessing the data from 2019, as 7.37% of all surgeries are classified as major joint replacements. These surgeries are generally not classified as urgent procedures, so two ORs suffice. 18 ORs will then be appointed as class 1 ORs. The data from 2019 suggested that five 24/7 ORs were rarely occupied outside operating hours and if this was the case, the ORs were not used simultaneously. Four 24/7 ORs instead of five 24/7 ORs also suffice, decreasing energy consumption. In total, 19 class 1+ surgeries have been executed in 2019 outside operating hours. None of these occurred simultaneously, not even on the same day. Appointing one class 1+ OR as 24/7 OR is viable. The three other 24/7 ORs are then classified as class 1 ORs. Additionally, two ORs must be appointed as emergency ORs for emergency procedures. These emergency ORs should be class 1 ORs, as class 1+ surgeries are generally not urgent.

When implementing two different types of machines (class 1 and class 1+), the single-stage job scheduling problem of the Amsterdam UMC can be described as $V_{18,2}\ |s_{k,j}|C_{max}$ if we define $V_{p,q}$ to be the scheduling variant applicable to the OR scheduling problem. p denotes the number of class 1 ORs and q denotes the number of class 1+ ORs at the clinical OR department. Two heuristics applicable to the $V_{18,2}\ |s_{k,j}|C_{max}$ job scheduling problem are proposed by Arnaout & Kulbashian (2008): LEPT and LEPST. The LEPT and LEPST heuristics cannot be applied directly to the $V_{18,2}\ |s_{k,j}|C_{max}$ job scheduling problem as the heuristics are designed for identical-machines scheduling. The $V_{18,2}$ $|s_{k,j}|C_{max}$ job scheduling problem is similar, but it assigns jobs to two different types of machines (class 1 and class 1+ ORs). Therefore, the heuristics are changed so that they can be applied to the scheduling problem. This results in the LEPT* and LEPST* heuristics. The MC simulation is used to compare the effectiveness of the two heuristics, and the LEPST* heuristic consistently outperforms the LEPT* heuristic when assessing the average maximum completion time. The LEPST* heuristic has an average maximum completion time of 455 minutes using 1000 iterations and $\alpha = 0.65$. This optimal value of control parameter α was determined by running the MC simulation for different values of α using 100 iterations.

Sustainability

Using the LEPST* heuristic, a reduction from the average maximum completion time $\bar{C}_{max}$ of 812 minutes to 455 minutes can be realized by implementing the proposed solutions. This significant reduction of 44% of the makespan is partially caused by the fact that all ORs are considered to be equipped with identical equipment and resources. In 2019, 1,654,175 kWh are consumed by the clinical OR department annually according to the implemented tool. After the implementation of the proposed changes, an estimated $862{,}352.27$ kWh is consumed annually. This corresponds to a reduction of 48% as opposed to 2019. $791{,}820.73$ kWh is estimated to be saved per year.

Using a CO2e emission intensity of 0.390 kg CO2e per kWh, we conclude that $791{,}820.73 * 0.390 = 308{,}810.085$ kg CO2e can be saved compared to 2019 (European Environment Agency, 2019).

Conclusion

The LEPST* heuristic effectively schedules the surgeries, and it outperforms the current scheduling and the LEPT* heuristic. This implies that the switch to nighttime operation can occur earlier due to the decrease in the average maximum completion time. Less operational hours are therefore required. 18 ORs can be changed to class 1 ORs while not hurting the efficiency of the clinical OR department, and four instead of five 24/7 ORs are required. The classification of the ORs is depicted in Figure 5-1. Two ORs should be appointed as emergency ORs. This research answers the research question, as proposed changes are recommended that should realize a reduction of energy consumption while not hurting the efficiency of the OR department. An increase in the efficiency of the OR department can be realized.

Recommendations

Specific recommendations to the Amsterdam UMC are stated in this section. The section first mentions the practical implications for the hospital. After this, recommendations for future research are given.

Implications

The clinical OR department currently consists of solely class 1+ ORs. This is unnecessary as class 1+ ORs are only recommended for major joint replacements as depicted in Appendix D. Major joint replacements make up for 7.36% of all executed procedures in 2019. $\lceil 20 * 0.0736 \rceil = 2$ class 1+ ORs suffice, which implies 18 class 1 ORs. The OR classification depicted in Figure 5-1 is recommended. Four instead of five 24/7 ORs suffice. One of the 24/7 ORs is classified as class 1+, while the remaining three 24/7 ORs are class 1 ORs. The elective ORs which switch to nighttime operation consists of one class 1+ OR, while the other 15 elective ORs are class 1 ORs. Two class 1 ORs should not be used for elective surgeries, as these ORs are destined for emergency surgeries only.

The class 1+ ORs must have a minimum air quality of ISO 7, the number of air changes must be at least 20 per hour, and the recovery time should not exceed three minutes. These requirements are already met in the Amsterdam UMC hospital using the installed UDF HVAC systems. These systems are equipped with a decentralized clean air system. It is recommended to install a centralized clean air system for the class 1+ ORs, as this saves energy. The class 1 ORs must meet at least ISO 5 requirements, with a minimum number of air changes of 20 per hour and a recovery time of maximum 20 minutes. These requirements can be met using turbulent HVAC systems. These systems are recommended as they consume less energy relative to UDF HVAC systems. A recirculation system is advised as this minimizes the energy consumption of turbulent HVAC systems.

It is advised to equip all ORs with the same advanced equipment for all surgeries. This simplifies the scheduling of surgeries significantly. On a tactical level, the LEPST* heuristic should be applied to the clinical OR department of the Amsterdam UMC to minimize the average maximum completion time. The LEPST* heuristic outperforms the LEPT* heuristic. It is recommended to automate this heuristic as depicted in Appendix M.3. This code was implemented in the MC simulation. Applying the heuristic by hand takes significant time, which is inefficient. Investing in automating the heuristic saves a significant quantity of time. A programming specialist is required to automate the LEPST* heuristic.

Further research

- The LEPST* heuristic does not include urgency classifications. The heuristic can be altered to include the urgency classifications so that urgent procedures are given high priority.
- It needs to be verified that the current UDF HVAC systems can be converted to turbulent HVAC systems while meeting class 1 requirements without major investments. Engineering specialists are required to verify this. Research also needs to investigate cost savings.
- This research assumes that sufficient resources (personnel, equipment) are available for more efficient scheduling. It needs to be verified that the more efficient scheduling is viable with the current resources. If this is not viable, increasing the hospital's resources might be considered.
- The scope of this research is the clinical OR department. Researching improvements for the day center might reduce more energy.
- The possibility to divide the ORs into class 1+ ORs, class 1 ORs, class 2 ORs, and even individual treatment rooms should be researched to realize more energy consumption reductions.
- Research the setup times more extensively, as one year does not include significant amounts of data concerning setup times.
- No indication of the surgery type was included in the data of 2019. Assumptions had to be made to determine the elective surgeries. The results of this research can be more accurate when researching which were emergency surgeries and which were elective surgeries.

Discussion

The goal of this research is to reduce the energy consumption of the clinical operating room department of the Amsterdam UMC by answering the following research question: *"How can the planning of the HVAC system usage and the scheduling of the surgeries in the ORs be optimized so that a reduction in energy consumption is realized without compromising the efficiency of the OR while obeying the guideline concerning air quality in the OR? "*

This research resulted in an expected reduction of approximately 308 tonnes of CO2e annually compared to 2019 by applying the LEPST* heuristic for surgery scheduling. This heuristic schedules surgeries on two types of ORs: Two ORs of class 1+ and 16 ORs of class 1. Two remaining ORs are used for emergency procedures. These are ORs of class 1. Four instead of five ORs will be 24/7 ORs, meaning that four instead of five ORs will not switch to nighttime operation, saving energy.

This is a significant decrease in CO2e emissions, and this study can therefore have a substantial impact on both the entire healthcare industry and the global environment as this research might inspire other hospitals besides the Amsterdam UMC to reduce their CO2e emissions. Niek Sperna Weiland (Hospital supervisor, anesthetist, and member of the Green Team OR) is satisfied with the clear conclusions and results of this research, and he thinks that the Amsterdam UMC can elaborate on this research in the future. He is very enthusiastic about the substantial expected energy savings.

A limitation of this study is that some assumptions had to be made concerning setup times. For example, we assumed setup times to be between zero and 90 minutes. This might be different in reality, affecting the criterion-related validity of the research. Additionally, a Monte Carlo simulation is used. This simulation method does not necessarily result in optimum results as the simulation is stochastic. The scheduling problem is NP-hard, and it uses a heuristic to find a near-optimal solution. This research, therefore, results in approximations of optimal solutions, but it does not provide exact solutions. However, the Monte Carlo simulation and the heuristic result in reliable approximations.

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Appendices

Appendix A: Map of the Amsterdam UMC

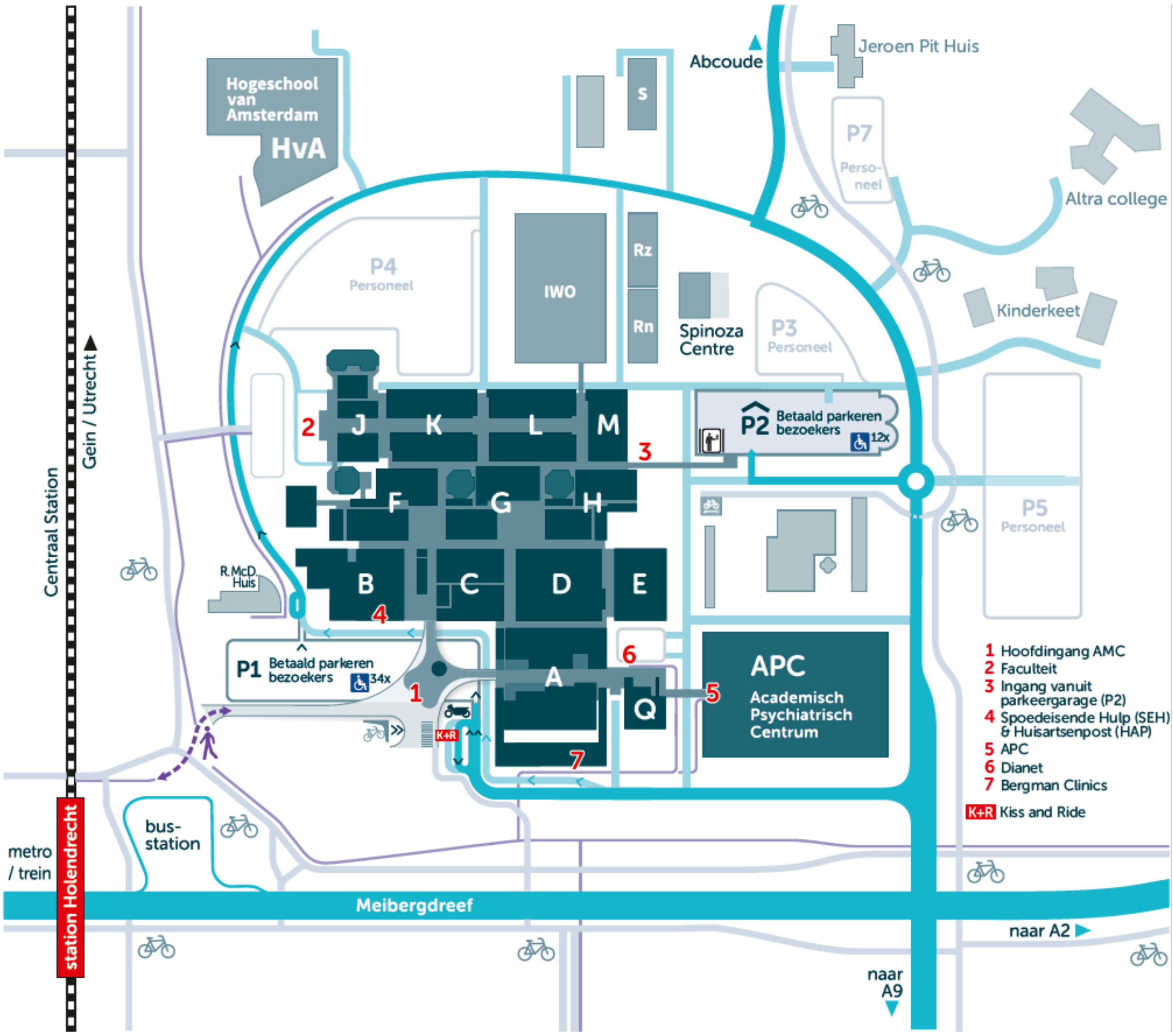

Figure A-1: Amsterdam UMC location AMC map

Appendix B: Schematic overview of the OR department’s pressure levels

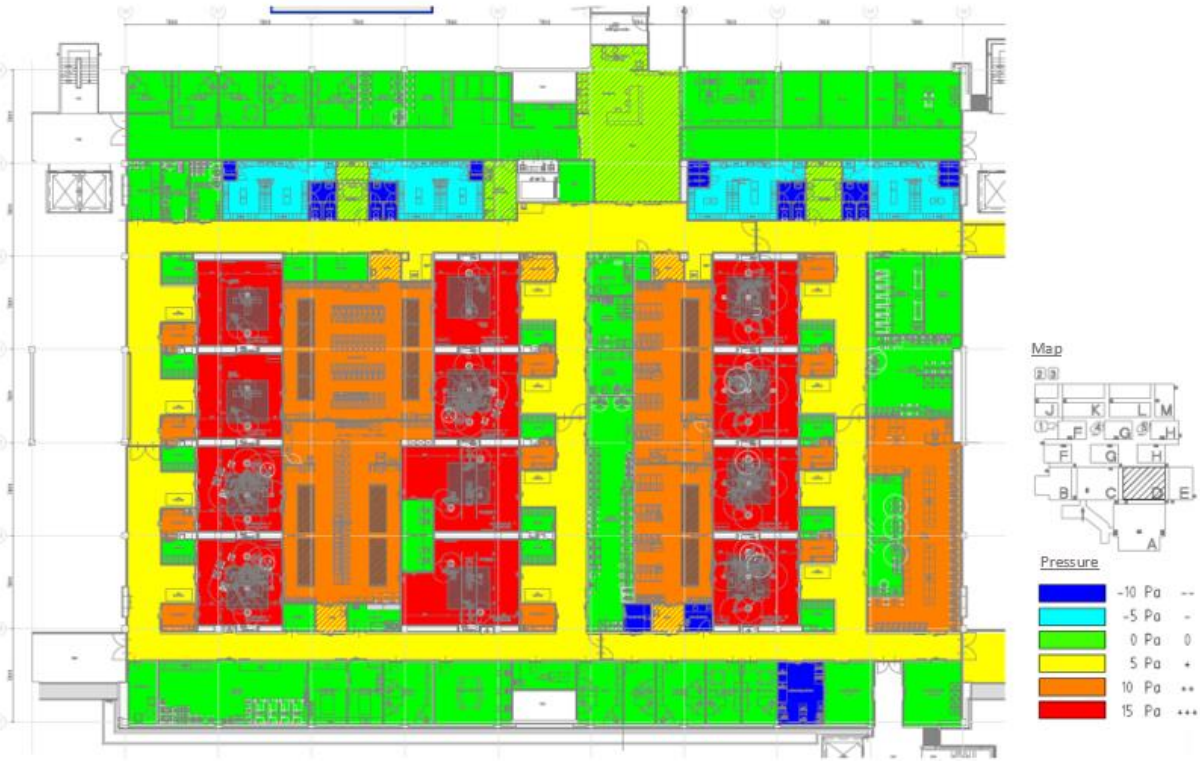

Figure B-1: Schematic overview of the clinical OR department's pressure levels

Appendix C: Semi-structured interviews

This appendix depicts the structured element of the interviews that have been executed during this research. The interviews are semi-structured, so there was a structure in each interview. However, there were unstructured elements in the interviews. These elements are not depicted in this appendix. This appendix provides a general summary of the interviews, and it does not contain transcripts.

Appendix C.1: Interview with Ingrid Spijkerman (Amsterdam UMC)

Mijn doel is om de OK afdeling te verduurzamen. Hierbij richt ik mij op de luchtbehandelingssystemen. Mijn idee is om een aantal OKs op klasse 1+ te laten en de rest terug te schalen naar klasse 1 door het luchtdebiet te verminderen. Dit bespaart energie. Ook ben ik aan het kijken naar de mogelijkheden om de planning van de operaties efficiënter te maken. Natuurlijk heb ik ook onderzoek gedaan naar de vorige richtlijnen en de nieuwe richtlijnen. Hier zou ik een paar vragen over willen stellen.

- Waarom is de nieuwe richtlijn opgesteld?
  Belangenverstrengeling in de vorige richtlijn door multidisciplinair team. Veel discrepantie en verwarring rondom de richtlijn maakte een nieuwe richtlijn nodig. De Inspectie Gezondheidszorg (IGZ) handhaafde de orthopedierichtlijn.

- Op welke manier was u betrokken bij het samenstellen van de nieuwe richtlijn?
  Ik ben lid van de expertgroep Luchtbehandeling op de OK.

- Is de energieverbruik en duurzaamheid een belangrijke factor geweest tijdens het opstellen van de nieuwe richtlijn?
  De duurzaamheid komt naar voren in de operationele kosten. Operationele kosten zijn de kosten om een luchtbehandelingsysteem operationeel te houden. Energiekosten en personeelskosten voor controle en onderhoud zijn hierbij de grootste kostenposten. In de WIP-richtlijn 'Luchtbehandeling in operatiekamer en opdekruimte in operatieafdeling klasse 1' uit 2014 concludeerde de expertgroep dat op basis van het beschikbare bewijs geen uitspraak kan worden gedaan over de kosten van een mengend ten opzichte van een verticaal UDF systeem. Ook de huidige werkgroep kan niet inschatten of er een verschil is in operationele kosten tussen het gebruik van een UDF en een mengend system, omdat de grootte van deze kostenposten afhangt van veel verschillende lokale factoren. De richtlijn noemt ook dat, in de regel, mengende systemen minder energie verbruiken. Hier is alleen niet veel onderzoek naar gedaan door de expertgroep.

- Wat is in uw ogen verandert in de nieuwe richtlijn ten opzichte van de vorige richtlijn?
  Een van de veranderingen is het loslaten van het advies een UDF systeem te hanteren. Eisen omtrent de luchtkwaliteit mogen behaald worden met beide systemen.

- Wat is de reden van de nieuwe classificatie (Klasse 1+ en klasse 1)?
  De expertgroep stelde klasse 1 samen en voor de orthopaedische operaties ontstond klasse 1+. Wij vonden dat er een andere classificatie nodig was omdat er veel discrepantie was omtrent de vorige classificatie.

- Hoe komt het dat men overal klasse 1 prestatieniveau 1 OKs is gaan bouwen? De richtlijn van 2014 gaf al aan dat dit enkel nodig was voor gewrichtsvervangende operaties. Het AMC bijvoorbeeld heeft bij de klinische OKs alleen maar OKs van klasse 1 prestatieniveau 1.

Uit gemakzucht. Het is natuurlijk makkelijker om geen onderscheid te maken in de OKs.

- In hoeverre verschillen OKs met klasse 1 prestatieniveau 2 van klasse 2 OKs en in hoeverre mogen er meer operaties uitgevoerd worden in klasse 1 prestatieniveau 2 OKs?
  Het ontwerp verschilt natuurlijk aanzienlijk, de klasse 2 OKs hebben geen luchtbehandelingssysteem. In de nieuwe richtlijn staat een uitgebreide beschrijving van de operaties die in klasse 2 uitgevoerd mogen worden.

Appendix C.2: Interview with Jelle Koeman (Amsterdam UMC)

Mijn doel is om de OK afdeling te verduurzamen. Hierbij richt ik mij op de luchtbehandelingssystemen. Mijn idee is om een aantal OKs op klasse 1+ te laten en de rest terug te schalen naar klasse 1 door het luchtdebiet te verminderen. Dit bespaart energie. Ook ben ik aan het kijken naar de mogelijkheden om de planning van de operaties efficiënter te maken. Ik heb een aantal vragen met betrekking tot de luchtbehandelingssystemen.

- Waarom gaan de luchtbehandelingssystemen terug naar 50% tijdens de nachtschakeling? Kunnen ze niet uit uit of anders nog lager?
  Ze kunnen niet uit doordat dit de spoed OKs die 24/7 aan staan nadelig kunnen beinvloeden door luchtlekkages.

- Zou een situatie waarbij grote gewrichtvervangende operaties uitgevoerd worden in specifieke Klasse 1+ OKs een mogelijkheid zijn? Hierbij zou de rest van de OKs Klasse 1 kunnen hebben.
  Nu is dat niet echt een mogelijkheid, alle OKs zijn ingericht voor klasse 1+ en kunnen niet zomaar terug geschaald worden zonder verbouwingen.

- Waarom 100 luchtverversingen per uur? Volgens de richtlijnen moeten klasse 1 OKs minimaal 20 luchtverversingen
  100 houdt de gerecirculaire en primaire luchtverversingen in. 20 is alleen primair.

- kWh verbruik van een enkel luchtbehandelingssysteem klasse 1 prestatieniveau 1 en 2?
  Weet ik niet uit mijn hoofd, zal ik aanvragen bij het bedrijf dat metingen gedaan heeft en het naar je doorsturen.

- Is het mogelijk om een keer de technische ruimte te zien samen met Anne Timmermans?
  Prima, gaan we inplannen. Ik zal je dan een rondleiding geven.

Appendix C.3: Interview with Karin de Vlaming (Amsterdam UMC)

Mijn doel is om de klinische OK afdeling te verduurzamen. Hierbij richt ik mij op de luchtbehandelingssystemen. Mijn idee is om een aantal OKs op klasse 1+ te laten en de rest terug te schalen naar klasse 1 door het luchtdebiet te verminderen. Dit bespaart energie. Ook ben ik aan het kijken naar de mogelijkheden om de planning van de operaties efficiënter te maken, hier zou ik wat vragen over willen stellen.

- Hoe wordt de dagelijkse planning van operaties nu gemaakt? Zit hier een bepaalde methode achter?
  De planning komt tot stand als gevolg van de jaarlijkse begroting van de OK-uren. Hierna wordt een meer concrete wekelijkse planning gemaakt die voortkomt uit een wekelijkse bijeenkomst tussen alle specialismen. Uiteindelijk wordt de dagelijkse planning vervolgens dagelijks afgerond.

- Worden bepaalde OKs specifiek toegewezen aan bepaalde specialismen?
  De OKs zijn in de basis allemaal hetzelfde, maar ze verschillen in apparatuur en uitrusting. Om deze reden worden er bepaalde specialismen over het algemeen in dedicated OKs ingepland.

- Waarom gaan de luchtbehandelingssystemen terug naar 50% tijdens de nachtschakeling? Kunnen ze niet uit uit of anders nog lager?
  Deze vraag kun je beter stellen aan de technici van het AMC, zij weten precies hoe de systemen er hier uitzien en waarom hiervoor gekozen is. Hier is volgens mij voor gekozen om de andere OKs stabiel te houden en om te zorgen dat de OKs snel weer up en runing zijn. De technici hebben voor de 50% gekozen en dit zal ongetwijfeld niet nog minder kunnen.

- Hoeveel wisseltijd is er nodig om na een operatie de OK voor te bereiden voor de volgende operatie en verschilt deze tijd per operatie?
  Verschillende operaties hebben natuurlijk ander apparatuur nodig en dit veroorzaakt verschillen in de wisseltijd, maar de meeste wisseltijd komt van het transporteren van de patiënten.

- In de data van 2019 zie ik veel tijd tussen opeenvolgende operaties in. Hoe komt dat?
  Het transporteren van patiënten kost natuurlijk tijd. Daarnaast zijn er ook acute OKs waar de operaties op dezelfde dag pas ingepland worden als dit nodig is. Dit zorgt ervoor dat er veel tijd tussen de operaties zitten.

- In hoeverre denkt u dat het nodig is dat er 5 OKs 24/7 aan staan?
  Om de patiënt gerust te stellen door genoeg OKs vrij te geven moeten er genoeg OKs beschikbaar zijn. Ook duurt het in sommige gevallen te lang om een OK op te starten wanneer hij nog uitstaat. Er is dus voor gekozen om 5 OKs ’s nachts vrij te geven om zo de zorgkwaliteit te waarborgen. Wel denk ik dat het mogelijk is om er een minder in te zetten ’s nachts.

- Zou een situatie waarbij grote gewrichtvervangende operaties uitgevoerd worden in specifieke Klasse 1+ OKs een mogelijkheid zijn? Hierbij zou de rest van de OKs Klasse 1 kunnen hebben.

Als dit technisch mogelijk is zou dit zeker een mogelijkheid zijn. Dit moet gecheckt worden met de technici van het AMC aangezien zij precies weten wat er kan in dit ziekenhuis. We hebben namelijk de meest geavanceerde luchtbehandelingssystemen. Validatie is dus erg belangrijk.

- En hoeveel Klasse 1+ OKs denkt u dat er dan nodig zullen zijn? Denkt u dat 2 voldoende zullen zijn? (klasse 1+ is alleen voor grote gewrichtsvervangende operaties)
  Ik denk dat 2 á 3 voldoende moet zijn. Houd hierbij wel rekening met onderhoud en potentiële storingen. Dit mag niet voor problemen zorgen dus ik zou wel aan de veilige kant zitten.

Appendix C.4: Interview with Wilco van Nieuwenhuyzen (Interflow)

Mijn doel is om de OK afdeling te verduurzamen. Hierbij richt ik mij op de luchtbehandelingssystemen. Mijn idee is om een aantal OKs op klasse 1+ te laten en de rest terug te schalen naar klasse 1 door het luchtdebiet te verminderen. Dit bespaart energie. Ook ben ik aan het kijken naar de mogelijkheden om de planning van de operaties efficiënter te maken. Ik heb een paar vragen met betrekking tot de luchtbehandelingssystemen in het AMC.

- Heeft Interflow de OKs in het AMC opgeleverd en voert Interflow het onderhoud uit?
  Nee, Interflow voert alleen de validatie van de OKs uit. Dit betekent dat wij alle waarden meten en controleren of deze op gewenste waarden zitten.

- Weet u wat het huidige verbruik van de luchtbehandelingssystemen in operatiekamers met klasse 1 prestatieniveau 1 in het Amsterdam UMC is?
  Dat weet ik niet uit mijn hoofd. Ik heb hier geen exacte gegevens voor maar ik kan je wel een Excel bestand doorsturen waarin het verbruik van de OKs in het AMC benaderd kan worden. Door verschillende waardes als input in te vullen in het bestand kun je dit berekenen.

- Weet u wat het verbruik in het AMC zou zijn als het luchtdebiet en ventilatievouden verminderd worden?
  Om dit te benaderen kun je het Excel bestand gebruiken, waarbij je de input parameters luchtdebiet en ventilatievouden verminderd.

- ’s Nachts wordt de ventilatie van 5 van de luchtbehandelingssystemen teruggeschakeld naar 50%. Weet u wat dan het energieverbruik is en is het niet mogelijk om de ventilatie verder terug te schakelen?
  Om dit te benaderen kun je ook het Excel bestand gebruiken.

- Hoe zien de luchtbehandelingssystemen er bij het Amsterdam UMC uit? Hebben deze centrale verse luchtkasten of decentrale verse luchtkasten per OK?
  Ik weet niet zeker hoe deze systemen eruit zien, wel denk ik dat er per OK een decentrale verse luchtkast van beschikking is.

- Het aantal luchtwisselingen is momenteel ca. 100 keer per uur. De richtlijnen schrijven minimaal 20 luchtwisselingen per uur voor. Hoe is dit verschil te verklaren? Kan dit minder zonder dat het systeem zijn verdringende werking verliest?
  Dit komt doordat de luchtbehandelingssystemen een verdringende werking hebben. Hierdoor moet het luchtdebiet hoog genoeg zijn om de verdringende werking te behouden.

Met 20 luchtwisselingen per uur is het niet mogelijk om die verdringende werking te verzekeren. Het luchtbehandelingssysteem verandert dan in een mengend luchtbehandelingssysteem. Dat is de reden dat het ziekenhuis het aantal luchtwisselingen momenteel op circa 100 per uur houdt.

Appendix C.5: Interview with Anne Brouwer (Royal HaskoningDHV)

Mijn doel is om de OK afdeling te verduurzamen. Hierbij richt ik mij op de luchtbehandelingssystemen. Mijn idee is om een aantal OKs op klasse 1+ te laten en de rest terug te schalen naar klasse 1 door het luchtdebiet te verminderen. Dit bespaart energie. Ook ben ik aan het kijken naar de mogelijkheden om de planning van de operaties efficiënter te maken. Ik heb een paar vragen met betrekking tot het omzetten van de verdringende luchtbehandelingssystemen naar mengende luchtbehandelingssystemen in het AMC.

- Kan een verdringend systeem teruggeschakeld worden van ISO 5 naar ISO 7 zonder zijn verdringende werking te verliezen (en minimaal 20 luchtwisselingen per uur en een hersteltijd van maximaal 20 minuten te behouden)?

Als het systeem zijn verdringende werking behoudt, dan bereik ook altijd ISO 5 en zal de hersteltijd ook gewoon 3 minuten blijven. Verdringend wil zeggen dat je echt de lucht vanuit het plenum naar beneden wegduwt. Er is daarmee een constante schone luchtstroom over het operatiegebied. Bij verlagen van de luchtstroom (luchtdebiet) verliest de luchtstroom haar verdringende werking en wordt het meer een mengend systeem. De luchtwisselingen gaan dan terug van 70-80 per uur (verdringend) naar de genoemde 20 luchtwisselingen. Dus het antwoord is nee, met dergelijke lage ventilatievouden is er geen sprake van een verdringend systeem zoals bedoeld in de richtlijnen.

- Is het mogelijk om verdringende luchtbehandelingssystemen zonder een verbouwing om te zetten naar een mengend systeem en hoe kan dit gerealiseerd worden? Bespaart dit energieverbruik ten opzichte van een downflowsysteem bij minimaal 20 luchtwisselingen, ISO 7, en een hersteltijd van maximaal 20 minuten? Hoeveel energie zou het systeem dan verbruiken?

Ja, dit is heel goed mogelijk. Je kunt een regeling inbouw waarmee het luchtdebiet kan worden verminderd van hoog (verdringend) naar laag (mengend). Bij verlagen van het debiet zal het inblaasplenum functioneren als een groot inblaasrooster en mengende ventilatie gaan geven. Het is hiervoor wel noodzakelijk dat de ventilatoren in de luchtbehandelingskast inderdaad regelbaar zijn en je moet dus wat extra regeltechniek toevoegen. In het OK bedienpaneel kun je dan een omschakelknop opnemen. Belangrijk om goed te valideren dat bij omschakelen de OK inblaas inderdaad weer heen en terug gaat naar de juiste waarden en in de hoogste stand ook weer voldoet aan ISO 5, hersteltijd 3 minuten. Belangrijk ook om de schakelstand onderdeel uit te laten maken van de time-out procedure om schakelfouten te voorkomen. Ik zal een bijlage sturen met een indicatie van de berekeningen.

- Omdat klasse 1+ (ISO5) nog maar noodzakelijk is voor een aantal ingrepren (uitsluitend orthopaedie) denk ik aan een statisch systeem waarbij je een paar OKs inregelt als ISO 5 en de rest als ISO 7.

Ja, het aantal ingrepen waarvoor Klasse 1+ of P1 nodig is, is heel beperkt. Het gaat alleen om gewrichtsvervangende operaties of operaties met soortgelijk implantaten/endoprothesen. Kleine implantaten hoeft zeker niet in klasse 1+. En alle andere operaties van andere discipline hoeven van de verenigingen niet in Klasse 1+.

Even voor de goede orde, dat was in de WIP 2014 ook al heel duidelijk aangegeven! Wat dat betreft is er met de nieuwe luchtrichtlijn helemaal niets nieuws onder de zon. Alleen op een of andere manier heeft men dat niet goed gelezen en is iedereen overal P1 OK's gaan maken.

- Nog een laatste vraag: als je het ventilatievoud gaat verlagen richting ISO 7 voorwaarden, maar je houdt ISO5 voorwaarden op, bijvoorbeeld, de OK ernaast. Is dan de drukhierarcie nog wel goed te garanderen? Met andere woorden blaas je dan geen lucht vanuit een ISO5 OK een ISO 7 OK op?

Nee, dat zou geen probleem moeten zijn. Met de verse lucht wordt de druk hiërarchie geregeld. Dit werkt over het gehele OK complex. Bovenop de verse lucht wordt per OK lucht gerecirculeerd (vaak door een aparte recirculatie unit per OK). Die unit jaagt constant lucht over het plenum. Wat je als je van Klasse 1+ naar Klasse 1 gaat (of van P1 naar P2) is dat je die recirculatie hoeveelheid gaat reduceren. Maar de verse lucht moet gelijk blijven (vanwege luchtjes, anesthesiedampen, bezetting personen en dus om de drukhierarchie te handhaven).

Met recirculatie in een kamer kan je geen drukverschillen creëren naar andere ruimten, dat kan alleen via het verse luchtdeel door toe- en afvoer hoeveelheden verschillende in te stellen van elkaar (maar toevoer dan afvoer is overdruk en andersom).

Let op: het kan zijn dat bij jullie de systemen net even anders in elkaar zitten, maar in basis is dit hoe het zou moeten werken.

Je kunt ook nog in de nachturen het verse luchtdeel gaan aftoeren, maar dan loop je op een gegeven moment wel tegen grens van het handhaven van de druk hierarchie aan, maar zeker ook een interessante mogelijkheid.

En natuurlijk gewoon overdag en 's avonds de Klasse 1+ op laag toeren zetten als ie niet gebruikt wordt (kan evt. op een bewegingsmelder). Na 15 minuten is zo'n systeem weer up en running.

Overigens nog wel een opmerking over ISO 5 en 7. Deze waarden gelden in rust. En die ISO 5 haal je uiteindelijk in een P2 OK wel als je maar lang genoeg wacht. Wat het name het verschil is is de hersteltijd. Die is 3 minuten voor klasse 1+ en 20 minuten voor de andere. Om die 3 minuten heb je een grotere luchthoeveelheid om deeltjes snel af te kunnen voeren.

Appendix D: Surgery classification as proposed in the revised guideline

WV	Operatiekamer klasse 1+	Operatiekamer klasse 1	Operatiekamer klasse 2	Zelfstandige behandelkamer
Nederlandse Orthopaedische Vereniging	– Electieve grote gewrichtsvervangende operaties (knie, heup, schouder)	– Overige grote orthopedische implantaatchirurgie bijv wervelkolomoperaties met implantaten, operaties waarbij een groot implantaat wordt geplaatst (bijv. pen of plaat en vergelijkbare implantaten) – Overweeg bij scoliose-operaties operatiekamer klasse 1+ – Operaties waarbij een groot gewricht wordt geopend (bijv. knie of enkel en vergelijkbare gewrichten), – Operaties waarbij een groot bot wordt vrijgelegd (bijv. bij fractuurchirurgie en vergelijkbare operaties)	– Operaties waarbij donormateriaal (auto- of allograft) en/ of klein implantaat (bijv. schroef) wordt geplaatst (bijv. kruisbandoperaties en schouderstabilisaties en vergelijkbare operaties) – Operaties waarbij een klein bot wordt vrij gelegd (bijv. midden- of voorvoet reconstructies en vergelijkbare operaties, handchirurgie) – Arthroscopische procedures waarbij geen implantaat of donormateriaal (auto- of allograft) wordt geplaatst (bijv. alle meniscectomieën en vergelijkbare operaties) – Kleine orthopedische ingrepen zonder dat daarbij een gewricht wordt geopend (bijv. tennisarm en vergelijkbare operaties) – Alle kleine operaties onder lokaal anesthesie (bijv. hamerteencorrectie en vergelijkbare operaties)	– Abcesincisie/ abcesdrainage – Wondverzorging
Nederlandse Vereniging voor Anesthesiologie		– Implantatie van electroden en stimulatoren in het kader van neuromodulatie. – Implantatie van subcutaan geplaatste systemen voor neuraxiale toediening van medicatie		– neuraxiale injecties, inclusief plaatsen van catheters – perifere zenuwblokkades, inclusief plexusblokkades, met of zonder achterlaten van catheter – vasculaire toegang

WV	Operatiekamer klasse 1+	Operatiekamer klasse 1	Operatiekamer klasse 2	Zelfstandige behandelkamer
Nederlandse Vereniging voor Cardiologie			– Percutane klepinterventies (waaronder TAVI, PPVI) – PCI, PFO/ASD sluiting, Mitraclip, congenitale stents – PM, ICD – Catheterablaties – Implanteerbare looprecorder (ILR)	– SG inbrengen, tijdelijke PM-draad – Hartbiopten – CAG – Hartcatherisaties (R/L)
Nederlandse Vereniging voor Dermatologie en Venereologie			– Alle ingrepen onder algehele anesthesie	– Alle ingrepen onder plaatselijke verdoving. – Mohs-chirurgie (Huidbiopsieën en shave excisies mogen op een spreek-/onderzoekskamer)
Nederlandse Vereniging voor Heelkunde		– Alle kinderheelkundige chirurgie waarbij kinderen onder algehele narcose moeten worden gebracht		
Nederlandse Vereniging voor Keel-Neus-Oorheelkunde en Heelkunde van het Hoofd-Halsgebied		– Brughoekchirurgie – Ooroperaties (sanerend en reconstructief) uitgebreider dan myringoplastiek – Subtotale petrosectomie – CI & ABI – Endonasale intracraniele chirurgie – Rhinoplastieken met en zonder gebruik van synthetische implantaten – HH-oncologische chirurgie – Parotis- en andere grote wekedelenchirurgie – Facelifts, voorhoofdlifts – Sinus-frontalischirurgie	– Neus-bijholte operaties – Endonasale sinus-frontalischirurgie	– Trommelvliesbuisjes – ATE's – Myringoplastieken – M-plastieken – UPPP – Biopten – Mohs chirurgie – Ooglidchirurgie – Littekencorrecties, dermabrasie – Septumchirurgie
Nederlandse Vereniging voor Mondziekten, Kaak- en Aangezichtschirurgie			– Alle MKA-chirurgische ingrepen onder algehele anesthesie	– Alle MKA-chirurgische behandelingen op de polikliniek
Nederlandse		– Alle neurochirurgische operaties die niet	– Ulnaristranspositie / -decompressie.	– Operatie carpaaltunnelsyndroom

WV	Operatiekamer klasse 1+	Operatiekamer klasse 1	Operatiekamer klasse 2	Zelfstandige behandelkamer
Nederlandse Vereniging voor Plastische Chirurgie		– Ingrepen OK > 3 uur – Augmentatie mastopexie – Borstreconstructies m.b.v. implantaat / gesteelde lap / vrije lap – Mamma-augmentatie – Facelift en necklift – Gewrichtsvervangende handchirurgie – Dijbeenlift / lower bodylift – Abdominoplastiek met liposuctie – Grotere trauma's waarvan de OK-tijd moeilijk ingeschat kan worden: hand, aangezicht, romp – Reconstructies d.m.v. vrije weefselverplaatsing / replantaties / microchirurgie – Craniofaciale chirurgie – Genderchirurgie	– Liposuctie – Laserliposuctie – Mastopexie – Mammareductie – Voorhoofdslift – Lipofilling borsten, billen > 50 ml – Alle geplande handchirurgie (excl. gewrichtsvervangend implantaat, CTS, TVS, benigne tumoren / littekens) – Abdominoplastiek – Rhinoplastiek – Oncoplastische mammachirurgie – Armlift – Schisis – Urogenitale chirurgie kinderen	– Ooglidcorrectie boven – Ooglidcorrectie onder / midface – Schaamlipcorrectie – Benigne tumoren / littekens – Flaporen – CTS – Acute kleine handchirurgie – TVS – Maligne tumoren waarvoor kleine reconstructies – Tepel- / tepelhofcorrecties – Mohs chirurgie met reconstructie – SSG / FTG reconstructies – Botox – Filler – Laser
Nederlandse Vereniging voor Radiologie		– Hybride vasculaire procedures met chirurgische incisie – Vasculaire endoprothesen bij (complexe) thoraco-abdominale aneurysmata.	– Percutane vasculaire interventies (incl. Port-a-cath. getunnelde centraal veneuze lijn plaatsing, TIPS) – Vertebroplastiek	– Percutane non-vasculaire interventies (biopten, drainage, ablaties, injectie contrast/medicatie) – Percutane thrombine injectie bij aneurysma spurium – Plaatsing ongetunnelde centraal veneuze lijn
Nederlandse Vereniging voor Thoraxchirurgie	–	– Hartchirurgie – Longchirurgie – Aortachirurgie – Overige chirurgische intrathoracale ingrepen		– Wondinfectie – Thoraxdrainage
Nederlandse Vereniging voor Urologie		- Laparoscopische ingrepen met /zonder deviatie - Open ingrepen met / zonder deviatie - Implantatie / prothesiologie	- Endourologische ingrepen - Percutane ingrepen	- Kortdurende transurethrale ingrepen / diagnostiek - Plaatsen / wisselen nefrostomie catheter

Table D-1: Surgery classification as proposed in the revised guideline, completed by each specialisms' corresponding association

Appendix E: Surgery classification and allocation example

Specialism	Class 1	Class 2	Independent treament room
General surgery	• All interventions under general anesthesia	• Insert port-a-cath • Crossectomie v.	• Removal atheromas • Nail excision
Cardiology		• Implant a pacemaker • Cardiac catheterization • Place stents • Angioplasty	
Dermatology	• All interventions under general anesthesia	• Mohs Micrographic Surgery	• Skin biopsies • Excisions of benign and malignant • Skin conditions • Minor skin grafts • Ambulatory phlebectomy
Throat, nasal and ear surgery	• All interventions under general anesthesia • Neck gland dissection • Rhinoplasty (with implants)	• Interventions under local anaesthesia	• Pain relief of abscess • Lip biopsy
Neurosurgery	• All neurosurgical operations that are not executed in class 1 or independent treatment room	• Ulnar transposition/ decompression	• Surgery for carpal tunnel syndrome (CTS) • Remove ommaya • Wound infection treatment • Apply skull traction
Ophthalmology	• Cataract surgery • Orbital implants • Glaucoma surgeries • Corneal transplants • Refractive surgery		• Eyelid surgery such as ectropion surgery and blepharochalasis surgery
Orthopedics	• Implant prostheses • Fractures	• Tennis elbow surgery • Hammertoe surgery	• Abscess incision • Wound treatment
Oral diseases and maxillofacial surgery	• All interventions under general anesthesia		• Interventions under local anaesthesia
Radiology		• Stent placement •Catheterizations	• Punctures ultrasound or CT scan
Thoracic surgery	• Heart surgery • Lung surgery • Other intrathoracic surgeries		• (At most) Open surgical wound if underlying infection is suspected • Installing chest drain

Table E-1: Surgery classification and allocation example

Appendix F: Example of daily planning

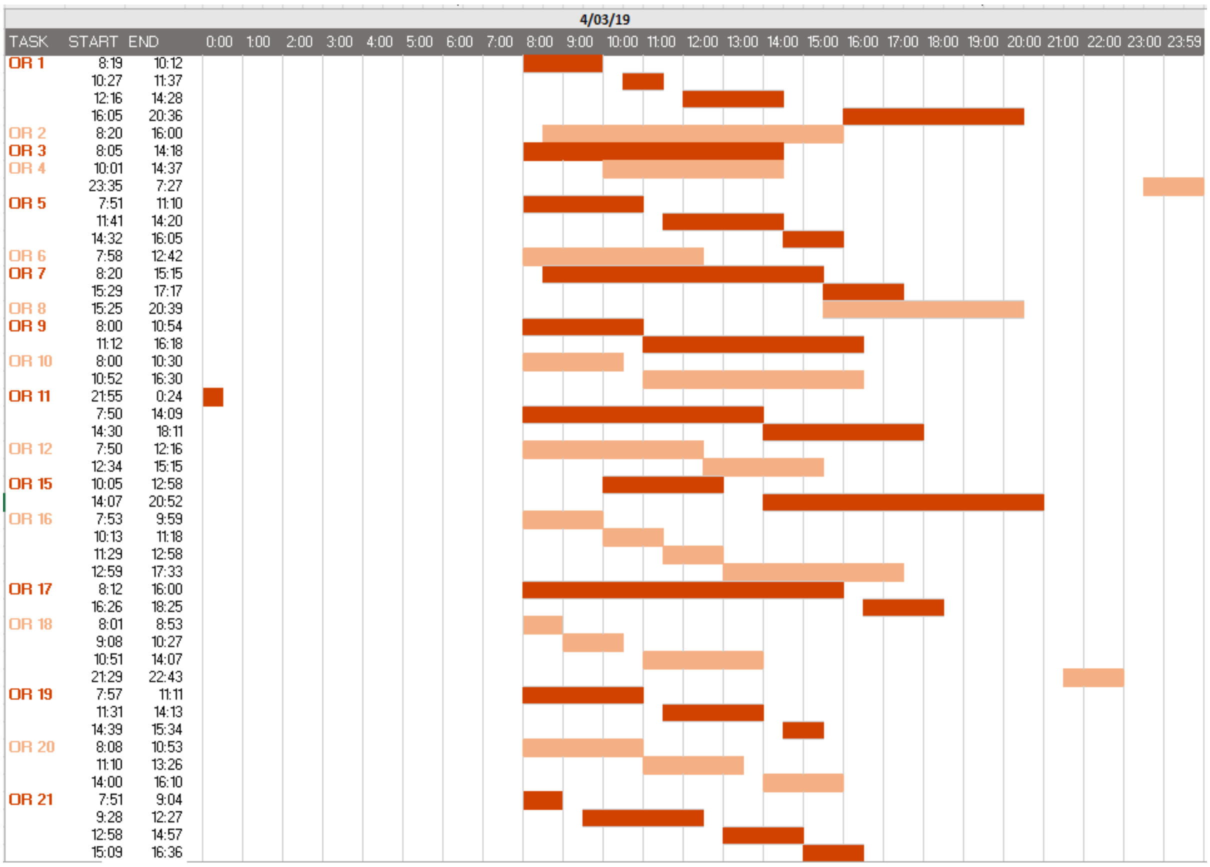

Figure F-1: Example of daily planning

Appendix G: Requirements for critical parameters

Measurement	Criteria	Comments	Alarm threshold
Degree of protection protected area	≥ 3.0 ≥ 2.0	Center of protected area Extreme edge of protected	N.A.
Recovery time	≤ 3 min	Center of protected area	N.A.
Concentration of particles (0,5 µm particles)	≤ 3,520 particles/m3	ISO 5 at the center of the protected area	N.A.
Pressure difference from clean to polluted air	Minimum according to initial determination	N.A.	Alarm value lower limit, delay 5 min
Temperature	18.0 - 24.0 °C Max Δ 1.5 °C	T1 (adjustable) T1 - T2	< -1.0 °C > +1.0 °C Delay 1 min
Relative humidity	50-65 %	N.A.	< -5.0 % > 25 % Delay 5 min
Filter integrity	≤0.01 %	HEPA filter	N.A.
Outgoing airflow velocity	0.24-0.36 m/s	Scatter max 20 %	< 0.06 m/s > 0.06 m/s
Airflow	4,425 m3/h 11,095 m3/h	Zone T1 Zone T2	N.A.
Illuminance	600 lux	N.A.	N.A.
Sound	45 dB(A)	N.A.	N.A.

Table G-1: Requirements for critical parameters in the clinical ORs of the Amsterdam UMC

Appendix H: Frequently applied HVAC system configurations

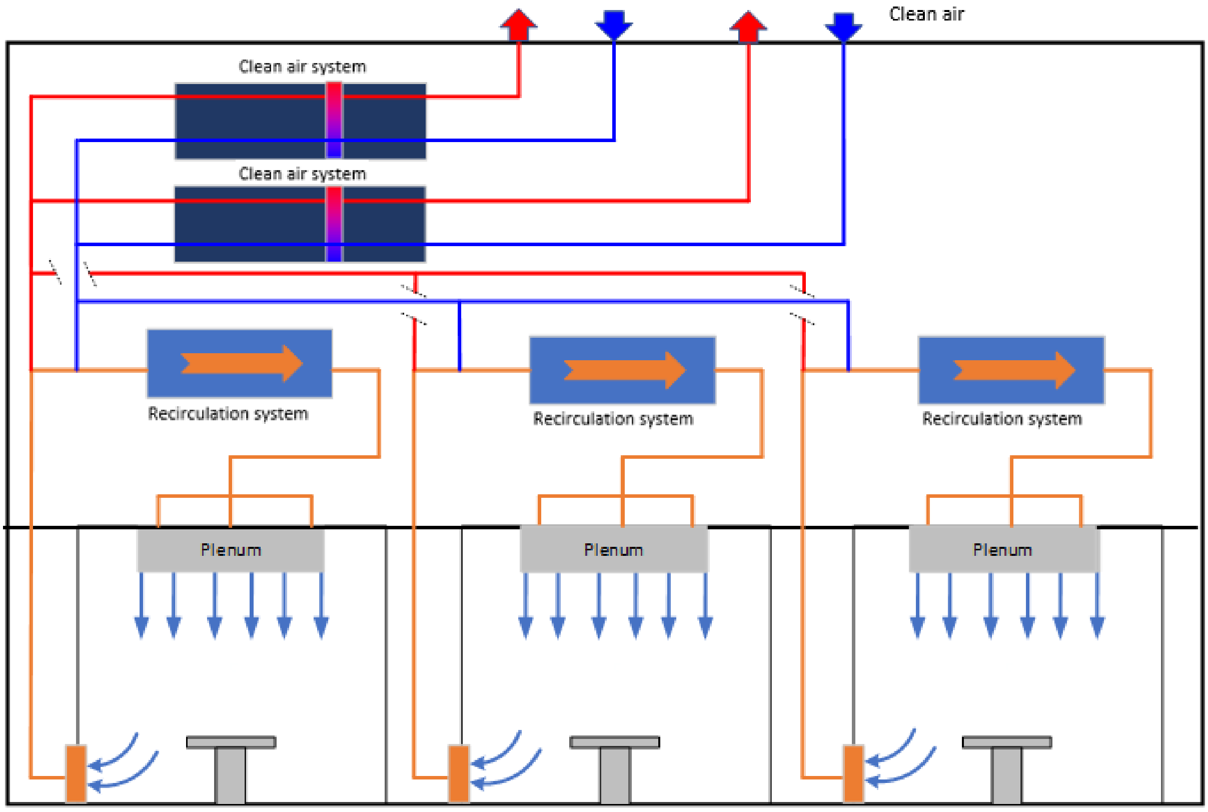

Figure H-1: Class 1 performance level 1 – Centralized clean air system

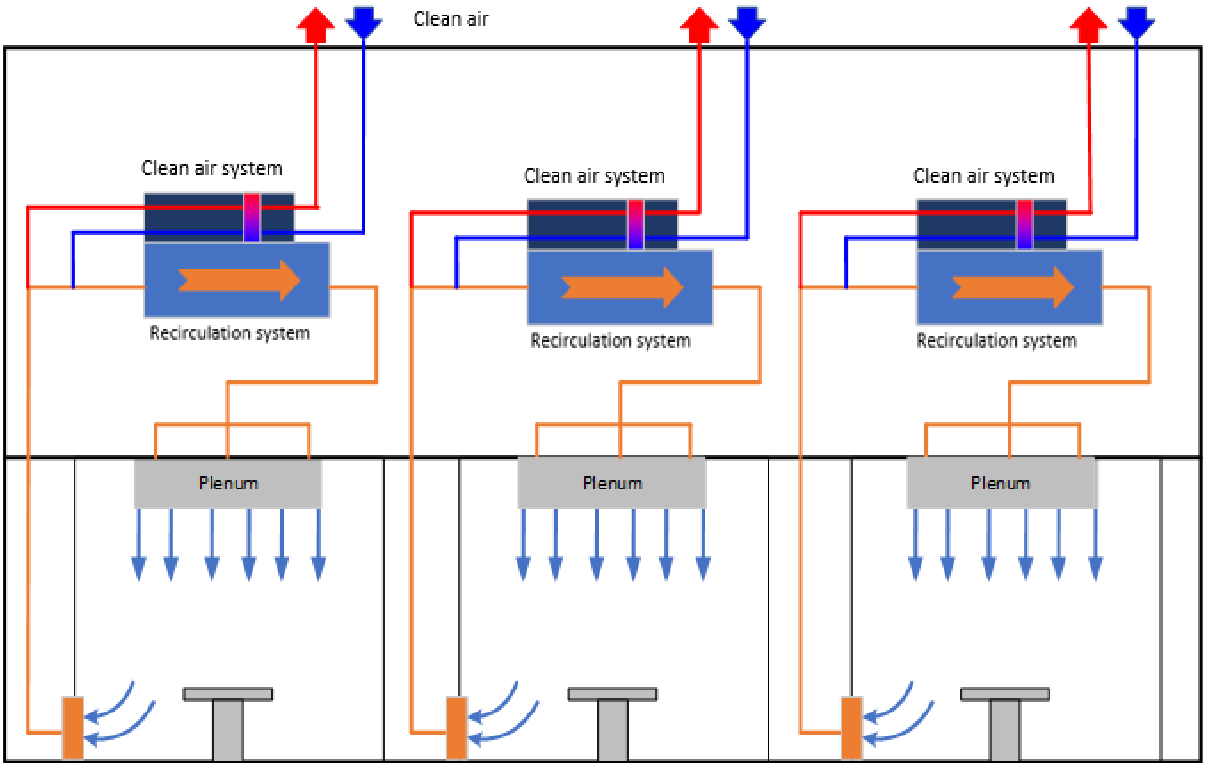

Figure H-2: Class 1 performance level 1 – Decentralized clean air system

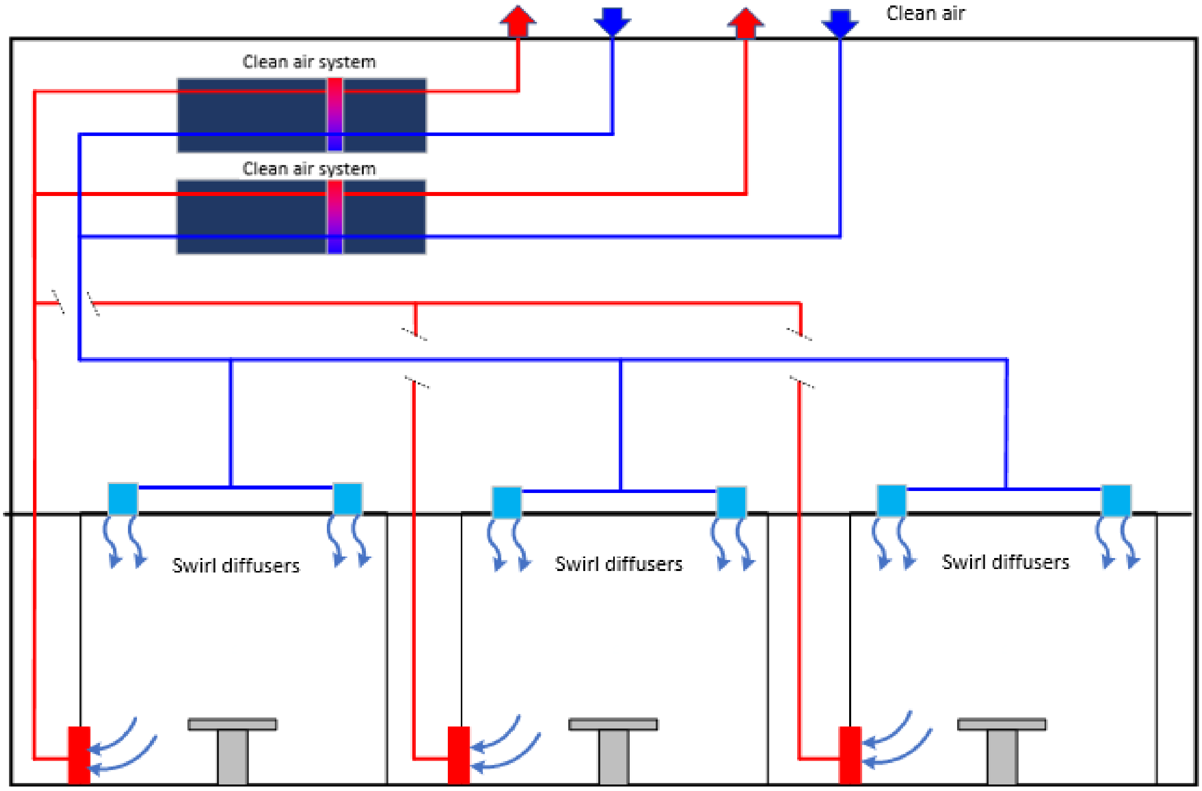

Figure H-3: Class 1 performance level 2 – Without recirculation system

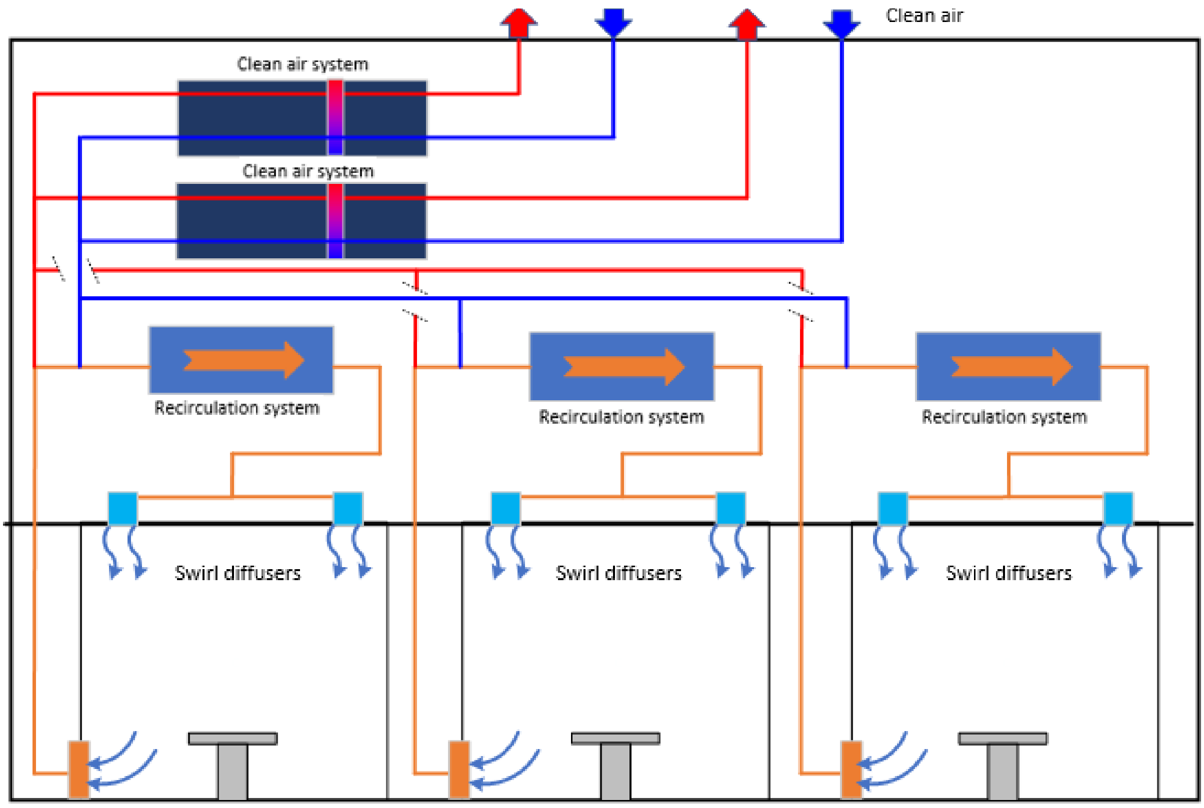

Figure H-4: Class 1 performance level 2 – With recirculation system

Appendix I: Energy consumption tool assumptions

- 18 ORs of 50 m^2 cleanroom, 2 ORs (OR 7 + OR 8) of 70 m^2 cleanroom;
- ORs 4, 5, 8, 12, and 14 are 24/7 ORs;
- There are 52 weeks and 8,760 hours in a year. ORs shifting to nighttime operation operate in daytime operation between 6:30 and 21:00 (14.5 hours) from Monday – Friday, excluding official holidays (8 days in the Netherlands);
- Airflow rate reduction during nighttime operation is 50%. Reduction of energy consumption due to the airflow rate reduction is also assumed to be 50%;
- €0.09 / kWh (J. Koeman, personal communication, June 16, 2022);
- Airflow flow rate (supplemented ventilator) is equal to 6,250 m^3/h;
- Airflow flow rate (OR ventilator) is equal to 9,000 m^3/h;
- Airflow flow rate (storage room ventilator) is equal to 3,000 m^3/h;
- Airflow flow rate (exhaust ventilator) is equal to 2,500 m^3/h;
- External pressure (supplemented ventilator) is equal to 150 Pa;
- External pressure (OR ventilator) is equal to 350 Pa;
- External pressure (storage room ventilator) is equal to 350 Pa;
- External pressure (exhaust ventilator) is equal to 200 Pa;
- Internal pressure (supplemented ventilator) is equal to 343 Pa;
- Internal pressure (OR ventilator) is equal to 552 Pa;
- Internal pressure (storage room ventilator) is equal to 600 Pa;
- Internal pressure (exhaust ventilator) is equal to 100 Pa;
- Static efficiency (all ventilators) is equal to 0.75;
- Motor efficiency (all ventilators) is equal to 0.85;
- Lights electric power is equal to 15 W/m^2;
- Heat load is equal to 25 W/m^2;
- Coefficient of performance cooling machine is equal to 4.1;
- Other electric power (pumps, control system, etc.) is equal to 1.5 kW

Appendix J: Surgical procedures for class 1+ ORs

Procedure	Primary_procedure_id
BEKKEN - EXTERNE FIXATEUR NA GESLOTEN REPOSITIE	1071002320
BEKKEN - INCISIE EN SPOELDRAINAGE BEKKENGEWRICHT	1071002377
BEKKEN - KRAPPE EXCISIE AFWIJKING - EXCOCHLEATIE BOT	1071002288
BEKKEN - OSTEOSYNTHESE	1071002322
BEKKEN - OSTEOSYNTHESE ACETABULUM	1071002418
BEKKEN - OSTEOSYNTHESE ACETABULUM OVV PLAAT OS KLEIN	1071003978
BEKKEN - OSTEOSYNTHESE OVV GECANN. SCHROEVEN	1071003980
BEKKEN - OSTEOSYNTHESE OVV PLAAT OS GROOT	1071003979
BEKKEN - OSTEOSYNTHESE OVV PLAAT OS KLEIN	1071003977
BEKKEN - RADICALE EXCISIE AFWIJKING BOT	107100640
BEKKEN - SPONGIOSAPLASTIEK	1071002309
BEKKEN - VERWIJDEREN OSTEOSYNTHESEMATERIAAL	1071002715
BEKKEN - WINNEN BOT UIT CRISTA VOOR AUTOTRANSPLANT.	1071002281
BOT - BIOPSIE	1071002791
BOT - DEF.PERCUT.EPIFYSIOD.-WEGNEMEN-DEEL-EPIF	107100559
BOT - DRAINAGE ABCES ONTSTEKINGEN	1071002767
BOT - EXCOCHL.EN-OF SEKWESTROTOM.-MIDDELGR.BEEND.	1071004435
BOT - TRANSPLANTATIE BOT EN-OF KUNSTSTOF	1071004134
BOT - VERWIJD.EXOSTOSEN KLEINE BEEND.- VOOR DE 1E	107100699
BOT - VERWIJDEREN 1 OF MEER SCHROEVEN UIT EEN BOT	1071002731
BOT - VERWIJDEREN CENTRALE MERGPEN	1071002714
BOT - VERWIJDEREN EXTERNE FIXATEUR	107100686
BOT - VERWIJDEREN OSTEOSYNTHESEMATERIAAL	1071002742
BOT - VERWIJDEREN PLAAT EN SCHROEVEN UIT 1 BOT	1071002728
BOT - VERWIJDEREN PLATEN EN SCHROEVEN	1071002723
BOT - VERWIJDEREN SNAARTRACTIE OF EXT.FIXATEUR	1071002739
BOT-SPIEREN - BEHANDELING GROTE DIEPE ABCESSEN	1071003875
BOVENARM - AMPUTATIE	1071002067
BOVENBEEN - AMPUTATIE	1071002492
BOVENBEEN - KRAPPE EXCISIE BOT	1071002402
BOVENBEEN - KRAPPE EXCISIE BOT OVV FEMURKOP	1071003992
BOVENBEEN - REVISIE AMPUTATIESTOMP	1071002494
BOVENBEEN - VARISERENDE DEROTERENDE OSTEOTOMIE	1071002408
CLAVICULA - PLAATOSTEOSYNTHESE	1071002019
ELLEBOOG - PROTHESE IMPLANTATIE RADIUSKOP	1071004732
ENKEL - PLAATOSTEOSYNTH.BIMALLEOL. NA OPEN REPOS.	1071002637
ENKEL - PLAATOSTEOSYNTH.TRIMALLEOL.-OPEN REPOSITIE	1071002639
ENKEL - PLASTIEK LIGAMENT-CHRON.LUXATIE-ARTROTOMIE	1071002680
ENKEL - REVISIE GEWRICHTSPROTHESE	1071003885
ENKEL - SCHROEFOSTEOSYNTH.BIMALLEOL.NA OPEN REPOS.	1071002638
FEMUR - GESLOTEN REPOSITIE FRACTUUR-MERGPENFIXATIE	1071002431
FEMUR - PER-INTER-SUBTROCH.FRACT.HOEKPLAATOSTEOSYNT	1071002427
FEMUR - PER-INTER-SUBTROCH.FRACTUUR GAMMA-NAIL-FIX.	1071002426
FEMUR DIST. - HOEKPLAATOSTEOSYNTHESE	1071002442

FEMUR DIST. - PLAATOSTEOSYNTHESE	1071002441
FEMUR DIST. - SCHROEFOSTEOSYNTHESE	1071002443
FEMUR PROX. - DYNAMISCHE HEUPSCHROEF - HALS	1071002421
FEMUR PROX. - HOEKPLAATOSTEOSYNTHESE - HALS	1071002420
FEMUR PROX. - INTRAMEDULLAIRE FIXATIE	1071002423
FEMUR PROX. - INTRAMEDULLAIRE FIXATIE OVV GAMMA NAIL LANG	1071004011
FEMUR PROX. - INTRAMEDULLAIRE FIXATIE OVV NAIL LFN	1071004007
FEMUR PROX. - INTRAMEDULLAIRE FIXATIE OVV TFN	107100463
FEMUR PROX. - OP.BEH.EPIFYSIOLYSIS CAPUT FEMORIS	1071002445
FEMUR PROX. - OSTEOSYNTHESE COLLUM FEMORIS	1071002419
FEMURSCHACHT- INTRAMEDULLAIRE FIX.NA GESL.REPOSITIE	1071002434
FEMURSCHACHT- INTRAMEDULLAIRE FIX.NA OPEN REPOSITIE	1071002433
FEMURSCHACHT- INWENDIGE FIXATIE ZONDER REPOSITIE	1071002448
FEMURSCHACHT- PLAATOSTEOSYNTHESE	1071002438
FIBULA - PLAATOSTEOSYNTHESE NA OPEN REPOS.SCHACHT	1071002535
FIBULA - SCHROEFOSTEOSYNTHESE NA OPEN REPOS.DISTAAL	1071002534
HEUP - INBRENGEN KOP-HALSPROTHESE - NNO	1071002470
HEUP - INBRENGEN KOP-HALSPROTHESE - NNO OVV MUELLER	1071004018
HEUP - REVISIE TOTAL HIP - BEIDE COMP.MET OPBOUW	1071002480
HEUP - REVISIE TOTAL HIP ACETABULUM MET OPBOUW	1071002478
HEUP - REVISIE TOTAL HIP FEMURCOMP. MET OPBOUW	1071002479
HEUP - TOTALE HEUPPROTHESE HYBRIDE	1071002476
HEUP - TOTALE HEUPPROTHESE MET HYDROXIE APATIET	1071002477
HEUP - VERVANGEN ONDERDEEL VAN HEUPPROTHESE	1071002473
HUMERUS - BEHANDELING PSEUDO-ARTROSE- FIX.EN PLASTIEK	1071002008
HUMERUS - INWENDIGE FIXATIE HUMERUS REPOSITIE	1071002012
HUMERUS - INWENDIGE FIXATIE HUMERUS REPOSITIE OVV GROOT LCP	1071004013
HUMERUS - MERGPENFIXATIE - SCHACHT	1071002031
HUMERUS - PLAATOSTEOSYNTHESE - SCHACHT	1071002027
HUMERUS - PLAATOSTEOSYNTHESE PROXIMAAL	1071002030
HUMERUS - PLAATOSTEOSYNTHESE SUPRA-TRANSCOND.FRACT.	1071002032
HUMERUS - PLAATOSTEOSYNTHESE SUPRA-TRANSCOND.FRACT. OVV GROOT LCP	1071004015
KNIE - PROTHESE HEMIARTROPLASTIEK MEDIAAL	1071003871
KNIE - REVISIE FEMURCOMPONENT KNIEPROTHESE	1071003879
KNIE - REVISIE KNIEPROTHESE	1071002800
KNIE - REVISIE KNIEPROTHESE ALLE COMPONENTEN	1071002798
KNIE - REVISIE TIBIACOMPONENT KNIEPROTHESE	1071002797
KNIE - VERVANGEN LAGER --SPACER -- KNIEPROTHESE	1071004716
KNIE - VERVANGEN ONDERDEEL VAN KNIEPROTHESE OVV INLAY WISSEL	107100471
KNIE - VERWIJDEREN PROTHESE GEWRICHT	1071002576
ONDERARM - OPER.BEH.FRACTUUR DISTALE RADIUS	1071004439
ONDERARM - OPERATIEVE BEHANDELING FRACTURA MONTEGGIA	1071004465
ONDERARM - PLAATOSTEOSYNTHESE ULNA EN RADIUS	1071002097
ONDERARM - PROTHESE IMPLANTATIE DISTALE ULNA	1071002125
ONDERBEEN - INTRAMEDULL.FIX.NA GESL.REPOS.CRURISFRACT.	1071002537
ONDERBEEN - PLAATOSTEOSYNTHESE NA OPEN REPOS.CRURIS	1071002536
POLS - PROTHESE IMPLANTATIE POLSGEWRICHT	1071002219
PRIMAIRE HEUP MET CEMENT, ROUTINE	107100790

PRIMAIRE HEUP MET CEMENT, COMPLEX	107100792
PRIMAIRE HEUP MET CEMENT, INTERMEDIATE	107100791
PRIMAIRE HEUP ZONDER CEMENT COMPLEX	107100650
PRIMAIRE HEUP ZONDER CEMENT INTERMEDIATE	107100649
PRIMAIRE HEUP ZONDER CEMENT ROUTINE	107100648
RADIUS - PLAATOSTEOSYNTHESE DISTAAL	1071002100
RADIUS - PLAATOSTEOSYNTHESE INCL.GALEAZZI	1071002110
RADIUS - SCHROEFOSTEOSYNTHESE DISTAAL	1071002101
RADIUS - SCHROEFOSTEOSYNTHESE WGS RADIUSKOPFRACTUUR	1071002104
-RE-SPONDYLODESE 2 OF 3 OF 4 SEGMENTEN - CERVICAAL	1071004514
-RE-SPONDYLODESE 2 OF 3 OF 4 SEGMENTEN - THORACAAL	1071004515
-RE-SPONDYLODESE 2 OF 3 OF 4 SEGMENTEN- LUMBOSACRAAL	1071004517
-RE-SPONDYLODESE 2 OF 3 OF 4 SEGMENTEN-CRANIOCERVICAAL	1071004518
-RE-SPONDYLODESE 5 OF MEER SEGMENTEN CERVICOTHORAC	1071004506
-RE-SPONDYLODESE 5 OF MEER SEGMENTEN LUMBAAL	1071004505
-RE-SPONDYLODESE 5 OF MEER SEGMENTEN THORACAAL	1071004504
-RE-SPONDYLODESE 5 OF MEER SEGMENTEN THORACOLUMB	1071004507
SCHOUDER - PROTHESE IMPLANT.HUMERUSKOP-SCHOUDERKOM	1071002052
SCHOUDER - PROTHESE IMPLANTATIE HUMERUSKOP	1071002051
TIBIA - HOEKPLAATOSTEOSYNTHESE - PROX-PLATEAUFRACT.	1071002540
TIBIA - INTRAMEDULL.FIXATIE SCHACHT NA GESL.REPOS.	1071002530
TIBIA - INTRAMEDULL.FIXATIE SCHACHT NA GESL.REPOS. OVV ETN 10+11MM	1071004003
TIBIA - INTRAMEDULL.FIXATIE SCHACHT NA OPEN REPOS.	1071002531
TIBIA - INTRAMEDULL.FIXATIE SCHACHT NA OPEN REPOS. OVV ETN 10+11MM	1071004005
TIBIA - ONBLOEDIGE REPOSITIE-AANLEGGEN GIPS-SCHACHT	1071002525
TIBIA - OPER.BEH.INTRA-ARTICULAIRE PLATEAUFRACTUUR	1071002542
TIBIA - OPER.BEH.PSEUDO-ARTROSE MET BOTPLASTIEK	107100689
TIBIA - PLAAT-FIXATIE WEGENS PROX.TIBIAFRACTUUR	1071002544
TIBIA - PLAATOSTEOSYNTHESE SCHACHT	1071002528
TIBIA - SCHROEFOSTEOSYNTHESE - PROX-PLATEAUFRACTUUR	1071002541
TIBIA - SCHROEFOSTEOSYNTHESE TIBIA-PILON.	1071002647
ULNA - OPERATIEVE BEHANDELING SCHACHTFRACTUUR	1071002109
ULNA - PLAATOSTEOSYNTHESE INCL.MONTEGGIA	1071002107
ULNA - PLAATOSTEOSYNTHESE IVM OLECRANONFRACTUUR	1071002112
WERVELKOLOM - FRACT.BEH.LUMB.MET SPONDYL.EO.OSTEOSYN.POST	1071002319
WERVELKOLOM - INBRENGEN STACKABLE CAGE - CERVICAAL	1071002337
WERVELKOLOM - OPER.BEHAND.FRACTUUR MET INWENDIGE FIXATIE	1071002321
WERVELKOLOM - OPERAT.BIJSTELL.INTERN DISTRACTIESYST.	1071004219
WERVELKOLOM - OPERAT.PLAATSING INTERN DISTRACTIESYST.	1071004552
WERVELKOLOM - OPERATIEVE BEHANDELING WERVELFRACTUUR	1071002315
WERVELKOLOM - RESPONDYLODESE	1071002361
WERVELKOLOM - SPONDYLODESE CERV.ANT-KORT TRAJ-EO.INSTRUM.	1071002357
WERVELKOLOM - SPONDYLODESE CERV.POSTERIOR	1071002340
WERVELKOLOM - SPONDYLODESE CERV.POSTERIOR MET SCHROEVEN	1071002343
WERVELKOLOM - SPONDYLODESE CERV.POST-KORT TRAJ-EO.INSTRUM	1071002359
WERVELKOLOM - SPONDYLODESE CERVICAAL ANTERIOR	1071002344
WERVELKOLOM - SPONDYLODESE CERVICAAL ANTERIOR 1 SEGMENT	1071002347
WERVELKOLOM - SPONDYLODESE CRANIOCERVICAAL POSTERIOR	1071002341

WERVELKOLOM - SPONDYLODESE LUMB.ANT-KORT TRAJ-EO.INSTRUM.	1071004201
WERVELKOLOM - SPONDYLODESE LUMB.POST-KORT TRAJ-EO.INSTRUM	1071002355
WERVELKOLOM - SPONDYLODESE LUMBAAL POSTERIOR	1071002371
WERVELKOLOM - SPONDYLODESE LUMBAAL POSTERIOR OVV EXPEDIUM	1071004001
WERVELKOLOM - SPONDYLODESE THOR.POST-KORT TRAJ-EO.INSTRUM	1071002363
WERVELKOLOM - SPONDYLODESE THOR.POST-LANG TRAJ-EO.INSTRUM	1071002364
WERVELKOLOM - SPONDYLODESE THORACAAL POSTERIOR	1071002369
WERVELKOLOM - SPONDYLODESE THORACAAL POSTERIOR OVV EXPEDIUM	1071004002
WERVELKOLOM - SPONDYLODESE VAN DE DENS - ANTERIOR	1071002345
WERVELKOLOM - VERTEBRECTOMIE CERVICAAL MET SPONDYLODESE	1071002365
WERVELKOLOM - VERTEBRECTOMIE LUMBAAL MET SPONDYLODESE	1071002367
WERVELKOLOM - VERTEBRECTOMIE THORACAAL MET SPONDYLODESE	1071002366
WERVELKOLOM - VERTEBROPL.MET BALLON--KYPHOPLASTIEK-- LUMB	1071002312

Table J-1: Surgical procedures for class

Appendix K: Implemented Excel functions

Appendix K.1: Day of the week

```
=TEXT($C2; "dddd")
```

Appendix K.2: Procedure classification

```
=VLOOKUP($G2; 'Procedure classification'!$A$2:$C$1709; 3; FALSE)
```

Appendix K.3: Setup times

```
=IFERROR(IF(AND(C4=C3; B4=B3); D4-E3; "")*1440; "")
```

Appendix K.4: CDF

```
=GAMMA.DIST($I3; $F$20; $F$21; TRUE)
=WEIBULL.DIST($I3; $F$20; $F$21; TRUE)
=NORM.DIST($I3; $F$4; $F$8; TRUE)
=LOGNORM.DIST($I3; $F$4; $F$8; TRUE)
=EXPON.DIST($I3; 1/$F$4; TRUE)
```

Appendix K.5: Critical value

```
=CHISQ.INV.RT(0,05; COUNT($I$3:$I$19)-1)
```

Appendix K.6: Surgery class probability

```
=COUNTIF($J$2:$J$9814; "Class 1+")
=COUNTIF($J$2:$J$9814; "Class 1")
```

Appendix L: Original Excel file of historical data of 2019

location_nm	Room_nm	Operatiedatum	IN_OR_dttm	OUT_OR_dttm	Minutes_in_OR	primary_procedure_nm	primary_procedure_id	log_id
AMC KLINISCHE OK	AMCOK01	2019-01-02 00:00:00.000	2019-01-02 09:00:00.000	2019-01-02 12:01:00.000	181	FEMUR - INCISIE EN DRAINAGE BV OSTEOMYELITIS	1071002397	237713
AMC KLINISCHE OK	AMCOK01	2019-01-02 00:00:00.000	2019-01-02 12:26:05.000	2019-01-02 13:38:00.000	72	ONDERBEEN - AMPUTATIE	1071002607	354473
AMC KLINISCHE OK	AMCOK01	2019-01-02 00:00:00.000	2019-01-02 14:04:16.000	2019-01-02 16:26:00.000	142	ULNA - PLAATOSTEOSYNTHESE IVM OLECRANONFRACTUUR	1071002112	354441
AMC KLINISCHE OK	AMCOK02	2019-01-02 00:00:00.000	2019-01-02 08:59:04.000	2019-01-02 13:05:00.000	246	KNIE - VERLENGINGSPLASTIEK KNIEBUIGERS	1071002601	305520
AMC KLINISCHE OK	AMCOK02	2019-01-02 00:00:00.000	2019-01-02 13:35:19.000	2019-01-02 14:33:25.000	58	HUID - VACUUM WONDVERZEGELING	1071002869	354156
AMC KLINISCHE OK	AMCOK02	2019-01-02 00:00:00.000	2019-01-02 14:41:55.000	2019-01-02 15:52:00.000	71	LARYNX - DIAGNOSTISCHE LARYNGOSCOPIE - DIRECT OVV KIND	1071003651	354448
AMC KLINISCHE OK	AMCOK03	2019-01-02 00:00:00.000	2019-01-02 08:39:41.000	2019-01-02 14:20:34.000	341	HART - IMPLANTATIE AORTAKLEPPROTHESE	1071000749	353759
AMC KLINISCHE OK	AMCOK04	2019-01-02 00:00:00.000	2019-01-02 08:35:52.000	2019-01-02 14:20:00.000	345	HART - IMPLANTATIE AORTAKLEPPROTHESE	1071000749	352389
AMC KLINISCHE OK	AMCOK04	2019-01-02 00:00:00.000	2019-01-02 14:47:52.000	2019-01-02 17:32:00.000	165	MANDIBULA - OPEN REPOSITIE FRACTUUR MEERVOUDIG MET IMF	1071003230	354387
AMC KLINISCHE OK	AMCOK05	2019-01-02 00:00:00.000	2019-01-02 09:13:07.000	2019-01-02 11:15:00.000	122	KNIE-O.BEEN - LOKALE REVISIE OSTEOMYELITIS - GENTAKRALEN	1071002504	354378
AMC KLINISCHE OK	AMCOK05	2019-01-02 00:00:00.000	2019-01-02 13:28:52.000	2019-01-02 14:50:00.000	82	HUID - FULL-THICKNESS GRAFT- ALLE LOK.BEHALVE HAND	1071002891	353681
AMC KLINISCHE OK	AMCOK05	2019-01-02 00:00:00.000	2019-01-02 19:46:31.000	2019-01-02 21:10:00.000	84	LYMF.SYST. - EXCISIE LYMFEKLIER	1071001095	354559
AMC KLINISCHE OK	AMCOK06	2019-01-02 00:00:00.000	2019-01-02 09:01:59.000	2019-01-02 09:50:00.000	49	BUIK - HERNIA INGUINALIS ELECTIEF-LAPAROTOMIE-RE	1071001503	351365
AMC KLINISCHE OK	AMCOK06	2019-01-02 00:00:00.000	2019-01-02 10:02:53.000	2019-01-02 11:48:00.000	106	DIKKE DARM - OPHEFFEN STOMA	1071001348	342897
AMC KLINISCHE OK	AMCOK06	2019-01-02 00:00:00.000	2019-01-02 12:11:35.000	2019-01-02 14:46:00.000	155	THORAX - CORRECTIE KIPPENBORST	1071002300	264147
AMC KLINISCHE OK	AMCOK06	2019-01-02 00:00:00.000	2019-01-02 14:57:07.000	2019-01-02 17:18:00.000	141	ILEUM - OPHEFFEN STOMA OPEN PROCEDURE	1071001352	354433
AMC KLINISCHE OK	AMCOK07	2019-01-02 00:00:00.000	2019-01-02 08:34:00.000	2019-01-02 13:58:00.000	324	HERSENZENUW - IMPLANT.ELEKTRODE DBZ INTRACRAN.STIMULATOR	1071000157	147456
AMC KLINISCHE OK	AMCOK07	2019-01-02 00:00:00.000	2019-01-02 14:00:00.000	2019-01-02 17:16:00.000	196	HERSENEN - INBRENGEN RESERVOIR VENTRIKEL	1071000034	353391
AMC KLINISCHE OK	AMCOK08	2019-01-02 00:00:00.000	2019-01-02 13:30:00.000	2019-01-02 17:04:00.000	214	HART - VERVANGEN ICD DRAAD-EPICARD.MBV VATS	1071004731	354169
AMC KLINISCHE OK	AMCOK09	2019-01-02 00:00:00.000	2019-01-02 08:45:24.000	2019-01-02 10:42:00.000	117	KAAK - CONDYLECTOMIE - ENKELZIJDIG	1071003244	313445
AMC KLINISCHE OK	AMCOK09	2019-01-02 00:00:00.000	2019-01-02 10:56:10.000	2019-01-02 15:27:00.000	271	MAXILLA - OSTEOTOMIE - LE FORT I	1071003207	318668
AMC KLINISCHE OK	AMCOK09	2019-01-02 00:00:00.000	2019-01-02 15:57:13.000	2019-01-02 17:47:00.000	110	MANDIBULA - OPER.BEHAND.ENKELVOUDIGE MANDIBULA FRACTUUR	1071003224	354566
AMC KLINISCHE OK	AMCOK12	2019-01-02 00:00:00.000	2019-01-02 14:59:26.000	2019-01-02 18:25:25.000	206	HERSENEN - EVAC.INTRACEREBR.HEMAT.SUPRATENT.CRANIOTOM.	1071000051	354605
AMC KLINISCHE OK	AMCOK14	2019-01-02 00:00:00.000	2019-01-02 11:38:10.000	2019-01-02 13:06:00.000	88	SECTIO CAESAREA	1071001959	354482
AMC KLINISCHE OK	AMCOK17	2019-01-02 00:00:00.000	2019-01-02 08:56:14.000	2019-01-02 13:33:00.000	277	PANCREAS - RESECTIE CAUDAAL - PARTIEEL OPEN PROCEDURE	1071001444	349424
AMC KLINISCHE OK	AMCOK17	2019-01-02 00:00:00.000	2019-01-02 13:52:00.000	2019-01-02 16:05:00.000	133	GALBLAAS-CHOLECYSTECTOMIE - ROBOT ASSIST	1071004781	345661
AMC KLINISCHE OK	AMCOK18	2019-01-02 00:00:00.000	2019-01-02 08:53:39.000	2019-01-02 10:17:00.000	84	SECTIO CAESAREA	1071001959	325000
AMC KLINISCHE OK	AMCOK18	2019-01-02 00:00:00.000	2019-01-02 10:27:48.000	2019-01-02 11:17:00.000	50	UTERUS - HYSTEROSCOPIE	1071003008	332231
AMC KLINISCHE OK	AMCOK18	2019-01-02 00:00:00.000	2019-01-02 11:33:19.000	2019-01-02 16:16:00.000	283	BUIK - PROEFLAPAROTOMIE	1071001460	349380
AMC KLINISCHE OK	AMCOK20	2019-01-02 00:00:00.000	2019-01-02 08:45:15.000	2019-01-02 12:45:00.000	240	DIKKE DARM - PROCTOCOLECT.MET ILEO-ANALE ANAST. J-POUCH	1071001304	325803
AMC KLINISCHE OK	AMCOK20	2019-01-02 00:00:00.000	2019-01-02 12:58:10.000	2019-01-02 17:33:00.000	275	DIKKE DARM - PROCTOCOLECTOMIE VIA LAPAROSCOPIE	1071003710	338913
AMC KLINISCHE OK	AMCOK01	2019-01-03 00:00:00.000	2019-01-03 08:00:00.000	2019-01-03 10:53:46.000	173	FIBULA - OSTEOTOMIE	1071002514	347466
AMC KLINISCHE OK	AMCOK01	2019-01-03 00:00:00.000	2019-01-03 11:06:26.000	2019-01-03 16:33:53.000	327	TIBIA - PLAATOSTEOSYNTHESE TIBIA-PILON.	1071002646	353097
AMC KLINISCHE OK	AMCOK02	2019-01-03 00:00:00.000	2019-01-03 08:21:22.000	2019-01-03 16:53:00.000	512	WERVELKOLOM - SCHEDELTRACTIE AANBRENGEN OA. HALO	1071002384	261510
AMC KLINISCHE OK	AMCOK03	2019-01-03 00:00:00.000	2019-01-03 08:00:00.000	2019-01-03 13:18:00.000	318	AORTOCORONAIRE BYPASS MET 1 ARTERIËLE GRAFT, INCLUSIEF EVENTUELE VE	1071003927	353753
AMC KLINISCHE OK	AMCOK04	2019-01-03 00:00:00.000	2019-01-03 09:51:13.000	2019-01-03 12:57:00.000	186	DIKKE DARM - RESECTIE SIGMOID ZONDER PRIMAIRE ANASTOMOSE OPEN PR	1071001316	354358
AMC KLINISCHE OK	AMCOK04	2019-01-03 00:00:00.000	2019-01-03 14:04:35.000	2019-01-03 16:00:00.000	116	DIKKE DARM - RESECTIE ILEOCAECAAL MET PRIM.ANASTOMOSE OPEN PROCE	1071001331	317055
AMC KLINISCHE OK	AMCOK05	2019-01-03 00:00:00.000	2019-01-03 10:18:42.000	2019-01-03 10:48:00.000	30	HUID - INC.-DRAIN.ABCES-FISTEL ROMP-LIES-BIL-PERIN	1071002805	354603

Appendix M: Data elective procedures 2019

location_nm	Room_nm	Operatiedatum	IN_OR_time	OUT_OR_time	Minutes_in_OR	primary_procedure_nm	primary_procedure_id	log_id	Class	Day
AMC KLINISCHE OK	AMCOK01	02/01/2019	09:00:00	12:01:00	181	FEMUR - INCISIE EN DRAINAGE BV OSTEOMYELITIS	1071002397	237713	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK01	02/01/2019	12:26:05	13:38:00	72	ONDERBEEN - AMPUTATIE	1071002607	354473	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK01	02/01/2019	14:04:16	16:26:00	142	ULNA - PLAATOSTEOSYNTHESE IVM OLECRANONFRACTUUR	1071002112	354441	Class 1+	Wednesday
AMC KLINISCHE OK	AMCOK02	02/01/2019	08:59:04	13:05:00	246	KNIE - VERLENGINGSPLASTIEK KNIEBUIGERS	1071002601	305520	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK02	02/01/2019	13:35:19	14:33:25	58	HUID - VACUUM WONDVERZEGELING	1071002869	354156	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK02	02/01/2019	14:41:55	15:52:00	71	LARYNX - DIAGNOSTISCHE LARYNGOSCOPIE - DIRECT OVV KIND	1071003651	354448	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK03	02/01/2019	08:39:41	14:20:34	341	HART - IMPLANTATIE AORTAKLEPPROTHESE	1071000749	353759	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK04	02/01/2019	08:35:52	14:20:00	345	HART - IMPLANTATIE AORTAKLEPPROTHESE	1071000749	352389	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK04	02/01/2019	14:47:52	17:32:00	165	MANDIBULA - OPEN REPOSITIE FRACTUUR MEERVOUDIG MET IMF	1071003230	354387	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK05	02/01/2019	09:13:07	11:15:00	122	KNIE-O.BEEN - LOKALE REVISIE OSTEOMYELITIS - GENTAKRALEN	1071002504	354378	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK05	02/01/2019	13:28:52	14:50:00	82	HUID - FULL-THICKNESS GRAFT- ALLE LOK.BEHALVE HAND	1071002891	353681	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK05	02/01/2019	19:46:31	21:10:00	84	LYMF.SYST. - EXCISIE LYMFEKLIER	1071001095	354559	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK06	02/01/2019	09:01:59	09:50:00	49	BUIK - HERNIA INGUINALIS ELECTIEF-LAPAROTOMIE-RE	1071001503	351365	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK06	02/01/2019	10:02:53	11:48:00	106	DIKKE DARM - OPHEFFEN STOMA	1071001348	342897	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK06	02/01/2019	12:11:35	14:46:00	155	THORAX - CORRECTIE KIPPENBORST	1071002300	264147	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK06	02/01/2019	14:57:07	17:18:00	141	ILEUM - OPHEFFEN STOMA OPEN PROCEDURE	1071001352	354433	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK07	02/01/2019	08:34:00	13:58:00	324	HERSENZENUW - IMPLANT.ELEKTRODE DBZ INTRACRAN.STIMULATOR	1071000157	147456	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK07	02/01/2019	14:00:00	17:16:00	196	HERSENEN - INBRENGEN RESERVOIR VENTRIKEL	1071000034	353391	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK08	02/01/2019	13:30:00	17:04:00	214	HART - VERVANGEN ICD DRAAD-EPICARD.MBV VATS	1071004731	354169	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK09	02/01/2019	08:45:24	10:42:00	117	KAAK - CONDYLECTOMIE - ENKELZIJDIG	1071003244	313445	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK09	02/01/2019	10:56:10	15:27:00	271	MAXILLA - OSTEOTOMIE - LE FORT I	1071003207	318668	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK09	02/01/2019	15:57:13	17:47:00	110	MANDIBULA - OPER.BEHAND.ENKELVOUDIGE MANDIBULA FRACTUUR	1071003224	354566	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK12	02/01/2019	14:59:26	18:25:25	206	HERSENEN - EVAC.INTRACEREBR.HEMAT.SUPRATENT.CRANIOTOM.	1071000051	354605	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK14	02/01/2019	11:38:10	13:06:00	88	SECTIO CAESAREA	1071001959	354482	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK17	02/01/2019	08:56:14	13:33:00	277	PANCREAS - RESECTIE CAUDAAL - PARTIEEL OPEN PROCEDURE	1071001444	349424	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK17	02/01/2019	13:52:00	16:05:00	133	GALBLAAS-CHOLECYSTECTOMIE - ROBOT ASSIST	1071004781	345661	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK18	02/01/2019	08:53:39	10:17:00	84	SECTIO CAESAREA	1071001959	325000	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK18	02/01/2019	10:27:48	11:17:00	50	UTERUS - HYSTEROSCOPIE	1071003008	332231	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK18	02/01/2019	11:33:19	16:16:00	283	BUIK - PROEFLAPAROTOMIE	1071001460	349380	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK20	02/01/2019	08:45:15	12:45:00	240	DIKKE DARM - PROCTOCOLECT.MET ILEO-ANALE ANAST. J-POUCH	1071001304	325803	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK20	02/01/2019	12:58:10	17:33:00	275	DIKKE DARM - PROCTOCOLECTOMIE VIA LAPAROSCOPIE	1071003710	338913	Class 1	Wednesday
AMC KLINISCHE OK	AMCOK01	03/01/2019	08:00:00	10:53:46	173	FIBULA - OSTEOTOMIE	1071002514	347466	Class 1	Thursday
AMC KLINISCHE OK	AMCOK01	03/01/2019	11:06:26	16:33:53	327	TIBIA - PLAATOSTEOSYNTHESE TIBIA-PILON.	1071002646	353097	Class 1	Thursday
AMC KLINISCHE OK	AMCOK02	03/01/2019	08:21:22	16:53:00	512	WERVELKOLOM - SCHEDELTRACTIE AANBRENGEN OA. HALO	1071002384	261510	Class 1	Thursday
AMC KLINISCHE OK	AMCOK03	03/01/2019	08:00:00	13:18:00	318	AORTOCORONAIRE BYPASS MET 1 ARTERIËLE GRAFT, INCLUSIEF EVENTUE	1071003927	353753	Class 1	Thursday
AMC KLINISCHE OK	AMCOK04	03/01/2019	09:51:13	12:57:00	186	DIKKE DARM - RESECTIE SIGMOID ZONDER PRIMAIRE ANASTOMOSE OPEN	1071001316	354358	Class 1	Thursday
AMC KLINISCHE OK	AMCOK04	03/01/2019	14:04:35	16:00:00	116	DIKKE DARM - RESECTIE ILEOCAECAAL MET PRIM.ANASTOMOSE OPEN PRC	1071001331	317055	Class 1	Thursday
AMC KLINISCHE OK	AMCOK05	03/01/2019	10:18:42	10:48:00	30	HUID - INC.-DRAIN.ABCES-FISTEL ROMP-LIES-BIL-PERIN	1071002805	354603	Class 1	Thursday
AMC KLINISCHE OK	AMCOK05	03/01/2019	13:25:54	14:55:00	90	VOET - AMPUTATIE OF EXARTICULATIE TEEN	1071002702	354688	Class 1	Thursday
AMC KLINISCHE OK	AMCOK07	03/01/2019	08:03:33	12:17:00	254	HERSENZENUW - IMPLANT.ELEKTRODE DBZ INTRACRAN.STIMULATOR	1071000157	317678	Class 1	Thursday
AMC KLINISCHE OK	AMCOK07	03/01/2019	12:32:00	16:25:40	233	HERSENEN - SUBC.PLAATSEN TWEEZIJD.PULSGEN.VAN DBS N.STIM.	1071000086	323566	Class 1	Thursday
AMC KLINISCHE OK	AMCOK10	03/01/2019	08:05:31	12:15:00	250	OOR - PRE-COCHLEAIRE IMPLANTATEN - VOLWASSENEN	1071000519	328747	Class 1	Thursday
AMC KLINISCHE OK	AMCOK10	03/01/2019	12:36:16	19:28:00	412	OOR - PRE-COCHLEAIRE IMPLANTATEN - VOLWASSENEN	1071000519	331906	Class 1	Thursday
AMC KLINISCHE OK	AMCOK11	03/01/2019	08:05:00	11:59:41	234	OOR - RAD.OP.TYMPANOPL.M.PART.OBLIT.MASTOIDHOLTE	1071000515	292840	Class 1	Thursday
AMC KLINISCHE OK	AMCOK11	03/01/2019	12:15:53	14:56:00	161	OOR - VERW.EXOSTOSEN MET LOSPREPAREREN GEHOORGANG	1071000470	281702	Class 1	Thursday
AMC KLINISCHE OK	AMCOK11	03/01/2019	15:20:00	16:52:00	92	OOR - MYRINGOPLASTIEK ENDAURAAL	1071000508	291848	Class 1	Thursday
AMC KLINISCHE OK	AMCOK12	03/01/2019	08:04:58	22:58:00	894	SCHEDEL - EXCISIE TUMOR SCHEDELBASIS MEDIAAL	1071000089	352504	Class 1	Thursday
AMC KLINISCHE OK	AMCOK14	03/01/2019	08:22:50	09:27:00	65	SECTIO CAESAREA	1071001959	354696	Class 1	Thursday

Table L-1: Data elective procedures 2019

Appendix N: Implemented Excel Visual Basic code

Appendix N.1: Generating processing times class 1+

```
Sub GenerateDataPrTime1plus()
Dim i, j, NrOfJobs As Integer
Dim Random, duration, BinLB, BinUB, CPrLB, CPrUB, FirstPr As Double

NrOfJobs = 684 'Same as number of observations in real distribution
FirstPr = Worksheets("Class 1+ PT Emp. distr.").Cells(2, 5) 'Set _
probability of first bin

For j = 1 To NrOfJobs 'Loop generating jobs
Random = Rnd() 'Generate random number between 0 and 1 to determine _
the bin
duration = 0 'Initialize duration
    For i = 1 To 16 'Set corresponding bin and probability values
    CPrLB = Worksheets("Class 1+ PT Emp. distr.").Cells(1 + i, 5)
    CPrUB = Worksheets("Class 1+ PT Emp. distr.").Cells(2 + i, 5)
    BinLB = Worksheets("Class 1+ PT Emp. distr.").Cells(2 + i, 1)
    BinUB = Worksheets("Class 1+ PT Emp. distr.").Cells(2 + i, 3)
    |
        If Random <= FirstPr Then 'Assign duration value of the _
        first bin with corresponding duration
            duration = 40
            Exit For 'Duration assigned to job, so exit for loop
        ElseIf Random > CPrLB And Random <= CPrUB Then 'Assign _
        duration according to corresponding bin
            duration = WorksheetFunction.RandBetween(BinLB, BinUB)
            Exit For 'Duration assigned to job, so exit for loop
        End If
    Next i

Worksheets("Class 1+ PT Emp. distr.").Cells(1 + j, 8) = duration
'Print duration to excel sheet

Next j
End Sub
```

Figure N-1: Excel VBA generating processing times class 1+

<u>Appendix N.2: Generating jobs MC simulation</u>

```
Sub GenerateJobs()
Dim Random, Class1rndpt, Class1plusrndpt, Class1rndst, Class1plusrndst, _
duration, setup As Double
Dim i, j As Integer
Dim class As String

For i = 1 To 171 'Generate 171 jobs (this was the average number of elective jobs _
in one working week in 2019
    duration = 0 'Initialize
    setup = 0 'Initialize
    Random = Rnd() 'Generate random number between 0 and 1
    Class1rndpt = WorksheetFunction.RandBetween(1, 8217) 'Processing time of job _
    is determined by selecting a random duration from the empirical distributions
    Class1plusrndpt = WorksheetFunction.RandBetween(1, 684)
    Class1rndst = WorksheetFunction.RandBetween(1, 4398) 'Setup time of job _
    is determined by selecting a random duration from the empirical distributions
    Class1plusrndst = WorksheetFunction.RandBetween(1, 365)

    'determine class
    If Random <= 0.9232 Then 'Class 1
        duration = Worksheets("Class 1 PT Emp. distr.").Cells(Class1rndpt + 1, 8)
        'Extract random processing time from Class 1 PT Emp. distr. sheet
        setup = Worksheets("Class 1 ST Emp. distr.").Cells(Class1rndst + 1, 8)
        'Extract random setup time from Class 1 ST Emp. distr. sheet
        class = "Class 1"
    Else 'class 1+
        duration = Worksheets("Class 1+ PT Emp. distr.").Cells(Class1plusrndpt + 1, 8)
        'Extract random processing time from Class 1+ PT Emp. distr. sheet
        setup = Worksheets("Class 1+ ST Emp. distr.").Cells(Class1plusrndst + 1, 8)
        'Extract random setup time from Class 1+ PT Emp. distr. sheet
        class = "Class 1+"
    End If

    Worksheets("MC sim").Cells(i + 8, 2) = class 'print class
    Worksheets("MC sim").Cells(i + 8, 3) = duration 'print processing time
    Worksheets("MC sim").Cells(i + 8, 4) = setup 'print setup time

Next i

Worksheets("MC sim").Range("A8:E197").Sort Key1:=[B1], Order1:=xlDescending, Key2:=[C1], _
Order2:=xlDescending, Header:=xlYes 'First sort table by class and then by processing time

For i = 1 To 171
    Worksheets("MC sim").Cells(i + 8, 1) = i 'Assign job number to each job
Next i

End Sub
```

Figure N-2: Excel VBA generating jobs

Appendix N.3: Scheduling jobs MC simulation

```
Sub ScheduleJobs()
Dim i, j, k, Minimumk, Class1plusORs, TotalORs As Integer
Dim ComplTime(), ComplTime1() As Double

Class1plusORs = Worksheets("MC sim").Cells(11, 8).Value 'Input variable
TotalORs = Worksheets("MC sim").Cells(13, 8).Value 'Input variable

ReDim ComplTime(1 To 5, 1 To TotalORs), ComplTime1(1 To 5, 1 To TotalORs) As Double
'Define size of the multidimensional array according to the input parameters

For i = 1 To 5
    For k = 1 To TotalORs
        ComplTime(i, k) = 0 'Initialize arrays
    Next k
Next i

Worksheets("MC sim").Range("K9:Q200").ClearContents 'Remove previous results

'LEPT
j = 1 'Initialize days
Minimumk = 1 'Initialize OR with min completion time

For i = 1 To 171 'Loop over jobs
    If Worksheets("MC sim").Cells(i + 8, 2) = "Class 1+" Then 'Assign class 1+ surgeries
        For k = 1 To Class1plusORs
            If ComplTime(j, k) + Worksheets("MC sim").Cells(i + 8, 3) + _
            Worksheets("MC sim").Cells(i + 8, 4) < ComplTime(j, Minimumk) + _
            Worksheets("MC sim").Cells(i + 8, 3) + Worksheets("MC sim").Cells(i + 8, 4) _
            Then 'Find OR to assign job
                Minimumk = k
            End If
        Next k

        If ComplTime(j, Minimumk) + Worksheets("MC sim").Cells(i + 8, 4) <= 570 Then
        'Assign job to this day
            ComplTime(j, Minimumk) = ComplTime(j, Minimumk) + _
            Worksheets("MC sim").Cells(i + 8, 3) + Worksheets("MC sim").Cells(i + 8, 4)
        Else 'Assign job to OR 1 next day
            j = j + 1 'Add one day
            ComplTime(j, 1) = ComplTime(j, 1) + Worksheets("MC sim").Cells(i + 8, 3) + _
            Worksheets("MC sim").Cells(i + 8, 4)
        End If
    End If
    Next i

j = 1 'Initialize days
Minimumk = Class1plusORs + 1 'Initialize OR with min completion time

For i = 1 To 171 'Loop over jobs
If Worksheets("MC sim").Cells(i + 8, 2) = "Class 1" Then 'Assign class 1 surgeries
    For k = 1 To TotalORs
            If ComplTime(j, k) + Worksheets("MC sim").Cells(i + 8, 3) + _
            Worksheets("MC sim").Cells(i + 8, 4) < ComplTime(j, Minimumk) + _
            Worksheets("MC sim").Cells(i + 8, 3) + Worksheets("MC sim").Cells(i + 8, 4) _
            Then 'Find OR to assign job
                Minimumk = k
            End If
    Next k

    If ComplTime(j, Minimumk) + Worksheets("MC sim").Cells(i + 8, 4) <= 570 Then
    'Assign surgery to this day
        ComplTime(j, Minimumk) = ComplTime(j, Minimumk) + _
        Worksheets("MC sim").Cells(i + 8, 3) + Worksheets("MC sim").Cells(i + 8, 4)
    Else 'assign job to first class 1 OR next day
        j = j + 1
        ComplTime(j, Class1plusORs + 1) = ComplTime(j, Class1plusORs + 1) + _
        Worksheets("MC sim").Cells(i + 8, 3) + Worksheets("MC sim").Cells(i + 8, 4)
    End If
End If
Next i

'Print results
j = 1
For i = 1 To 5
    For k = 1 To TotalORs
        Worksheets("MC sim").Cells(j + 8, 11) = i
        Worksheets("MC sim").Cells(j + 8, 12) = k
        Worksheets("MC sim").Cells(j + 8, 13) = ComplTime(i, k)
        j = j + 1
    Next k
Next i
```

```
'LEPST
j = 1 'Initialize days
Minimumk = 1 'Initialize OR with min completion time

Worksheets("MC sim").Range("A8:E197").Sort Key1:=[B1], Order1:=xlDescending, Key2:=[E1], _
Order2:=xlDescending, Header:=xlYes 'First sort by class, then descending by LEPST value

For i = 1 To 171 'Loop over jobs
    If Worksheets("MC sim").Cells(i + 8, 2) = "Class 1+" Then 'Assign class 1+ surgeries
        For k = 1 To Class1plusORs
            If ComplTime1(j, k) + Worksheets("MC sim").Cells(i + 8, 3) + _
            Worksheets("MC sim").Cells(i + 8, 4) < ComplTime1(j, Minimumk) + _
            Worksheets("MC sim").Cells(i + 8, 3) + Worksheets("MC sim").Cells(i + 8, 4) _
            Then 'Find OR to assign job
                Minimumk = k
            End If
        Next k

       If ComplTime1(j, Minimumk) + Worksheets("MC sim").Cells(i + 8, 4) <= 570 Then
       'Assign job to this day
            ComplTime1(j, Minimumk) = ComplTime1(j, Minimumk) + _
            Worksheets("MC sim").Cells(i + 8, 3) + Worksheets("MC sim").Cells(i + 8, 4)
        Else 'Assign job to OR 1 next day
            j = j + 1 'Add one day
            ComplTime1(j, 1) = ComplTime1(j, 1) + Worksheets("MC sim").Cells(i + 8, 3) + _
            Worksheets("MC sim").Cells(i + 8, 4)
        End If
    End If
    Next i

j = 1 'Initialize days
Minimumk = Class1plusORs + 1 'Initialize OR with min completion time

For i = 1 To 171 'Loop over jobs
If Worksheets("MC sim").Cells(i + 8, 2) = "Class 1" Then 'Assign class 1 surgeries
    For k = 1 To TotalORs
            If ComplTime1(j, k) + Worksheets("MC sim").Cells(i + 8, 3) + _
            Worksheets("MC sim").Cells(i + 8, 4) < ComplTime1(j, Minimumk) + _
            Worksheets("MC sim").Cells(i + 8, 3) + Worksheets("MC sim").Cells(i + 8, 4) _
            Then 'Find OR to assign job
                Minimumk = k
            End If
    Next k

    If ComplTime1(j, Minimumk) + Worksheets("MC sim").Cells(i + 8, 4) <= 570 Then
    'Assign surgery to this day
        ComplTime1(j, Minimumk) = ComplTime1(j, Minimumk) + _
        Worksheets("MC sim").Cells(i + 8, 3) + Worksheets("MC sim").Cells(i + 8, 4)
    Else 'assign job to first class 1 OR next day
        j = j + 1
        ComplTime1(j, Class1plusORs + 1) = ComplTime1(j, Class1plusORs + 1) + _
        Worksheets("MC sim").Cells(i + 8, 3) + Worksheets("MC sim").Cells(i + 8, 4)
    End If
End If
Next i

'Print results
j = 1
For i = 1 To 5
    For k = 1 To TotalORs
        Worksheets("MC sim").Cells(j + 8, 15) = i
        Worksheets("MC sim").Cells(j + 8, 16) = k
        Worksheets("MC sim").Cells(j + 8, 17) = ComplTime1(i, k)
        j = j + 1
    Next k
Next i

Worksheets("MC sim").Range("A8:E197").Sort Key1:=[B1], Order1:=xlDescending, _
Key2:=[C1], Order2:=xlDescending, Header:=xlYes
'First sort by class, then descending by processing time

End Sub
```

Figure N-3: Excel VBA scheduling jobs

Appendix N.4: Iteration

```
Sub Iterate()
Dim iteration(), Iteration1(), Total(), Total1(), Average(), Average1(), TotalAvg, _
TotalAvg1  As Variant
Dim NrOfIterations, i, j As Integer

NrOfIterations = Worksheets("MC sim").Cells(10, 8)
'Use input of the dashboard for the number of iterations

ReDim iteration(1 To NrOfIterations, 1 To 5), Iteration1(1 To NrOfIterations, 1 To 5) _
, Total(1 To NrOfIterations), Total1(1 To NrOfIterations), _
Average(1 To NrOfIterations), Average1(1 To NrOfIterations) As Variant
'Every iteration results in an average maximum completion time

For i = 1 To NrOfIterations 'Iterate using for loop
    Call GenerateJobs 'Generate jobs using GenerateJobs sub
    Call ScheduleJobs 'Schedule jobs using ScheduleJobs sub
    For j = 1 To 5 'Loop over days
        iteration(i, j) = _
        Application.WorksheetFunction.MaxIfs(Worksheets("MC sim").Range("M9:M148"), _
        Worksheets("MC sim").Range("K9:K148"), j)
        'Take the maximum completion time of the corresponding day of LEPT
        Total(i) = Total(i) + iteration(i, j)

        Iteration1(i, j) = _
        Application.WorksheetFunction.MaxIfs(Worksheets("MC sim").Range("Q9:Q148"), _
        Worksheets("MC sim").Range("O9:O148"), j)
        'Take the maximum completion time of the corresponding day of LEPST
        Total1(i) = Total1(i) + Iteration1(i, j)
    Next j
    Average(i) = Total(i) / 5 'Calculate average of every iteration for LEPT
    Average1(i) = Total1(i) / 5 'Calculate average of every iteration for LEPST
Next i

For i = 1 To NrOfIterations
    TotalAvg = TotalAvg + Average(i) 'Add averages of every iteration
    TotalAvg1 = TotalAvg1 + Average1(i) 'Add averages of every iteration
Next i

Worksheets("MC sim").Cells(19, 8) = TotalAvg / NrOfIterations
'Calculate and print resulting average over all iterations for LEPT
Worksheets("MC sim").Cells(21, 8) = TotalAvg1 / NrOfIterations
'Calculate and print resulting average over all iterations for LEPST

End Sub
```

Figure N-4: Excel VBA iteration