TÉCNICO LISBOA

Multicriteria sorting methodology to support the maintenance management of medical equipment: The case of Hospital da Luz Lisboa

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“Nothing in life is to be feared, it is only to be understood.
Now is the time to understand more, so that we may fear less.”

Marie Curie

Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

Preface

The work presented in this thesis was performed at the company Luz Saúde (Lisbon, Portugal), during the period February-October 2020, under the supervision of Eng. Marta Meneses. The thesis was co-supervised at Instituto Superior Técnico by Prof. José Rui Figueira and Prof. Ana Sara Costa and within the frame of the hSNS FCT - Research Project (PTDC/EGEOGE/30546/2017): Portuguese public hospital performance assessment using a multicriteria decision analysis framework.

Acknowledgments

With this dissertation marking the conclusion of my academic journey, I fall short of words to express the gratitude for the participation and assistance of so many people along the way, whose names may not all be enumerated.

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To my supervisor from *Hospital da Luz Lisboa*, Marta Meneses and to Joana Manso, I am grateful that you took interest in a project I had envisioned and always showed availability to help mold it to meet the hospital's needs. In addition, the opportunity of accompanying you and witnessing the daily reality of the maintenance operations in such a dynamic hospital gave me insights that were crucial to the development of this dissertation.

As I look back at my academic path, I have come to realize how little I would have been able to accomplish had I not been surrounded by incredible individuals. I want to acknowledge my fellow Son Goku's, it has been a great pleasure to share this journey with you. My lifelong friends, for the unconditional support. All the friendships created in Técnico Lisboa, for making these five years the best of my life. A special thank you to seven incredible girls: Margarida, Leo, Mila, Mada, Rosa, Carlota and Sofia, you were my good luck charm.

Last but not least, my family, my permanent backbone and my primary source of inspiration in every step of this journey. To my sister Joana, for the 23 years of being my role model and for always living up to the high expectations. To my father, for being the reason I knew I wanted to become an engineer and to my mother, my number one fan, for living the wins and fails in my life as if they were her own. No words seem adequate enough to show you how thankful I am.

Resumo

Os equipamentos médicos são caracterizados por um fluxo constante de inovações, que está a revolucionar a prestação de cuidados em saúde. Isto leva à necessidade por parte das organizações de incorporarem metodologias de apoio à gestão dos mesmos. Assim, a criação de ferramentas de apoio à manutenção destes equipamentos pode ser considerada uma oportunidade. Neste contexto, a *Luz Saúde*, que lidera um dos maiores grupos de prestação de cuidados em Portugal, pretende complementar o programa de manutenção no maior hospital da sua rede, o *Hospital da Luz Lisboa*. Atualmente, neste hospital, o alerta dos equipamentos com necessidade de intervenção ao nível da manutenção é efetuado sem o auxílio de métodos de apoio à decisão. Isto pode levar a decisões tomadas quando surgem complicações técnicas, não havendo modo de as prever e antecipar.

Perante este desafio, é aplicada uma metodologia de classificação multicritério, utilizando o método ELECTRE TRI-NC, num grupo de equipamentos considerados críticos para o hospital, os ventiladores. A metodologia envolve uma recolha e processamento de dados e, a partir das interações com decisores, a definição dos elementos para o modelo. A partir daí, é possível a execução do mesmo e os ventiladores são classificados segundo uma de cinco categorias. No final, concluímos que a maioria dos ventiladores se encontravam em condições de manutenção adequadas ou boas, o que se mostrou consistente com as expectativas dos decisores. Uma análise dos resultados evidenciou a robustez do modelo e validou a sua utilidade na avaliação dos ventiladores do *Hospital da Luz Lisboa*.

Palavras-chave: Manutenção de equipamentos médicos, Ventiladores, ELECTRE TRI-NC, Classificação, Apoio à decisão multicritério

Abstract

Medical equipment are characterized by a constant flow of innovations, which is transforming the delivery of healthcare. This creates the need for healthcare organizations to incorporate methodologies to support the maintenance management of these equipment. In this scope, tools that aid the maintenance process of medical equipment can be considered quite relevant. Within this context, *Luz Saúde*, the holding company of one of the largest healthcare groups in Portugal, intends to complement the medical equipment maintenance management program of the biggest hospital in its network, *Hospital da Luz Lisboa*. Currently, in this hospital, the maintenance condition is assessed in the absence of a decision support method. This fact can lead to a response only when technical complications arise, with no way to predict or anticipate them.

To address this challenge, a multicriteria sorting methodology, utilizing the ELECTRE TRI-NC method, is applied to critical medical equipment for the hospital, medical ventilators. The proposed methodology entails data collection and processing procedures and, from interactions with decision makers, the required elements for the model construction are defined. From there, the model is executed and each medical ventilator is classified into one of five categories. In the end, the model identified the majority of the medical ventilators in the analysis to be in adequate or good maintenance conditions, which was consistent with the decision makers' expectations. A detailed analysis of the results evidenced the robustness of the model and validated its utility in the assessment of the medical ventilators in *Hospital da Luz Lisboa*.

Keywords: Medical Equipment Maintenance, Medical Ventilators, ELECTRE TRI-NC, Classification, Multicriteria Decision Aiding

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Nomenclature

Greek symbols

λ	Minimum credibility level.
ρ	Selecting function.
σ	Credibility index.

Subscripts

a	Action.
B	Reference actions.
b	Subset of reference actions.
C	Category.
c	Concordance index.
d	Partial discordance index.
F	Family of criteria.
g	Criterion.
p	Preference threshold.
q	Indifference threshold.
v	Veto threshold.
w	Weight.

Acronyms

BiPAP Bi-level Positive Airway Pressure

CMMS Computerized Maintenance Management System

CMVM Securities Market Regulator (Comissão do Mercado de Valores Mobiliários, in portuguese)

CT Computerized Tomography

CPAP Constant Positive Airway Pressure

DA Decision Aiding

DIME Infrastructure, Maintenance and Equipment's Department (Direção de Infraestruturas, Manutenção e Equipamentos, in portuguese)

DM Decision Makers

EHR Eletronic Health Record

ERPS Equipment Replacement Planning System

FPV Fundamental Point of View

ICU Intensive Care Unit

JCI Joint Commision International

MCDA Multicriteria Decision Aiding

MERS Medical Equipment Replacement Score

MRI Magnetic Resonance Imaging

ND Not defined

NIV Non-Invasive Ventilation

PEEP Positive end-expiratory pressure

RR Respiratory Rate

WHO World Health Organization

Chapter 1

Introduction

In Chapter 1, a summary of the content and structure of the dissertation is presented. In this regard, the motivation behind the study is delineated and the problem at hand is exposed. Moreover, this dissertation aims to achieve are defined, as well as the methodology that is utilized in the process. Lastly, an outline of the present document is provided.

1.1 Motivation

Over the last decades, one of the greatest human accomplishments has been the remarkable increase in life expectancy. In Portugal, the average person born in 1970 was expected to live approximately 67 years old, whereas in 2018, the life expectancy at birth was about 81 years old (PORDATA, Base de Dados de Portugal Contemporâneo, 2020). In line with this reality, Lichtenberg (2017) attributed a significant part of the notable improvement in this health outcome to biomedical research and innovation.

Certainly, when it comes to health outcomes in general, the impact of technological progress cannot be overstated, as medical advances have allowed for an improved provision of care, enhanced assessment and monitoring of patients, higher access to information and even the reduction of the cost of treatments, among many other benefits (Funk, 2011).

Regarding health technologies, in particular medical devices, the World Health Organization (2007) has emphasized that these are essential to equip healthcare providers with the indispensable tools for the achievement of health-related development goals, though recognizing the economic and technical challenges these represent for health systems. Accordingly, in 2007, the World Health Organization (WHO) adopted the resolution *WHA60.29*, in which it is stated the urge for expansion of expertise in the field of health technologies and establishment of systems for the "assessment, planning, procurement and management of health technologies, in particular medical devices" (World Health Organization, 2007).

The fact is, in recent years, innovations in medical equipment have disrupted the health sector. Furthermore, the enormous impact that the *COVID-19* pandemic has had on health systems around the globe and the consequences it will have for many years to come have to be taken into consider-

ation. For this reason, it has become progressively more important to focus on the implementation of methodologies that support the management of medical equipment in healthcare settings, thus optimizing healthcare delivery and engaging in a more efficient life cycle planning of these devices.

It is in this context that the holding company of one of the major players concerning private healthcare corporations in Portugal, *Luz Saúde*, intends to complement its medical equipment maintenance management program, in particular, the assessment of equipment functionality. Consequently, the present dissertation is developed, introducing a method for the classification of the maintenance condition of medical ventilators in *Hospital da Luz Lisboa*, the biggest hospital in the *Hospital da Luz* network. It is important to note that medical ventilators are not only a critical group of medical equipment for the hospital in question, but also essential devices in the fight against *COVID-19*.

The introduction of a sorting method is made resorting to a Multicriteria Decision Aiding (MCDA) approach, ELECTRE TRI-NC, which has a non-compensatory character, introducing the possibility of the use of discriminating thresholds, veto thresholds, among others, in the definition of the criteria to be considered in the model.

On the whole, the application of such a methodology may constitute the first step towards the use of Decision Aiding (DA) procedures in the daily operations of the medical equipment maintenance department of an innovative and tech-driven healthcare provider such as *Luz Saúde*.

1.2 Objectives and Methodology

The present dissertation aims to provide a tool for the classification of the maintenance condition of critical medical equipment from *Hospital da Luz Lisboa*, introducing a multicriteria sorting method. With the employment of this MCDA method, called ELECTRE TRI-NC, the purpose is to strengthen the maintenance management program established in the hospital and its resource allocation efficiency, minimizing time and cost implications. In addition, when considering the healthcare organization in question, this study is looking to contribute to the validation of *Luz Saúde*'s commitment to excellence and innovation in healthcare.

In the development of this dissertation, the followed methodology involved various steps (see Figure 1.1).

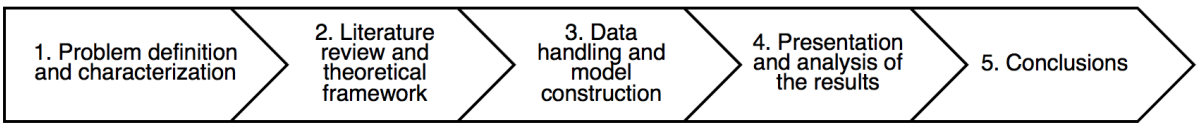

Figure 1.1: Steps in the development of the present dissertation, following an MCDA methodology.

Primarily, a presentation of the company, *Luz Saúde*, is carried out, emphasizing not only its history and structure, but also the ideology behind their provision of healthcare. Additionally, the specific hospital to which the study is applied, *Hospital da Luz Lisboa*, is introduced and based on its current maintenance management strategy, the context of the problem at hand is explained.

The second step involves conducting a literature review on several relevant topics. The concept of

a medical equipment maintenance program in healthcare organizations is explored and the specificities of medical ventilators, their associated principles and the assessment criteria that may be put to use for their classification are investigated. A theoretical framework is also undertaken, concerning MCDA processes and the method applied in this study, ELECTRE TRI-NC.

Thirdly, a data gathering, processing and analysis procedure is achieved and, from there, the model is constructed, with definition of the necessary parameters.

In the fourth step, the model is implemented and executed, resulting in the sorting of the selected medical equipment into predefined categories. The robustness of the model is analyzed and the policy implications for the company are assessed.

Finally, conclusions are taken, leading to a reflection on the findings, the potential limitations and the possibilities for future developments.

1.3 Dissertation Outline

This dissertation is organized into seven chapters, considering the abovementioned objectives. Succeeding the present chapter, the Introduction, Chapter 2 contextualizes the problem in question, the company and, more specifically, the hospital where it is inserted. From there, it is possible to define the terms under which the method is implemented. In particular, a selection is made on the group of medical equipment to which the model is applied, medical ventilators. Then, Chapter 3 focuses on the features of the selected medical equipment, the maintenance processes in healthcare settings and the possible approaches for the resolution of the case study. In Chapter 4, the theory behind MCDA and the sorting method utilized in this study is explored. Over to Chapter 5, the decision makers (DM) of the process are introduced and the categories, the performances and other necessary parameters for the construction of the decision model are defined. Afterward, Chapter 6 is devoted to the model execution and the exhibition of the results of the sorting methodology. In light of these results, analyses over the robustness level of the model and the managerial implications for *Hospital da Luz Lisboa* and *Luz Saúde* are presented. Lastly, in Chapter 7, the conclusions of the dissertation are presented, with subsequent discussion of the limitations of the study and the points for possible future work.

Chapter 2

Context and Problem Description

In Chapter 2 the main objective is to describe the problem at hand, in light of the context where it is inserted. Initially, there is a presentation of the company involved in this case study, *Luz Saúde*. The history and structure concerning this healthcare provider are examined and features of its mission, vision and values are highlighted, as they constitute motivating factors in the way decisions are made. Then, the focus turns to the specific hospital that is considered during the study, *Hospital da Luz Lisboa*. An introduction to the hospital is made and from there, an analysis of the current medical equipment maintenance management processes is performed. Thenceforth, from the group of critical medical equipment in *Hospital da Luz Lisboa*, there is an identification of the type of medical equipment that will be the focus of the present study.

2.1 Luz Saúde

As the holding company of one of the largest healthcare groups in Portugal, *Luz Saúde* presents an integrated network that includes hospitals, outpatient clinics and senior residences (Luz Saúde, 2017). The group stands out in the Portuguese healthcare market for providing specialized and complex services, through technologically sophisticated and front-line equipment displayed in various units. According to Luz Saúde (2017), in particular cases, these units exhibit medical equipment that are not available in any other healthcare facility in Portugal.

Regarding the history of the group, as reported by Luz Saúde (2018), the establishment of *Luz Saúde* dates back to July 2000, under the name *Espírito Santo Saúde*. At the time, the healthcare group was responsible for acquiring the majority shares of several hospitals and clinics. In 2007, the group's first private hospital built from the ground, *Hospital da Luz Lisboa*, started its activity. By 2009, the first senior residence, *Casas da Cidade Residências Sénior*, opened doors and at the end of the same year, a management contract for *Hospital Beatriz Ângelo* was signed, in the scope of a public-private partnership program. In 2014, when *Fidelidade – Companhia de Seguros S.A.* became the majority shareholder, the name of the corporation was modified and the name *Luz Saúde* was announced. In the same year, *Luz Saúde* became the first privately held healthcare provider to enter the stock market and be traded in

Euronext Lisbon. By 2016, *Luz Saúde* considered its areas of business to be concentrated in three main brands: *Hospital da Luz*, *Hospital do Mar Cuidados Especializados* and *Casas da Cidade Residências Sénior*. In January 2018, *Fosun* became a direct shareholder of *Luz Saúde* and at the end of the same year, the decision to delist the company from trading on the regulated market was implemented by the shareholders, after the approval process by the *Securities Market Regulator* (CMVM).

Currently, the group's network includes 30 units located in the north, central and central-south regions of Continental Portugal and in the Autonomous Region of Madeira and 15,057 employees (as of December 31, 2019) (Luz Saúde, 2019). *Luz Saúde*'s business model can be organized into three main operational segments (Luz Saúde, 2019):

- The private healthcare, that is composed of the 15 acute care hospitals and the 12 outpatient clinics;
- The public healthcare, where there is one hospital of the National Health Service operated by *Luz Saúde* under the Public-Private Partnership Program, which is *Hospital Beatriz Ângelo*.
- Other activities, such as two senior residences, a company that focuses on the internal distribution of materials and consumables, *GLSMED Trade* and *GLS Learning Health*, for the training of professionals, translational research and innovation in healthcare delivery and management. Also, a Corporate Center is responsible for providing centralized services to all units in the group.

In respect to the management structure of *Luz Saúde*, the board of directors is composed of a Chairman and eight directors, four of which are part of the Executive Committee, which, according to Luz Saúde (2019), is responsible for "the strategy and day-to-day management of the group's businesses". Furthermore, the Central Directorates, organized into specific areas, supports the Board of Directors and the group's operational units, ensuring their strategic homogeneity and standards (Luz Saúde, 2019).

Luz Saúde's structure "enables it to operate its healthcare units in a complementary and integrated way", through the referring of patients between the different units and the sharing of knowledge from a clinical and process management point of view (Luz Saúde, 2018).

When it comes to the vision, mission and values, it is important to highlight some features that allow *Luz Saúde* to be considered a leading healthcare provider. Overall, Luz Saúde (n.d.b) states that the company is committed to the fulfillment of three principals: *Excellence in healthcare*; *Technology and innovation*; *Talent and training*. Regarding 'Excellence in healthcare', the valuing of team medicine and multidisciplinary collaboration, the adoption of high ethical and professional standards and the involvement of the patient aim to contribute to the economic sustainability of the healthcare system. Concerning 'Technology and innovation', in this context, it means to provide the best quality healthcare taking into consideration what science and technology can offer. For this purpose, *Luz Saúde* uses personalized medicine based on the doctor-patient interaction and takes into consideration the "clinical genetics and molecular diagnostics alongside the adoption of computational medicine and data science technologies" (Luz Saúde, n.d.b). Besides, there is an investment in state-of-the-art technology and the promotion of scientific research. Finally, within the scope of 'Talent and training', it is part of *Luz Saúde*'s mission to build an organization capable of "attracting, developing and retaining exceptional people" (Luz Saúde,

n.d.b). Thus, the training and fostering of talent is a crucial point, with a culture based on meritocracy. Moreover, it is one of the company's goals to create collaborations with leading teaching and research institutions.

In line with the commitment of the company to research, innovation and the advanced training of professionals, *Hospital da Luz Learning Health* includes a simulation center, participates in acceleration programs, for instance, to support health startups and provides training courses and scientific events for health professionals (Luz Saúde, 2017).

According to Luz Saúde (2018), another ongoing goal across the group rests with the exhibition of certifications and accreditations, customer satisfaction assessments and compliance with quality and safety parameters in the various units. For instance, *Luz Saúde* has adopted the normative referential *NP EN ISO 9001 - Quality Management System* and the *NP EN ISO 14001 - Environmental Management System*, for the certification of their services.

2.2 Hospital da Luz Lisboa

Hospital da Luz Lisboa is currently the biggest hospital in the *Hospital da Luz* network, providing support to all *Hospital da Luz* units in the Greater Lisbon region (Luz Saúde, n.d.a). The hospital is considered a reference in the health sector nationally and internationally and has an accreditation by the *Joint Commission International* (JCI) for quality since 2018. Though embracing all medical and surgical valences, *Hospital da Luz Lisboa* has dedicated areas organized in centers of excellence, such as oncology, cardiovascular diseases, diabetes, obesity, robotic surgery and headaches, among others (Luz Saúde, n.d.a).

With an emphasis on medical excellence and innovation, the hospital employs the distinctive technology *Da Vinci Si HD*, a surgical system to be used in robotic assisted minimally invasive surgery (Intuitive Surgical, n.d.). Moreover, the Centre of Cardiac Rhythm from *Hospital da Luz Lisboa* is unique in Portugal and one of the five largest european centers to treat atrial fibrillation by robotic ablation (Hospital da Luz, 2019).

2.2.1 Managing of Medical Equipment

In *Hospital da Luz Lisboa*, the Infrastructures, Maintenance and Equipment Department (DIME) is involved in a variety of processes in the management of the hospital. Among other areas of action, DIME is responsible for the one concerning medical equipment and their maintenance process, in which precise operating and safety guidelines are followed.

When it comes to DIME's organizational structure, two sections can be differentiated: The *equipment* and *infrastructure* sections, both working in interaction with the director, the deputy director and the administrative support (Hospital da Luz Lisboa, n.d.). Focusing on the equipment section, it is possible to distinguish three distinct areas: *medical equipment*, *hospital equipment* and *general equipment* (Hospital da Luz Lisboa, n.d.).

For a visual representation of the aforementioned, the organizational structure of DIME is displayed (see Figure 2.1).

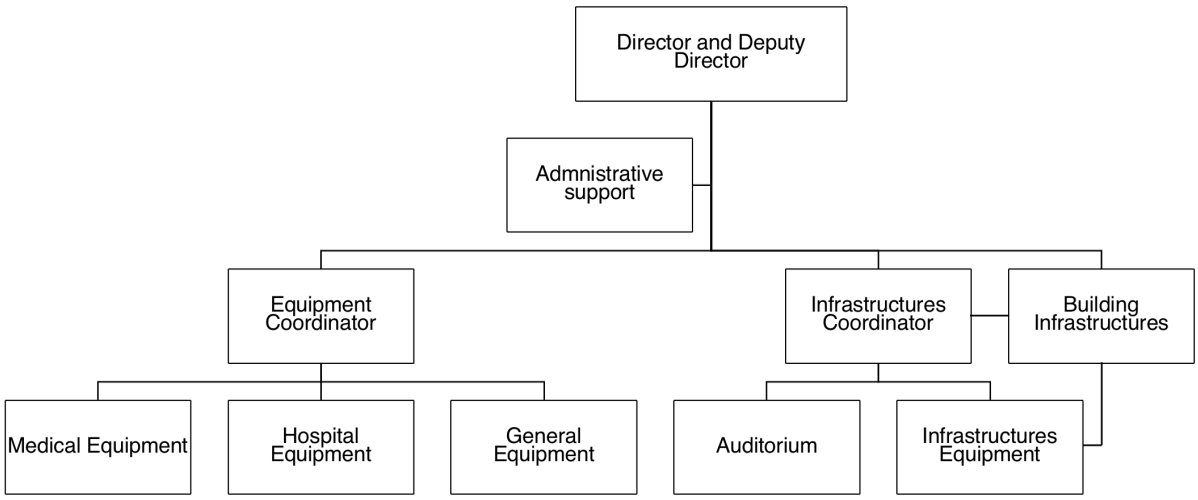

Figure 2.1: DIME's organizational structure. Note: Adapted May 20, 2020 from Hospital da Luz Lisboa (n.d.), Organigrama HLLisboa [Organizational chart HLLisboa]).

Regarding medical equipment in *Hospital da Luz Lisboa* and its life cycle, DIME is involved in the initial acquisition process, through to the reception and installation of equipment, in the monitoring during its working period and until the moment that equipment is taken out of the service (Hospital da Luz Lisboa, 2018).

On another note, it is important to bear in mind that the maintenance strategy for medical equipment in a hospital environment should ensure not only the operable condition of the different equipment but also the adequacy according to each service's necessities. According to Hospital da Luz Lisboa (2018), two concrete examples capable of illustrating maintenance processes included in *Hospital da Luz Lisboa* are the following:

- Preventive maintenance: planned activity that, according to World Health Organization et al. (2011c), allows to "prolong the life of the device and prevent failure". Preventive maintenance procedures and their frequency are defined for each medical equipment and can differ according to the age and equipment utilization (López-Carranza and Del Hierro-Gutiérrez, 2019). DIME is responsible for the scheduling of such interventions according to the accepted periodicities, defined in the hospital's preventive maintenance program (Hospital da Luz Lisboa, 2018);

- Corrective maintenance or repair: this is the process that comes after a failure circumstance and that enables the restoration of the physical integrity, safety or performance of the device (World Health Organization et al., 2011c). In *Hospital da Luz Lisboa*, whenever a malfunction event is reported to the Technical Assistance Center, an electronic file is created and a record of the equipment or device affected is registered, along with the service it belongs to, the malfunction description, among others (Hospital da Luz Lisboa, 2018).

The corrective and preventive procedures in *Hospital da Luz Lisboa* are performed by the manufacturers of the equipment in question or their representatives, through certified and qualified technicians

(Hospital da Luz Lisboa, 2018). In addition, the equipment in inventory is tested when new by the manufacturer. As mentioned above, DIME oversees both the preventive and corrective maintenance processes and verifies that these are carried out according to the established procedures.

In the strive for clinical excellence, *Hospital da Luz Lisboa* is aware of the importance of controlling the maintenance operations and consequently, as of October 2019, a Computerized Maintenance Management System (CMMS) software was implemented, denominated *Valuekeep*, created by the company *Primavera*. Since its implementation, the focus of this software has been mostly on the management of the hospital's equipment, even though it has also been utilized for aiding in the infrastructure management. As declared by Primavera Business Solutions (n.d.), this platform includes solutions for several processes in healthcare settings:

- Asset management;
- Human and material resources management;
- Preventive and corrective maintenance management;
- Planning and management of work orders;
- Inventory management;
- Contract management;
- Organization of analytic information for decision support.

Despite the recent implementation of *Valuekeep*, this software is expected to have a great impact on the hospital's efficiency regarding the management, planning and control of the maintenance activities, for instance, by improving maintenance work scheduling, increasing the uptime of assets and maximizing reliability and safety for medical equipment (Primavera Business Solutions, n.d.).

As stated previously, *Hospital da Luz Lisboa* is committed to finding innovative solutions for a more efficient medical equipment maintenance management program, aiming to maximize the quality of care and cultivating the best functional and safety conditions for each device. Further, the financial burden that medical equipment constitute for the hospital and the healthcare organization as a whole is also a motivating factor worth pointing out. With the complexity associated with this topic, the introduction of new tools to support decision processes represents a promising way to anticipate complications and act as a complement to the maintenance strategies already employed by the hospital. For instance, methods that allow the assessment and classification of the hospital's medical equipment could simplify that which is, more than often, a difficult decision process. In fact, the introduction of these decision support models towards medical equipment can have an important impact on the resource allocation efficiency of *Hospital da Luz Lisboa*. Other benefits may also arise, such as the increase of satisfaction levels among health professionals and patients, as well as the consolidation of the company's mission towards technological innovation in healthcare. What is more, in *Hospital da Luz Lisboa*, these methods can also contribute to a higher level of safety and reliability in the use of medical equipment.

2.2.2 Critical Medical Equipment

The fact is the introduction of tools to support decision processes in healthcare settings can be quite beneficial. Therefore, the aim of this dissertation is to develop a decision model for assessing and classifying medical equipment, using a DA methodology. To do so, the first step should incorporate the designation of the devices that should be seen as a priority for the introduction of such a decision support tool. This identification must be performed in light of the context where *Hospital da Luz Lisboa* is inserted, as well as its necessities regarding medical equipment management.

According to the World Health Organization et al. (2011b), the first step in managing healthcare technology is to determine what items are to be managed, by creating an inventory. An *inventory* is a document that displays the itemized list of assets of an organization where each equipment is identified by a unique number. When utilized accurately, it may serve as a powerful tool to reflect the status of the hospital's assets, to track different features and to improve in many key aspects of hospital management (World Health Organization et al., 2011b). Apart from providing details regarding the type and quantity of each equipment and allowing to track the status of the medical equipment management program, it can also be used to identify training needs, planning for emergencies, managing service contracts, among others (World Health Organization et al., 2011b). As a complement to the inventory, the hospital also keeps a failure occurrence computerized list, containing all the reported incidents concerning medical equipment (DIME, n.d.b).

In *Hospital da Luz Lisboa*, as of February 18, 2020, more than 13300 active items were found in inventory and from those, over 500 were distinct ones (DIME, n.d.a). As mentioned above, the hospital makes a distinction between what is considered as medical equipment, hospital equipment and general equipment. Relative to medical equipment, more than 3300 existed along the 47 functional areas of the hospital, with over 300 of these being distinct ones (DIME, n.d.a). This is in line with the assertion that there is an "extreme diversity of the medical device arena, in terms of types of devices, degrees of complexity, applications, users and categories" (World Health Organization, 2010).

In the development of a decision model for the problem at hand, limiting its application to a group of medical equipment allows for the introduction of equipment specific features and performing a more detailed and complete analysis. That is why, from the inventory of *Hospital da Luz Lisboa*, a top priority group of equipment was identified for model implementation. With that being said, is it important to understand which medical equipment presented the highest level of criticality within the hospital at the time.

According to Marques et al. (2006), *critical equipment* is the one that presents the highest degree of complexity in the resolution of eventual failure or the one that presents more complications in case of a corrective procedure. In addition, for Marques et al., the definition of critical equipment is also important to avoid the reduction of productivity and competitiveness of a company. Focusing on the health sector, Stolze (2012) suggested that *critical medical equipment* may be defined as one that "is essential for patient care under normal operating conditions and whose failure could cause imminent serious injury or death to patients or users". Stolze further enumerated examples such as life support, resuscitation and mission-critical equipment, among others. Although several definitions may be employed, the critical

medical equipment concept can differ widely according to the context and may be viewed differently according to the considered perspective. The fact is, the process of prioritizing a specific type of medical equipment is complex and requires a transparent process based on reason, evidence and assessment of prioritized needs (World Health Organization, 2010).

When it comes to *Hospital da Luz Lisboa*, an initial research phase was initiated to analyze the hospital's inventory and select the medical equipment that could be critical for the hospital. Different equipment were considered, based on their function, the implications for the patient in case of failure, the service and its redundancy in the hospital. The following equipment were selected:

- Defibrillators - an electronic device that applies an electric shock to restore the rhythm of a fibrillating heart (Merriam-Webster, n.d.);

- Incubators - an apparatus for maintaining an infant (usually premature) in an environment of proper oxygenation, humidity, and temperature (Miller-Keane Encyclopedia and Dictionary of Medicine, Nursing, and Allied Health, Seventh Edition, 2003);

- Infant radiant warmers - a bed for stabilizing the body temperature of a newborn or premature infant that has a heat source positioned above the baby to keep his or her temperature constant (Medical Dictionary, 2009);

- Infusion and syringe pumps - medical device used to deliver controlled quantities of fluids such as nutrients, drugs, and blood to patients (Alina, 2020);

- Multi-parameter monitors - medical device designed to give number of information on one screen and provide multiple information that is needed to understand the patient condition (Pediatric On Call Children Healthcare, n.d.);

- Pacemakers - a system that sends electrical impulses to the heart in order to set the heart rhythm (MedicineNet, n.d.);

- Medical ventilators - a system to perform useful work, to augment or replace the patient's muscles in performing the work of breathing (Pillai, 2009).

From these, the decision of the specific type of equipment to focus on in this dissertation was made according to what DIME considered to be the highest priorities regarding the medical equipment maintenance management of the hospital at the date. Having said that, medical ventilators were chosen to be the object of the study. Being present in different functional units of the hospital, such as intensive care units (ICU), operating theaters, imaging, inpatients, external appointments, urgent care, special exams, maternity and neonatal care, medical ventilators are a life support type of equipment that, according to DIME, is the most fitting for the implementation of a new decision support methodology.

2.3 Summary

This chapter presented the key elements for the contextualization and understanding of the problem at hand. *Luz Saúde*, a leader in the healthcare sector in Portugal, is currently organized into three main operational segments: private healthcare, public healthcare and other activities. It is its commitment to 'Excellence in healthcare', 'Technology and innovation' and 'Talent and training' that allows the company to be distinguished when it comes to the provision of specialized and complex services.

Turning to the specific hospital within the company that is considered during the dissertation and also the biggest in the *Hospital da Luz* network, *Hospital da Luz Lisboa*, it is DIME which is accountable for the medical equipment maintenance management during the entire life cycle of an equipment. As medical equipment utilization is directed for "specific purposes of diagnosis and treatment of disease or rehabilitation following disease or injury" (World Health Organization et al., 2011c), the current maintenance program in the hospital includes preventive maintenance and corrective maintenance procedures, among others. When considering a possible increase in the efficiency of the process, *Hospital da Luz Lisboa* has already implemented a CMMS software, *Valuekeep*, with several dynamic functionalities.

The aim of this dissertation is to introduce a new DA tool that further complements the maintenance management program, by assessing and classifying medical equipment. To do so, an overview of the medical equipment which were considered critical for the hospital was required, so that the decision model could be implemented to a specific group of devices. Given the inventory of *Hospital da Luz Lisboa* and the diversity associated with it, the identification of the equipment that presented the highest priority level was made according to the equipment's function, the implications for the patient in case of failure, its service and its redundancy in the hospital. Matching these points with the considerations of DIME, medical ventilators were chosen to be the focus of the dissertation.

Chapter 3

Literature Review

This chapter is dedicated to the concepts underlying medical equipment that are fundamental for understanding the methodologies used in this dissertation. Firstly, a theoretical framework regarding medical equipment and their maintenance process in a hospital setting is carried out. From there, the focus turns to the specific medical equipment chosen to be the focal point of this the dissertation. A medical ventilator overview is also performed, exploring the basic principles, the underlying characteristics and the global importance that these devices can assume in healthcare settings nowadays. In addition, the identification of the various perspectives and aspects regarding medical ventilators assessment criteria is a crucial point of this chapter, as it constitutes the basis for the model construction down the line.

3.1 Medical Equipment and Maintenance Process

Neal Asher, an English science fiction author, has quoted: “If I could time travel into the future, my first port of call would be the point where medical technology is at its best because, like most people on this planet, I have this aversion to dying” (Asher, n.d.). The fact is, medical technologies are a critical component of a functioning health care system and it is their management that helps to ensure their safe and effective application (World Health Organization et al., 2011b).

World Health Organization et al. (2011c) defines *medical device* as “an article, instrument, apparatus or machine that is used in the prevention, diagnosis or treatment of illness or disease, or for detecting, measuring, restoring, correcting or modifying the structure or function of the body for some health purpose”. Regarding *medical equipment*, it can be considered a specification of the previous one, as medical equipment are medical devices that are used for “specific purposes of diagnosis and treatment of disease or rehabilitation following disease or injury” (World Health Organization et al., 2011c). These do not include implantable, disposable or single-use medical devices and can be used individually or in combination with other pieces of medical equipment, accessories or consumables (World Health Organization et al., 2011c).

As mentioned above, the importance of medical equipment is related to the fact that they “directly affect human lives” (World Health Organization et al., 2011b). In addition, another relevant aspect is

the considerable investment and maintenance costs that these usually entail. Therefore, the healthcare facilities that feature medical equipment must have a well-planned and strong maintenance management program and strategy which, in accordance with World Health Organization et al. (2011c), is able to "keep the medical equipment in a healthcare institution reliable, safe and available for use when it is needed". The maintenance strategy of medical equipment can cover a wide range of concepts, from overhauls and refurbishing, preventive and corrective maintenance, performance testing, calibration, quality assurance, safety testing, visual inspections and user maintenance (Dyro, 2004). Some of these procedures were already illustrated for *Hospital da Luz Lisboa* in Chapter 2.

There is no doubt that adequate planning, management and implementation of the maintenance strategy for medical equipment is relevant for the global efficiency and efficacy of a hospital. In fact, according to Song et al. (2020), this topic has attracted a lot of attention from health industries across the world, due to its high implications not only on the patient health but also to the organizations themselves. In this regard, these planning and management procedures must be aligned with the "overall strategic planning process of the health entity which will be in part based on mission and context" (Clark, 2020).

Along the medical equipment life cycle, healthcare organizations are responsible for taking decisions on acquisition, maintenance, utilization and replacement (Ouda et al., 2010). These decisions can involve a combination of several factors and inputs from multiple sources and are often subjective, time and cost consuming (Capuano, 2010; Clark, 2020). Besides, medical equipment life cycle decisions are usually associated with limited capital availability (Dondelinger, 2004). Therefore, such decisions should be carefully structured using formal mechanisms with clear reporting of the needs of the organization in question. In addition, these formal models should not follow a "one size fits all" approach, since one that is used in one organization or situation in particular may not be usable under different conditions (Fennigkoh, 1992).

Unfortunately, most organizations do not invest in healthcare technology evaluation and end up responding to medical equipment replacement requests only when extreme events occur (Clark, 2020):

- The device fails at a critical time;
- A physician classifies the equipment as obsolete and asks for its replacement;
- A department manager complains regarding the performance of the equipment;
- It is found that parts and support are no longer available during a repair operation;
- A medical device is unable to comply with the integration into the network to transfer data to the Electronic Health Record (EHR).

Focusing on the present dissertation, the introduction of a DA tool aims to support the current maintenance strategy, facilitating the assessment and classification of particular medical equipment and ensuring optimal equipment functionality. This is done resorting to a model developed for one type of equipment, medical ventilators, which possess specific characteristics that must be taken into account when building the most reliable model possible.

3.2 Medical ventilators

3.2.1 Basic Concepts and Principles

According to Pillai (2009), various definitions can be associated with the term *ventilator*, one of which includes the idea that a ventilator is a machine, "a system of related elements designed to alter, transmit and direct the applied energy in a predetermined manner to perform useful work, to augment or replace the patient's muscles in performing the work of breathing". In other words, a medical ventilator, or as it can also be designated, a breathing machine or respirator, is a life support machine that helps a patient to breathe, by moving air in and out of the lungs (Elsevier Interactive Patient Education, 2020b). It can be utilized in an operating room, an ICU, a rehabilitation unit, an ambulance or even at home (Elsevier Interactive Patient Education, 2020a). On the one hand, a medical ventilator may be employed to simply aid the breathing process of an individual or, on the other hand, to completely control that person's breathing (Elsevier Interactive Patient Education, 2020b).

Medical ventilators can function as non-invasive and/or invasive equipment:

1. Non-invasive ventilation

   Non-invasive ventilation (NIV) allows to avoid the need for endotracheal intubation and includes the possibility of the patient to remain fully alert, without the need for sedation or anesthesia (Francis, 2017). In this case, ventilators are most commonly connected via an external mask that should be air sealed, fitting over the nostrils and mouth of the patient (Francis, 2017). With this, there is also an avoidance of several endotracheal intubation's adverse effects that are usually associated with standard invasive ventilation, such as airway trauma, the increased risk of nosocomial pneumonia and complications associated with sedation (Parsons and Wiener-Kronish, 2007). Non-invasive ventilators are usually less sophisticated and smaller in size when compared to invasive ventilators and, in many cases, are utilized to decrease the work of breathing to the patient and improve the gas exchange (Brochard, 2003). NIV is considered a complementary technique that, to this day, is not able to replace invasive ventilation in every instance (Brochard, 2003). However, studies such as Nourdine et al. (1999), Girou et al. (2000) and Carlucci et al. (2001) were able to delineate cases for which it was proved that NIV should be used as a first-line treatment.

2. Invasive Ventilation

   Invasive ventilators are the most commonly found in ICU and operating units. They are connected to a tube that is inserted via the nose, the mouth or the neck into the trachea of the patient (Elsevier Interactive Patient Education, 2020a). The placing of this tube is done under local anesthesia with sedation or general anesthesia. As reported by Singer and Corbridge (2009), invasive ventilation is responsible for redistributing blood flow from "working respiratory muscles to other vital organs and is therefore a useful adjunct in the management of shock from any cause". In addition, this type of ventilation can also be used as a diagnostic tool.

Moreover, there are two main types of mechanical (or assisted) ventilation (Parsons and Wiener-Kronish, 2007):

- Positive pressure ventilation

  The application of pressure is done to the airway, which allows direct inflation of the lungs. This is the most common type of ventilation in the ICU and these ventilators may be found not only in hospitals, ambulances and other healthcare facilities, but can also be available for home care services (Francis, 2017). With these devices, different treatments can be applied. For instance, for Constant Positive Airway Pressure (CPAP), there is a continuous application of positive airway pressure to the patient (World Health Organization, 2020). In Bi-level Positive Airway Pressure (BiPAP) there is also a continuous positive airway pressure applied, however, the clinician is able to adjust two different pressures during the inspiratory and expiratory phases of a breath (World Health Organization, 2020).

- Negative pressure ventilation

  The application of pressure is done to the abdomen and thorax, which allows to draw air into the upper airway and then into the lungs. The tank ventilator, the chest shell, the poncho and the cuirass ventilators are examples of devices based on this type of ventilation technique (Panitch, 2019). A negative pressure ventilator is an alternative for a patient that does not tolerate the placement of a nasal device or the nasal positive pressure application (Panitch, 2019). However, even though negative pressure ventilation does not involve endotracheal intubation, “it cannot overcome substantial increases in airway resistance or decrease in pulmonary compliance” (Pillai, 2009). Besides, the possibility of upper airway obstruction can compromise the effectiveness of this type of ventilation (Corrado and Gorini, 2012).

According to the application desired, medical ventilators are of different types and contain diverse features associated with them:

- Intensive care ventilators

  Located in an ICU context, these equipment are usually connected to a gas supply source that delivers gas to subjects who cannot breathe on their own or who require assistance to maintain adequate ventilation (World Health Organization, 2020). In their utilization, various operating modes are possible, such as the assist or the control modes (World Health Organization et al., 2011a). When the latter is activated, the ventilator provides “mandatory breaths at preset time intervals and does not allow the patient to breathe spontaneously” (World Health Organization et al., 2011a). Combination modes may also be available and besides, different parameters may be adjusted, such as the fraction of inspired oxygen, the respiratory rate (RR), the positive end-expiratory pressure (PEEP), the tidal volume, the flow, among others (Pillai, 2009). The regulation and selection of these settings are performed according not only to the disease in question and its unique development in the individual, but also to the patient’s characteristics, for instance, the

gender or height. In its employment, among other problems, there is an associated risk of pneumonia, which should be minimized by following all the control procedures (World Health Organization et al., 2011a).

When it comes to the operating steps of intensive care ventilators, the first step is to check whether the unit is ready for utilization (World Health Organization et al., 2011a). Then, the adjusting of the settings is made and once completed, the ventilator-patient connection is performed. From there, there is constant monitoring and evaluating of the patient.

- Anesthesia ventilators

  As a requisite part of all modern anesthesia workstations, these ventilators integrate many intensive care ventilators' features and are able to perform ventilation procedures to the "most challenging patients brought to the operating room" (Jain and Swaminathan, 2013). With the improvement of technology, these ventilators are able to have sophisticated computerized controls and present changes to the breathing system that provide different and advanced types of ventilatory support (Jain and Swaminathan, 2013). Health professionals should be aware of the criticality of this type of equipment and the problems that can arise from its utilization. As an example, contamination of the circuit can possibly lead to nosocomial infections (Jain and Swaminathan, 2013).

- Ventilators for transport or mass-casualty care

  With this type of ventilator, it is crucial to bear in mind characteristics such as the degree of portability (including weight and manageability), as well as battery life (World Health Organization, 2020). These devices usually operate on an external battery and without a compressed gas source and are responsible for the delivery of air or oxygen-enriched gas into the breathing circuit (World Health Organization et al., 2011a). The operating steps are identical to the ones in the ICU ventilators and the complications associated with this type of ventilator usually involve user error, poorly maintained exhalation valve assemblies, and the use of poor-quality breathing circuits (World Health Organization et al., 2011a).

As already stated, ventilators provide temporary ventilatory support or respiratory assistance that can be required in diverse cases, such as chest injury situations, lung infections or brain and spinal cord injuries (Elsevier Interactive Patient Education, 2020a). A ventilator may also be needed when the patient is under anesthesia (for instance, during or after surgery), displays low oxygen levels in the blood, presents slow breathing (apnea) or fast breathing (tachypnea), amongst many others (Elsevier Interactive Patient Education, 2020a).

As for any life support and monitoring equipment, alarms and control systems constitute an integral part. In fact, these devices have numerous alarms incorporated that should be able to detect malfunctioning problems and respond to component failure events. Furthermore, considering the advancement of technology and the front-line devices available nowadays, ventilators may incorporate state-of-the-art safety functions that can be considered exceedingly intuitive for the user.

All in all, ventilators constitute one of the more complex and integral elements of critical care medicine for neonates, pediatrics and adults (Poor, 2018). It is important to bear in mind that these equipment do

not work in isolation, as they are based on complex interactions with the patient's respiratory system. Thereby, continual monitoring and adjusting of the settings to each individual and its unique condition are required (Poor, 2018). On the whole, it is the combination of an in-depth understanding of how each ventilator operates, the achievement of optimal equipment selection for each particular situation and an efficient medical equipment maintenance strategy that allows for the maximization of patient comfort and positive outcomes in a healthcare facility.

3.2.2 Medical Ventilator Assessment Criteria

When it comes to the assessment and classification of medical ventilators, they must be done as a consequence of the implementation of an efficient life cycle planning and management process (Clark, 2020). Generally, this process includes the management of the acquisition of new technologies, the assessment of the ones already present in the healthcare facility and their possible replacement, among others.

Although this dissertation's focus was the use of an MCDA model for medical ventilator assessment, it was found that this topic lacked specific literature. Therefore, an exhaustive literature review on the criteria to be featured in the model was required. Models applied to different medical equipment were considered, since they were able to provide relevant insights that were then adjusted and applied to the medical ventilator case. Besides, models for all parts of the planning and managing process were featured, including for aiding purchasing, evaluating and replacement decisions. Once again, since these models have common features, performing a comprehensive overview of the criteria for different parts of the planning and managing process led to a more complete analysis when it comes to possible assessment criteria.

As established earlier, one of the goals of the WHO is to "ensure improved access, quality and use of medical products and technologies" (World Health Organization et al., 2011b). Regarding medical ventilators, their assessment requires thorough consideration of the trade-offs between technological features, benefits, risks and costs and it usually involves multiple stakeholders and multiple, sometimes conflicting, criteria (Sloane et al., 2003).

Starting the analysis with the DA models for the acquisition of medical equipment, several criteria were considered, resulting in different outcomes for the same method.

Ramírez and Calil (2007) presented a decision-making computational model where the final grade attributed to a proposal was obtained combining the relative weights with the grades obtained after the evaluation of five criteria: clinical, financial, quality, safety and technical. These weights varied in accordance with the cost, the risk and the strategic importance of the medical equipment under evaluation (Ramírez and Calil, 2007).

In a particular case of purchasing a magnetic resonance imaging (MRI) scanning equipment, Lindgreen et al. (2009) studied the incorporation of sustainability related dimensions. By definition, *sustainability* focuses on meeting present needs without compromising future generations' needs and, in organizations, involves financial, environmental and social dimensions (WCED et al., 1987). In the

study, Lindgreen et al. (2009) focused on both the product's environmental and social sustainability in the process of acquisition of a high-tech medical equipment.

Pecchia et al. (2013) focused on sorting the user needs in the process of acquisition of a computerized tomography (CT) scanner, organizing them into four categories: performance, patient safety, usability and technical issues.

Later, Barrios et al. (2016) developed a model that also focused on the purchase of a CT scanner and that also featured the performance and patient safety aspects, adding, however, the technology level, the financial and the technical aspects.

Considering ventilator specific models, the literature found was more detailed when related to the acquisition of a specific type of medical ventilator.

In evaluating the most appropriate neonatal ventilator to purchase, Sloane et al. (2003) included diverse criteria:

1. Cost, taking into account the repair parts policy, the availability of rental supplements, the acquisition cost, the life cycle cost of ownership, the consignment parts program, the training programs and the service contracts;

2. Safety, exploring the interface to the hospital information and alarm system, the automatic disconnect alarm, the power off alarm, the emergency power backup and the alarm disable lock out;

3. Biomedical engineering, analyzing design features (such as resistance to chemical cleaners, optional air compressor support, size, internal battery and balance stability), maintenance aspects (such as self-diagnostics, frequency of maintenance, ease of routine maintenance and ease of repair) and factory support features (such as ease of upgrades, cost of upgrades, local service and parts support and service documentation).

4. Clinical factors, including daily maintenance concerns (such as infection and control management and ease and cost of daily maintenance), the modes of ventilation (such as responsive valve feature, patient's responsive models, combination modes, mode ranges and mode choices), the evaluation of alarm systems (such as the unique alarm sound and the apnea alarm system), the human aspects (such as the ease of training and user interface), the integral graphic monitor features, complexity and reliability, the heat and humidification system and the bronchodilator options.

As another example, Chatburn and Primiano (2001) proposed a model to purchase intensive care ventilators, where a cost and customer service analysis was made, together with a technical evaluation, taking into consideration features such as trigger variables, limit variables, cycle variables, modes, optional functions, ease of use, controls, waveform monitoring, patient monitor, optional signals and alarms.

Turning to medical equipment replacement models, as mentioned earlier, these usually feature criteria that are worth considering. In fact, although the outcomes of these models usually differ, many aspects are, more often than not, analogous to assessment models. Several of these replacement or prioritization models were developed over time and an analysis of the various criteria featured in these is performed below.

Fennigkoh (1992) introduced a model employed in *St. Luke's Medical Center* that addressed four primary replacement issues:

1. Equipment Service and Support, including age, maintenance cost (as a percentage of the device's purchase price), downtime (equipment that is not available when needed) and end of manufacturer support;

2. Equipment Function, evaluating whether they are life support devices, therapeutic devices, diagnostic devices, analytical/support devices;

3. Cost Benefits, conducting an analysis to check if the challenger offers increased or decreased revenues;

4. Clinical Efficacy, that includes aspects such as improved patient care, user preference and increased standardization.

Dondelinger (2004) proposed a model where the factors were divided into objective or subjective. Regarding the objective factors, the failure rate would be the first to be taken into consideration. Then, two other data elements would be introduced: the repair cost factor, as a proportion of the cumulative cost of repairs of that equipment to its acquisition price and the age factor, which was a proportion of the age of the equipment to its life expectancy. For the subjective factors, not only the advancements in technology were included, but also the evaluation of how well the replacement of one particular item would fit into the organization's five-year plan.

Rajasekaran (2005) presented a database, named Equipment Replacement Planning System (ERPS), in which the replacement rules have been programmed. The ERPS was developed to identify equipment "most in need of replacement in order to optimize the utilization of capital budget resources, the attention to patient safety and efficiency of the healthcare process" (Rajasekaran, 2005). To do so, there was an application of distinct replacement rules (Rajasekaran, 2005):

1. Technical Rules, that analyzed the possible termination of product support, the age of the device compared to its estimated useful life, the failure rate during the equipment's lifetime, its clinical obsolescence, the usability of the equipment and the physical condition for each equipment;

2. Safety Rules, based on: technology-related accidents that may have occurred; user errors that happen as a consequence of user or operator errors, poor user interface design, inadequate product labeling, misuse or abuse of the device and usage problems resulting from user-device interaction; the risk associated with the failure of the equipment, that depends on the functional category, the clinical application and the usage environment of such equipment; the number of recalls or alerts from regulatory agencies or the manufacturers;

3. Financial Rules, that consider the cost of ownership compared to acquisition cost, the financial impact of downtime, the availability of backup and the standardization level.

Taylor and Jackson (2005) developed a Medical Equipment Replacement Score (MERS) system with three primary components: technical, device safety, and mission-critical. While the technical component

score includes elements for condition, lifespan and discontinuation assessment, the device safety component score combines aspects regarding the physical safety and the technology related incidents.

Capuano (2010) proposed that the prioritization of equipment for replacement should be done according to their price, condition, support or product discontinuation, age, hours of vendor labor, the accumulated cost of parts, risk level and frequency of use.

Ouda et al. (2010) focused on the replacement criteria for medical equipment in developing countries and introduced a mathematical model that classified the equipment life status into groups, given:

1. Technical Criteria, such as useful lifetime ratio, utilization, downtime, technological change and vendor support;

2. Financial criteria, that may include the service and operating costs and availability of backup;

3. Safety Criteria, including factors such as hazards/alerts and user/technician errors;

Jamshidi et al. (2015) carried out a prioritization system for medical devices where criticality was based on the age of the equipment, the usage-related hazards, the utilization, the number of available identical devices, the recall events, the equipment function and its maintenance requirements. The model also included a risk score, that resulted from an analysis of the probability of occurrence of failures and their repeatability, as well as the analysis of the consequences of failures for patient safety, the device operator and maintenance personnel, economic loss and the meantime to repair the equipment.

Clark (2020) developed a comprehensive list of aspects to take into account when determining the replacement of equipment. This detailed list features factors such as age, risk, support status, reliability, condition assessment, regulation, as well as safety issues among recalls and alerts, adverse events, user errors and no problem found work orders. It also took into consideration the equipment's status (considering the manufacturer's perspective), purchase and maintenance costs, application, depreciation, the availability of backup equipment, upgrade level, cybersecurity, utilization, uptime, network integration, standardization and technological status. Moreover, the model included an analysis of the equipment's contribution to the standard of care, its clinical acceptance and the cost savings or revenue increased in the case of medical equipment replacement.

Another point is that the criteria for the establishment of a preventive maintenance program can provide valuable insights on features to be considered for the assessment of medical equipment. As defined in the previous chapter, health institutions should possess a preventive maintenance program that specifies the frequency of preventive maintenance for medical equipment, based on the evaluation of each device (López-Carranza and Del Hierro-Gutiérrez, 2019). Regarding the establishment of a risk-based inventory for determining the medical equipment to be included in a preventive maintenance, different algorithms were studied:

- *Fennigkoh and Smith Algorithm*, that classifies medical devices based on three factors: function, risk, and maintenance required (Biomedical Instrumentation & Planning, 2013);

- *WHO Modification*, suggesting a modification of the algorithm proposed by Fennigkoh and Smith,

taking into account an additional factor named “history of equipment failures” (World Health Organization et al., 2011b);

- *Clinical Evaluation Modification*, with the addition of the variable “clinical evaluation”, through a questionnaire “addressed to the heads of nursing and to the doctors in charge of the services where the medical equipment is used” (Sen Salinas, 2015);

- *Modification of Preventive Maintenance Index*, including the concept of “maintenance of the environment”, referring to the “maintenance of spaces, areas, locations and facilities in the hospital where medical equipment is located” (Rodríguez et al., 2001);

- *Wang and Levenson’s Algorithm*, that classifies medical devices according to the risk, the required maintenance and the priority factor (Gaitán, 2015);

- *Modification of Wang and Levenson*, that incorporates the use rate factor in determining the frequency of preventive maintenance (Gaitán, 2015).

3.3 Summary

By definition, medical equipment are used for diagnostic and treatment purposes or for specific rehabilitation cases. Moreover, medical equipment maintenance management plays an extremely important role within healthcare organizations and, as a consequence, there is an increasing focus on tools that help structure decisions, providing support to this process. When focusing on the case study at hand, the introduction of a DA tool for the classification of medical ventilators in a hospital environment requires a literature review on the basic principles of these equipment, as well as on their possible assessment criteria.

Medical ventilators are life support equipment, that aim to assist or completely control the breathing process of a patient. According to the patient-ventilator connection method, the type of ventilation can be considered either invasive or non-invasive. Medical ventilators can also be classified into two groups: positive-pressure or negative-pressure ventilators. Furthermore, on the basis of their purpose, different equipment with distinct features can be identified. On the one hand, intensive care ventilators are usually connected to a gas source and various operating modes and setting adjustments are possible. On the other hand, even though anesthesia ventilators integrate several aspects of the ICU ventilators, they are usually utilized in operating room settings. In the case of ventilators for transport or mass-casualty care, the degree of portability and battery life are important factors to take into consideration.

As a pivotal component of critical care medicine, the ventilator is a complex and intricate medical equipment. Further, the correct choice of a ventilator to a specific situation and the achievement of the optimal maintenance strategies for these devices should be a priority within healthcare facilities.

When it comes to medical ventilators’ assessment, models with different criteria may be developed and their application is dependent on the objectives of the analysis in question and the information utilized. In addition, models applied to other medical equipment and that aim to facilitate other decisions

in the planning and managing process, such as purchasing, replacement or preventive maintenance management of medical equipment, provide relevant insights regarding the criteria to be used in the DA model later on.

Overall, concerns regarding financial, clinical, safety, quality and technical aspects were consistent across the literature retrieved. Considering the specific criteria employed, age was the most commonly found, followed by the product support, the technology level of the equipment and the cumulative maintenance costs compared to the acquisition price. Moreover, the failure rate, the equipment-related accidents, the user errors and the alerts and recalls recorded were present in several studies, in addition to the analysis of the risk of the equipment, the existence of backup, the downtime, the physical condition, the utilization level and its standardization level. Besides, other factors were considered, such as sustainability-related concerns, the contribution to improved patient care and to the organization's strategic plan, the cybersecurity of the medical device, its network integration, upgrade level, clinical application and user preference.

Chapter 4

Multicriteria Decision Aiding

The present chapter focuses on MCDA, firstly, by giving an overview of the general DA methodology, with the objective of deepening the understanding of the several associated concepts. Then, the focus is on the sorting method that will be used in this dissertation, ELECTRE TRI-NC. In order to do this, an exploration of the underlying features as well as the main concepts, definitions and notation concerning this sorting method is performed. Lastly, the model application and execution are also explained.

4.1 Decision Aiding overview

Humans' capacity to reason hypothetically and deductively has been utilized for as long as man has existed. In an attempt to conceptualize before implementing or to think before acting, people express that which is the essence of DA, the "attempt to clarify the behavior of an intervening party in the decision process" (Roy, 2013). As an example, it is possible to date back to the tenth century BC, when King Solomon relied on an approach to solve what might be viewed as a close relative of an MCDA problem. This episode allegedly occurred when the king was faced with two women, both claiming to be the mothers of a baby standing before them. During the night, one of the women had lost her baby after rolling over in her sleep and crushing it. Solomon, who was allegedly known as a wise man, had to discover a manner to deal with this conundrum. This way, when he proposed to divide the surviving child in two with a sword, the true mother was revealed, as she was willing to give up her child in order to protect it. This gesture led to Solomon acknowledging the woman as the true mother and giving her the baby. Despite skepticism regarding the veracity of the story, it constitutes an example of a negotiation and mediation problem that can be utilized in the DA context.

Since then and to this day, decisions are a part of daily life. According to Roy (2013), whether relating to the choice of something to do or even the way in which to do it, any decision will involve components such as discovery, reasoning and even some irrational randomness. When it comes to the individuals or groups that influence a decision, the *actors*, it is their value system that will influence the decision process. The *value system* entails not only their beliefs but also the way that the actors' judgments will determine the objectives that will be found relevant and that affect their behavior (Figueira et al., 2013).

Moreover, an actor is also able to use an *information system*, as he recognizes added information that is of importance in this process (Roy, 2013). It is both the value and information systems that are responsible for influencing what is called the *relational network*, a ”solid framework of influences, alliances, coalitions, pressures between a given individual and all the others involved in a decision process” (Roy, 2013).

By definition, *DA* is the activity of the person who, through the use of explicit but not necessarily completely formalized models, helps to obtain elements of response to the questions posed by a stakeholder of a decision process (Roy, 2013). Taking this aspect into account, two actors of the DA process must be pointed out (Roy, 2013):

- The *DM*, an individual, entity or community that has an interest in the decision and whose preferences are imposed during the evolution of the process;
- The *analyst*, usually an expert, whose role is to deepen the understanding of the DM regarding a situation. The analyst also aims to clarify the possible implications of different behaviors in shaping a decision, relying on skill and intellectual honesty. Although the analyst is able to make suggestions and influence the process, the recommendation should, as much as possible, be independent from its own value system.

The co-interaction of these two entities will be crucial in developing a model to help the investigation. In other words, a framework to conceptualize the problem and to explore, master and communicate it. This is in line with the ‘European’ conception of MCDA, where the assignment model must be developed through a co-construction process between the analyst and the DM (Almeida-Dias et al., 2010). Furthermore, according to Bouyssou et al. (2006), during the interaction between these two entities, the DA process is developed following four main steps:

1. Representation of the problem situation: explicit definition and understanding of the problem at hand. In this process, the actors and their concerns are identified;
2. Problem Formulation: formalization of the interaction between the analyst and the DM, by a translation of the problem statement into decision support language. For instance, the criteria and actions of the decision process are identified. At this stage, it is important to note that the adoption of a particular problem formulation by the analyst will lead the DA process to different final recommendations;
3. Evaluation Model: given the problem formulation, there is a construction of an evaluation model that when applied, leads to a formal response to the problem situation;
4. Final Recommendation: translation of the output of the evaluation model, expressed in terms of the decision support language, into a format that can be utilized by the client. Also, the theoretical soundness, operational completeness and legitimation of such output are assessed.

The DA activity is established according to three foundations (Figueira et al., 2013): the *actions*, the *consequences* and the *modeling of one or several preference systems*. Regarding the actions, these

are the application points of the decision process and when incompatible with implementing any other, are called alternatives. When it comes to the consequences, these constitute attributes or aspects of an action that can interact with the value system of an actor and that are likely to influence the final decision. The consequences are the basis for comparing actions, as each action should be evaluated not only according to each elementary one but also to each group of these consequences and possibly, to each point of view (Roy, 1999). At last, it is the modeling of one or several preference systems that allows to assign to each pair of actions one of the relations: *preference*, *indifference* or *incomparability* (Figueira et al., 2013).

The comparison of two actions involves the assessment of the consequences associated with them. Nevertheless, it is the operationalization of the information associated with those consequences that leads to the definition of a *criterion* (Roy, 1999). When considering the case of DA, the term criterion designates a "way of evaluating which serves to position a potential action (or an alternative) on a preference scale corresponding to a well-identified point of view" (Roy, 1999). Bearing this in mind, the aim of a criterion is to incorporate information regarding one category of consequences and according to a specific feature of the problem. In DA, where human interactions and value systems are a major part, it may be difficult to build a criterion family that is coherent and correctly synthesizes all aspects of the problem. At this point, it is the analyst's duty to ensure that some logical requirements are respected when justifying options that are taken (Roy, 2013):

- Exhaustiveness, achieving all the relevant points to the decision process;
- Cohesiveness, regarding the necessary compatibility between the partial preferences considering each criterion and the DM's overall preferences;
- Nonredundancy, which is verified when leaving out a criterion of the family translates in violating one or both of the requirements above.

Additionally, for allowing comparisons, it is necessary to define on what terms each action on each criterion will be assessed, the *criterion scale*. The criterion scale can be direct, if it relates to the nature of the criterion itself, indirect, when proxy measurements of the criterion are used, or constructed, in case the scale is constructed specifically for the decision at hand (Bana e Costa and Beinat, 2005). Each scale allows to evaluate the performance of an action according to a specific criterion, which is translated into a score, that can be characterized by a pictorial object, a verbal statement or a number (Greco et al., 2016). The set of all possible performances according to each criterion must be completely ordered: if this order corresponds to the direction in which the preference increases, the criterion in question is to be maximized, otherwise it is to be minimized (Roy et al., 2014). In MCDA, different types of scales can be adopted (Bana e Costa and Beinat, 2005):

1. Qualitative or purely ordinal scale: only the order of the values is relevant, hence the quantification of the difference between scores is not meaningful in terms of the difference of preferences. It is the case with verbal scales, where no equal preference differences between consecutive degrees can be assumed or with numerical scales, when it is not possible to assume invariant preference difference along the scale.

2. Quantitative, cardinal or ratio scale: numeral scale where the ratio between two degrees is meaningful regardless of the two degrees that are being examined.

Going back to the decision process, the analyst is also responsible for establishing the terms of the decision problem and by doing so, to answer the questions (Roy, 2013): what are the types of results one expects to obtain? In what ways does he see himself aiding the DM? What methodology seems most fitting to address the problem?.

In order to do so, it is necessary to define the problematic, that is the "analyst's conception of the way he envisions the aid he will supply in the problem at hand" (Roy, 2013). There are four reference problematics that can be used in practice (Roy, 2013; Figueira et al., 2013):

- The choice problematic, where the objective of the DA process is the selection of a reduced number of actions while justifying the elimination of the others;

- The sorting problematic, that involves the assignment of each action to one of the categories among a predefined set;

- The ranking problematic, with the objective of partial or complete ordering of the actions from best to worst. This ranking includes the possibility of indifference or incomparability between two actions;

- The description problematic, a problematic that can be included in the preceding ones, nevertheless requires distinguishing. In this case, a description of the actions and even the consequences of such actions constitute the main objective and the analyst is responsible for enlightening the DM in a rigorous and complete way. In the end, this problematic leads to a better understanding and presentation of the problem rather than focusing on solving it.

The aforementioned problematics have been applied in MCDA contexts in diverse areas and fields. Take, for example the use of the choice problematic for performing site selection for a French engineering institute, the *Ecole Supérieure d'Ingénieurs de Marseille* (Khouadja and Roy, 1975), the application of a sorting problematic in the industrial development of a large electricity distribution company to sort "sector-application couples to which promotional priority should be given" (Charpentier and Jacquet-Lagrèze, 1976) or the successful employment of the ranking problematic in an advertisement campaign plan to create an importance based ordering procedure for periodicals (Abguéguen, 1971).

In fact, MCDA is able to provide structure and support to processes that involve not only multiple aspects to be considered but also that deal with imperfect information and diverse perspectives from actors (Roy, 1999). To this extent, it is natural that these methodologies are being considered when it comes to decision-making in healthcare, a sector that has an extreme complexity level, not only involving a great deal of uncertainty but also an enormous diversity of possible outcomes. In this dissertation, the aim is to apply an MCDA method to a sorting problematic related with medical equipment management (medical ventilators, specifically). To do so, the ELECTRE TRI-NC method is employed, which is presented in the next section.

4.2 The ELECTRE TRI-NC sorting method

ELECTRE TRI-NC is a multicriteria sorting based method that belongs to the ELECTRE family of methods, which stands for Elimination and Choice Expressing the Reality (*ELimination Et Choix Tradusant la REalité*, in french) (Roy, 2013). The introduction of the ELECTRE methods dates back to the 1960s, when Bernard Roy devised a method for a research team from SEMA, a European consultancy company (Roy, 2013). This method, which chose the best action(s) from a given set and soon was applied to ranking and sorting problems, was later referred to as the ELECTRE I (electre one) (Roy, 2013). Since their conception, ELECTRE methods have been widely used for MCDA in many real-world decision problems (Figueira et al., 2013).

ELECTRE methods are composed of two main procedures (Greco et al., 2016). Firstly, a multicriteria *aggregation procedure*, which comprises the construction of one or more outranking relations, given the performance of each action according to each criterion. Then, an *exploitation procedure*, which differs according to the problematic, producing different results according to it.

The method used throughout this dissertation, ELECTRE TRI-NC, will be applied in a sorting problematic and was designed to be utilized within the framework of a co-constructive process, which entails that the DA assignment model is "at least co-constructed through the interactive process between the analyst and the DM" (Almeida-Dias et al., 2010).

While ELECTRE TRI-NC displays several advantages that are presented throughout this section, it also poses some drawbacks that are common to all ELECTRE methods (Greco et al., 2016). For instance, regarding the inability to assign a score to an action, which might be useful and intuitive for the DM. What is more, intransitivities can occur and if the preferences were meant to respect transitivity, this can be seen as a limitation. Moreover, when the family of criteria exhibits an entirely quantitative nature, there are more appropriate methods available.

ELECTRE TRI-NC has three underlying assumptions that must be taken into account (Almeida-Dias et al., 2012). Firstly, this method is designed to be employed in contexts where the set of categories to which actions must be assigned to is completely ordered. In addition, each category is conceived *a priori* to receiving the actions, which will or might be processed in the same way. Finally, each category is characterized by a subset of reference actions judged by the DM as representative or informative of the actions that should be assigned to such a category.

Furthermore, the ELECTRE TRI-NC method presents main features in its application (Figueira et al., 2013):

- The absence of systematic compensation between "good performances" and "bad performances";
- The use of discriminating thresholds to cope with the imperfect nature of knowledge in DA. In fact, the definition of each criterion is often associated with some part of arbitrariness and subjectivity and the data that is utilized to build the criteria may be somewhat imprecise, ill-determined and uncertain (Roy et al., 2014);
- The consideration of positive and negative reasons in the modeling of preferences and also the

possibility of using veto thresholds, which reinforces the non-compensatory character of the method.

Generally, the ELECTRE TRI-NC method takes into account more than one reference action to characterize each category. This is a major difference when compared to previous methods of the ELECTRE family. For instance, in the ELECTRE TRI-B method, the actions to be assigned were compared to reference actions that represented lower and upper bounds of the categories, which can be very difficult for the DM to define (Almeida-Dias et al., 2010). As another example, the ELECTRE TRI-C method considers only one reference action to define each category, which indicates that ELECTRE TRI-NC "gives a particular freedom to the decision maker in the co-construction decision aiding process with the analyst to characterize the categories" (Almeida-Dias et al., 2012).

4.2.1 Concepts, definition and notation

Let $A = \{a_1, a_2, \ldots, a_i, \ldots\}$ denote the set of potential actions, which may be established *a priori* or can appear progressively during the DA process. The aim is to assign each of these actions to a set of ordered categories, denoted $C = \{C_1, \ldots, C_h, \ldots, C_q\}$ with $q \geq 2$. This way, the worst category is represented by C_1 whereas the best category is represented by C_q (Almeida-Dias et al., 2012). Moreover, a coherent family of criteria $F = \{g_1, \ldots, g_j, \ldots, g_m\}$ must be defined to allow the evaluation of the potential actions and their assignment to a category (Almeida-Dias et al., 2012).

Each criterion g_j is considered a pseudo-criterion, which entails having two thresholds associated with it: an *indifference threshold*, q_j and a *preference threshold*, p_j, where $p_j \geq q_j \geq 0$ (Almeida-Dias et al., 2012). In the particular case where $p_j = q_j = 0$, any difference in performance in favor of one of the two actions can be seen as significant for a strict preference on criterion g_j (Almeida-Dias et al., 2010). As mentioned above, the introduction of these thresholds takes into account the imperfect character of data as well as the arbitrariness that affects the definition of the criteria (Almeida-Dias et al., 2012). Besides, the following binary relations can be derived based on the definition of the abovementioned thresholds (Almeida-Dias et al., 2010):

1. $\mid g_j(a) - g_j(a') \mid \leq q_j$: a is indifferent to a' according to g_j, denoted aI_ja'
2. $g_j(a) - g_j(a') > p_j$: a is strictly preferred to a' according to g_j, denoted aP_ja'
3. $q_j < g_j(a) - g_j(a') \leq p_j$: a is weakly preferred to a' according to g_j, denoted aQ_ja' (ambiguous zone)

Introducing the set of characteristic reference actions, $B = \{B_1, \ldots, B_h, \ldots, B_q\}$, these are responsible for defining the categories and, for instance, $B_h = \{b_h^r, r = 1, \ldots, m_h\}$ represents the subset of reference actions that define category C_h, such that $m_h \geq 1$ and $h = 1, \ldots, q$. It is important to note that the two particular subsets of reference actions $B_0 = \{b_0^1\}$ and $B_q = \{b_{q+1}^1\}$ contain a reference action, such that $g_j(b_0^1)$ is the worst possible performance on criterion g_j and $g_j(b_{q+1}^1)$ is the best possible performance on the same criterion (Almeida-Dias et al., 2012).

By definition of characteristic reference actions, those that belong to B_{h+1} and B_h must define two consecutive distinct categories. Therefore, two conditions are imposed. Firstly, B_{h+1} should dominate

B_h, which is translated in (Almeida-Dias et al., 2012):

$$\forall j, g_j(b^s_{h+1}) - g_j(b^s_h) \geq 0, s = 1, \ldots, m_{h+1}; r = 1, \ldots, m_h; h = 1, \ldots, (q-1). \tag{4.1}$$

In addition, when considering the possible minimum differences in performance of the characteristic reference actions, it is also necessary to exclude the possibility of accepting two reference actions that are not significantly different in terms of performance on each criterion (Almeida-Dias et al., 2012). Consequently, the set of reference actions is required to fulfill the weak separability condition, defined by:

- Weak Separability: The set of characteristic reference actions fulfills the dominance condition and $\sigma(b^r_h, b^s_{h+1}) < 1, s = 1, \ldots, m_{h+1}; r = 1, \ldots, m_h; h = 1, \ldots, (q-1)$.

Under specific conditions, the DM can consider this condition too weak for defining distinct categories through characteristic actions (Almeida-Dias et al., 2010). Thus, two stronger conditions can also be defined (Almeida-Dias et al., 2012):

- Strict Separability: The set of characteristic reference actions fulfills the dominance condition and $\sigma(b^r_h, b^s_{h+1}) < \frac{1}{2}, s = 1, \ldots, m_{h+1}; r = 1, \ldots, m_h; h = 1, \ldots, (q-1)$.
- Hyper-strict Separability: The set of characteristic reference actions fulfills the dominance condition and $\sigma(b^r_h, b^s_{h+1}) = 0, s = 1, \ldots, m_{h+1}; r = 1, \ldots, m_h; h = 1, \ldots, (q-1)$.

4.2.2 Outranking concept

Preference relations in the method are modeled through outranking relations (Almeida-Dias et al., 2010). For instance, "a outranks a'" according to criterion g_j, denoted aS_ja', expresses the idea that a is at least as good as a' on criterion g_j. This outranking relation is validated without ambiguity when $g_j(a) - g_j(a') \geq -q_j$. However, when $-p_j \leq g_j(a) - g_j(a') \leq -q_j$, there is still the possibility that a and a' are indifferent.

These outranking relations rely on the introduction of three paramount concepts: *concordance*, *discordance* and *degree of credibility* (Almeida-Dias et al., 2012).

1. Concordance: concerns "the strength of the coalition of criteria being in favor of the outranking relation aS_ja'" (Figueira et al., 2013). The overall concordance favoring "a outranks a'" is modeled using a comprehensive concordance index, $c(a, a')$, that associates a single vector of weights, denoted w_j, such that $w_j > 0, j = 1, \ldots, n$ with the set of criteria (Almeida-Dias et al., 2012). Each intrinsic weight represents the voting power of that criterion when pairwise comparing two actions according to their performances (Figueira et al., 2011). Hence, the comprehensive concordance index can be defined as:

$$c(a, a') = \sum_{j \in C(aPa')} w_j + \sum_{j \in C(aQa')} w_j + \sum_{j \in C(aIa')} w_j + \sum_{j \in C(aQa')} w_j \varphi_j \tag{4.2}$$

where the parameter φ_j is, by definition:

$$\varphi_j = \frac{p_j - (g_j(a') - g_j(a))}{p_j - q_j} \in [0, 1[\tag{4.3}$$

and represents the way the voting power decreases for criteria $g_j \in C(aQa')$. It is important to note that $C(aIa')$ represents the subset of criteria such that aIa', while $C(aPa')$ concerns the set of criteria such that aPa' and $C(aQa')$ relates to the subset of criteria such that aQa' (Almeida-Dias et al., 2012).

When a criterion g_j is in strong opposition to the assertion that "a outranks a'", there is a way to model its veto power (Almeida-Dias et al., 2012). Thereby, an additional threshold, designated veto threshold, v_j (in which $v_j \geq p_j$) can also be assigned to certain criteria and is responsible for increasing their power. For instance, when "a outranks a'" on a large majority of the criteria, the extent to which some criteria are out of this majority should be evaluated before definitely drawing a final conclusion. So, v_j can be considered as the minimal advantage (or minimum difference in performance) of one action over the other, in a criterion g_j, that makes the statement "a outranks a'" incompatible with an overall outranking indifference or preference of one action over the other.

2. Discordance: the discordance concept is applied to those criteria that oppose to the assertion "a outranks a'" and so, have a veto power. For each one of these criteria, this veto power is taken into account by a partial discordance index, denoted by $d_j(a, a'), j = 1, \ldots, m$ (Almeida-Dias et al., 2012). By definition:

$$d_j(a,a') = \begin{cases} 1, & \text{if } g_j(a') - g_j(a) > v_j \\ \frac{(g_j(a') - g_j(a)) - p_j}{v_j - p_j}, & \text{if } p_j < g_j(a') - g_j(a) \leq v_j \\ 0, & \text{if } g_j(a') - g_j(a) \leq p_j \end{cases} \tag{4.4}$$

3. Credibility: the level of credibility of the assertion aS_ja' is reflected in a credibility index, that can be interpreted as the strength of the comprehensive outranking of a over a' (Figueira et al., 2013). In other words, it indicates the degree to which this assertion is more or less justified considering all the criteria. It is defined as:

$$\sigma(a,a') = c(a,a') \prod_{j=1}^{m} T_j(a,a') \tag{4.5}$$

where

$$T_j(a,a') = \begin{cases} \frac{1 - d_j(a,a')}{1 - c(a,a')}, & \text{if } d_j(a,a') > c(a,a') \\ 1, & \text{otherwise} \end{cases} \tag{4.6}$$

The introduction of a minimal degree of credibility, λ, bearing in mind all criteria from F, should be established by the DM in order to validate or not the outranking relation aS_ja'. This minimum credibility level should have a value within the range of [0.5,1] (Almeida-Dias et al., 2012). Taking this into account, binary relations can be defined:

1. λ-outranking ($aS^{\lambda}a'$)
2. λ-preference ($aP^{\lambda}a'$)
3. λ-indifference ($aI^{\lambda}a'$)
4. λ-incomparability ($aR^{\lambda}a'$)

It is relevant to point out that λ-indifference does not translate into the fact that a and a' are indifferent on all criteria, but that a and a' have similar performances in a sufficient subset of criteria so that the chosen λ is achieved. Moreover, for λ-incomparability, both "a outranks a'" and "a' outranks a" must fail to be validated (Almeida-Dias et al., 2010).

The ELECTRE TRI-NC method verifies a series of structural requirements, with beneficial features (Almeida-Dias et al., 2012):

- Conformity, once each characteristic action is required to be assigned to one category;
- Homogeneity, as two actions having an equal outranking credibility index with respect to the characteristic action are placed in the same category;
- Monotonicity, where if one action strictly dominates another, for instance a dominates a', then the minimum category that a can be assigned to is the one that a' is assigned to;
- Stability, being that when a merging or splitting operation is applied, the actions that were previously assigned to the non-modified categories are assigned to the same categories or to the new ones after the modification.

This last structural requirement calls for further explanation, once it requires the characterization of merging and splitting operations. By definition (Almeida-Dias et al., 2012):

- Merging operation: two consecutive categories, C_h and C_{h+1}, will be merged to become a new one, $C_h^{'}$, characterized by a new subset of reference actions, $B'_h = \{b_h^{r'}, r' = 1, \ldots, m'_h\}$, such that for all $g_j \in F$:
  1. For all $b_h^{r\prime}$, there is at least one b_h^r verifying $g_j(b_h^{r\prime}) - g_j(b_h^r) \geq 0$;
  2. For all $b_h^{r\prime}$, there is at least one b_{h+1}^s verifying $g_j(b_{h+1}^s) - g_j(b_h^{r\prime})) \geq 0$;
- Splitting operation: the category C_h is split into two new categories, C'_h and C''_h, characterized by two new distinct subsets of reference actions, $B'_h = \{b_h^{r\prime}, r' = 1, \ldots, m'_h\}$ and $B''_h = \{b_h^{r\prime\prime}, r'' = 1, \ldots, m''_h\}$, respectively, such that:
  1. For all b_{h+1}^s and $b_h^{r\prime\prime}$, $\sigma(b_h^{r\prime\prime}, b_{h+1}^s) < 1$;
  2. For all $b_h^{r\prime\prime}$ and $b_h^{r\prime}$, $\sigma(b_h^{r\prime}, b_h^{r\prime\prime}) < 1$;
  3. For all $b_h^{r\prime}$ and b_{h-1}^r, $\sigma(b_{h-1}^r, b_h^{r\prime}) < 1$;
  4. For all $b_h^{r\prime\prime}$, there is at least one b_h^r verifying $g_j(b_h^{r\prime\prime}) - g_j(b_h^r) \geq 0$, for all $g_j \in F$;
  5. For all $b_h^{r\prime}$, there is at least one b_h^r verifying $g_j(b_h^r) - g_j(b_h^{r\prime}) \geq 0$,for all $g_j \in F$;

4.2.3 Assignment procedure

The ELECTRE TRI-NC method's assignment procedure is composed of two joint rules, called *ascending rule* and *descending rule* (Almeida-Dias et al., 2012). They are used conjointly in order to highlight the highest category and the lowest category which can appear potentially adequate to receive an action

(Almeida-Dias et al., 2010). Both rules firstly pre-select a category between two possible ones, and secondly, they select an appropriate category by making use of a selecting function, $\rho(a, B_h)$, for a possible assignment of each action a (Almeida-Dias et al., 2012).

The definitions of the ascending and descending rules are the following:

- Ascending rule: choose a credibility level, $\lambda(\frac{1}{2} \leq \lambda \leq 1)$. Increase h from zero until the first value, k, such that $\sigma(B_k, a) \geq \lambda$:

  1. For $k = 1$, select C_1 as a possible category to assign action a;
  2. For $1 < k < (q + 1)$, if $\rho(a, B_k) > \rho(a, B_{k-1})$, then select C_k as a possible category to assign to a; otherwise select C_{k-1};
  3. For $k = (q + 1)$, select C_q as a possible category to assign a.

In the ascending rule, a category is select taking into account that: B_k will be the lowest subset of characteristic action a such that the statement "B_k outranks a" is validated with the chosen credibility level (Almeida-Dias et al., 2012).

- Descending rule: choose a credibility level, $\lambda(\frac{1}{2} \leq \lambda \leq 1)$. Increase h from $(q + 1)$ until the first value, t, such that $\sigma(a, B_t) \geq \lambda$:

  1. For $t = q$, select C_q as a possible category to assign action a;
  2. For $0 < t < q$, if $\rho(a, B_t) > \rho(a, B_{t+1})$, then select C_t as a possible category to assign to a; otherwise select C_{t+1};
  3. For $t = 0$, select C_1 as a possible category to assign a.

In the descending rule, a category is select taking into account that: B_t is the highest subset of characteristic actions such that the statement "a outranks B_t" is validated with the chosen credibility level (Almeida-Dias et al., 2012).

Therefore, the assignment procedure in this sorting method leads to the selection of two categories to which an action can be assigned. As a consequence, three different results are possible, which should be validated by the DM. Firstly, if the categories selected are the same, a single category is selected. On the other hand, if the categories selected are consecutive, then the DM should choose one of these two. Finally, if the selection of two categories leads to two non-consecutive categories, then the DM is responsible for choosing one of the two selected categories or an intermediate one.

4.2.4 Application of the method

Having described the ELECTRE TRI-NC method's structure, it is possible to turn to how the application of this method is carried out throughout this dissertation, using the *MCDA-ULaval*. *MCDA-ULaval* is a free software programmed in *Java*, that was developed in the *Université Laval* in Quebec, Canada and that supports the application of the ELECTRE family of algorithms (Verdasca, 2016).

This software allows for the creation of projects that can have multiple sets of data and is able to import and export data in a *CSV* format (Verdasca, 2016). Its user interface provides easy project management options as well as the possibility of changing the method and performing sensitivity analysis. Moreover, the possibility of automatic normalization of the weights, analysis of the different scenarios by means of diverse types of graphs and charts and the fact that *MCDA-ULaval* supports the insertion of criteria in ordinal or cardinal scales constitute added advantages.

Although the software presents some flaws when it comes to the lack of support for the beginner user and regarding some internal functionalities, *MCDA-ULaval* constitutes an useful and effective tool to assist MCDA processes (Verdasca, 2016).

4.3 Summary

This chapter was devoted to the acquaintance of MCDA and the basic concepts that are necessary for its understanding and application. DA is defined as the activity of the person who, through the use of explicit but not necessarily completely formalized models, helps to obtain elements of response to the questions posed by a stakeholder of a decision process. In this process, there are two fundamental actors: the DM, that is the individual, entity or community that expresses the preferences in the development of the model and the analyst, that enlightens the DM across the process. When it comes to the foundations of the DA activity, three pillars stand out: the actions, the consequences and the modeling of one or several preference systems.

Turning to the sorting method that was used in this dissertation, ELECTRE TRI-NC, it is a non-compensatory method that includes characteristics associated such as the use of discriminating thresholds, the possibility of introducing veto thresholds, among others. The concepts, definitions and notations of ELECTRE TRI-NC allow to then explore the outranking concept in such a way that binary relations such as outranking, preference, indifference and incomparability can be defined. The assignment procedure of ELECTRE TRI-NC uses two joint rules, the ascending and descending rules to obtain results.

In regard to the application of the method, *MCDA-ULaval* was the software chosen to support this DA procedure, a method developed in the *Université Laval*, in Quebec.

Chapter 5

Case Study

Chapter five of this dissertation introduces the present case study, in light of the four main steps of the DA process: (i) Representation of the problem situation, (ii) Problem Formulation, (iii) Evaluation Model and (iv) Final Recommendation. For each of these, the ventilator classification problem is scrutinized and the interactions between the analyst and DM are described.

5.1 Overview

As mentioned in previous chapters, healthcare entities hold responsibilities throughout the medical equipment life cycle, from the acquisition process to the reception of the equipment, its maintenance, monitoring and replacement. Moreover, during the equipment lifetime, several management decisions are made, aiming to anticipate complications and promoting a high quality of care at all times. Usually, various factors are associated with these decisions, as well as several inputs from different sources. What is more, when these decisions fail to be carefully structured in a healthcare organization, undesirable events can occur: equipment failure at a critical time, dissatisfaction from the health professionals regarding the performance or technological level of a medical device, unavailability of parts or support from the manufacturer or the rise of interoperability constraints.

In *Hospital da Luz Lisboa*, DIME is responsible for maintenance management decisions. The cost implications of these decisions, their subjectivity and their complex and time-consuming character lead to the need for implementation of an efficient life cycle planning and management program. The hospital has already recognized the importance of employing such a program and has invested in strategies for this purpose. For instance, *Hospital da Luz Lisboa* keeps an updated and organized inventory of all its medical devices, as well as an equipment failure occurrence computerized list that contains valuable information for the assessment of medical equipment during their lifetime. Moreover, the hospital has recently introduced a software solution, called *Valuekeep*, that supports the maintenance operations, among several other processes.

However, concerning the planning and management program in *Hospital da Luz Lisboa*, DIME is aware of the importance of developing additional tools that complement the maintenance strategies already employed and that align themselves with the overall vision, mission and values of the hospital

and, ultimately, *Luz Saúde*. In particular, when it comes to the assessment and classification of medical equipment in *Hospital da Luz Lisboa*, the implementation of mindfully structured DA mechanisms aims to ensure optimal equipment functionality. As a consequence, a better resource allocation efficiency in the hospital is expected, with an increase in the satisfaction levels among health professionals as well as the consolidation of the company's mission towards technology and innovation.

Taking the aforementioned into consideration, a DA tool for the classification of the maintenance condition of medical equipment was requested, through the introduction of an MCDA model to provide support to the current maintenance strategy. As previously stated, there is an inherent relevance associated with medical equipment, since these have a direct impact on human lives. That is why the method employed, ELECTRE TRI-NC, exhibits characteristics that allow obtaining a better classification of medical equipment. Firstly, ELECTRE TRI-NC has a non-compensatory character, once "good performances" on one criterion do not compensate for "bad performances" in another. In decisions that have life implications, this is an aspect that cannot be overlooked. In addition, the method also introduces the concept of veto thresholds that are used to increase the power of certain criteria and reinforce this non-compensatory character, expressed by the application of a veto power. Besides this, ELECTRE TRI-NC features discriminating thresholds, that allow coping with the arbitrariness and subjectivity in the definition of the criteria and the overall imperfect nature of data, typically present in that which is a complex and demanding context.

When developing a requisite and rigorous model, the context and the peculiarities of the organization must be taken into account. Additionally, the identification of one type of medical equipment to be the focus of the study allowed for including particular characteristics that were crucial for a meticulous assessment. Considering this, in order to perform the specification of the study to a single type of medical equipment, the concept of critical medical equipment was analyzed and *Hospital da Luz Lisboa*'s case was scrutinized. Ultimately, DIME recognized that, at the date of February 18, 2020, medical ventilators presented the highest priority for the introduction of a classification model from a maintenance perspective.

In the process of creating an MCDA model for the classification of medical ventilators in *Hospital da Luz Lisboa*, since a co-constructive approach was utilized, the interaction between the analyst and the DM, entities defined in section 4.1, cannot be considered neutral. In fact, it is an integral part of the DA process, since the rationality model is built according to how the client answers preference related questions (Bouyssou et al., 2006).

Besides, the analyst followed a multicriteria methodology in the construction of the model and by doing so, the decision process was structured in four previously mentioned steps: (i) Representation of the problem situation, (ii) Problem Formulation, (iii) Evaluation Model and (iv) Final Recommendation. These four products of the decision aiding process can be further discussed and detailed for the present case study.

5.2 The problem situation

The first step of the DA process consisted on identifying and representing the problem in question. By interacting with the DM, the analyst is able to build a shared in-depth understanding of the problem in order to answer the following questions: who has a problem? Why is this a problem? Who is responsible in this situation? What concerns does the DM bring forward? What is the level of commitment of the DM to the problem in question? (Bouyssou et al., 2006).

Regarding the present dissertation, the focus was on the classification of the medical ventilators found at *Hospital da Luz Lisboa*. DIME, the department responsible for medical equipment maintenance in *Hospital da Luz Lisboa*, recognized this subject as a crucial problem for the hospital, as the overall performance of this type of life support equipment is determinant in achieving the best possible health outcomes. Moreover, medical equipment in general constitute a high financial burden for the healthcare organization, and, from these, medical ventilators in particular are a significant part, since these are intricate devices that are highly required in multiple functional areas of the hospital. The maintenance of technologically advanced and top-quality ventilators also contributes to the satisfaction of the professionals that deal with the devices, resulting in a higher capacity for attracting, developing and retaining human resources in *Luz Saúde*.

As mentioned in section 4.1, the DM represents the individual, entity or community that is interested in the decision process and that is responsible for providing the judgments that are imposed in such a process. Considering the case study at hand, different parties were considered. This type of MCDA model requires clinical expertise in the analysis of a detailed and ever-changing topic, which could be provided by health professionals and technical experts. Also, the consideration of the managerial concerns for the health organization is an important issue, which may require a management department members' perspective. This decision process can be seen as demanding and time-consuming for some and, thereby, the availability of the individuals was also factored in. In this study, the DM, two biomedical engineers from *Luz Saúde* and members of DIME in *Hospital da Luz Lisboa*, have proximity with the administrative sectors, the health professionals and the technical staff of the hospital. This way, they possessed the necessary knowledge not only when it came to maintenance management processes in the hospital, but also to equipment related matters and their clinical application. The DM accompanied the integral DA process and provided their shared judgments with determinant information in every step of the construction and analysis of the MCDA model.

Regarding the classification of medical ventilators in *Hospital da Luz Lisboa*, the concerns expressed by the DM were consistent with the most frequently found across the literature reviewed in section 3.2.2, even though the objectives of the methodologies did not always match. The safety when ventilating a patient, the quality of the treatment provided, the overall performance of the equipment and its technology and technical status were unanimously identified as primary matters to be analyzed. To do so, knowledge of the inherent characteristics of the different ventilators featured in the model were nec-

essary, as well as details regarding the functioning of these in *Hospital da Luz Lisboa*. Moreover, as a private healthcare organization, financial concerns arose and so, information of this nature was required. The DM also voiced that the viewpoints of health professionals from *Hospital da Luz Lisboa* should be integrated, factoring these in the assessment of the usability of each ventilator. Lastly, within many organizations, there has been an enlarging debate concerning the inclusion of "sustainability principles and sustainable development" (Chiarini and Vagnoni, 2016). For medical devices in particular, the need for sterility and the stringent standards usually applied have delayed the implementation of sustainability practices (Mann et al., 2018). However, the DM recognized that embracing this topic in medical equipment maintenance management, and specifically, in the classification of ventilators produces a more valuable output and provides a point of differentiation within the organization.

5.3 Problem formulation

Once the problem statement has been identified, the second step of the DA process includes its translation into decision support language, by establishing the actions and criteria of the DA process. The analyst may present the DM with several problem formulations and the DM should check whether the concerns previously expressed are appropriately addressed. This is a critical point of the decision process since the adoption of a particular problem formulation leads to different final recommendations.

5.3.1 Actions

As mentioned in section 4.1, the actions are the application points of the decision process and in the case study at hand, the existing medical ventilators in *Hospital da Luz Lisboa*'s inventory at the date of February 18, 2020, were the basis for the actions to be included in the model. There were 47 individual ventilators present in the initial sample, from which, a data selection procedure was carried out.

The ventilators for transport were excluded since these were considered by the DM as less critical medical equipment to the hospital due to their lower level of complexity. The DM also alluded to the fact that, due to their characteristics, this type of medical ventilators did not bring up the same maintenance management concerns as the other types of ventilators and so, their classification should not rely on the same model. Moreover, the medical ventilators that were marked in the inventory as having a "not defined (ND)" brand or model were also excluded from the analysis, once this information is necessary for their assessment.

The data selection procedure resulted in a total of 39 medical ventilators, with 22 anesthesia ventilators, 11 intensive care ventilators and six neonatal ventilators. Each ventilator had an active number, which acted as a unique identifier of the medical device in the hospital. Having said that, the alternatives or actions a_m, for $m = 1, \ldots, 39$, are presented in Table 5.1.

Table 5.1: Medical ventilators in *Hospital da Luz Lisboa* that constitute the actions or alternatives of the present case study. The action's description contains the active number, the model, the brand and the type of medical ventilators it is refering to.

Action	Description
a_1	14AH131, *Fabius MRI*, *Drager*, Anesthesia Ventilator
a_2	14AC373, *Fabius Tiro*, *Drager*, Anesthesia Ventilator
a_3	14AC717, *Fabius Tiro*, *Drager*, Anesthesia Ventilator
a_4	14AD179, *Fabius Tiro*, *Drager*, Anesthesia Ventilator
a_5	14AD215, *Fabius Tiro*, *Drager*, Anesthesia Ventilator
a_6	14AG442, *Fabius Tiro*, *Drager*, Anesthesia Ventilator
a_7	14AG453, *Fabius Tiro*, *Drager*, Anesthesia Ventilator
a_8	14AG712, *Fabius Tiro*, *Drager*, Anesthesia Ventilator
a_9	14AG786, *Fabius Tiro*, *Drager*, Anesthesia Ventilator
a_{10}	14AG807, *Fabius Tiro*, *Drager*, Anesthesia Ventilator
a_{11}	14AG827, *Fabius Tiro*, *Drager*, Anesthesia Ventilator
a_{12}	14AH137, *Fabius Tiro*, *Drager*, Anesthesia Ventilator
a_{13}	14AH254, *Fabius Tiro*, *Drager*, Anesthesia Ventilator
a_{14}	14AD002, *Primus*, *Drager*, Anesthesia Ventilator
a_{15}	14AD015, *Primus*, *Drager*, Anesthesia Ventilator
a_{16}	14AD035, *Primus*, *Drager*, Anesthesia Ventilator
a_{17}	14AD067, *Primus*, *Drager*, Anesthesia Ventilator
a_{18}	14AD142, *Primus*, *Drager*, Anesthesia Ventilator
a_{19}	14AG544, *Primus*, *Drager*, Anesthesia Ventilator
a_{20}	14AG964, *Primus*, *Drager*, Anesthesia Ventilator
a_{21}	14AG977, *Primus*, *Drager*, Anesthesia Ventilator
a_{22}	14AD051, *Zeus*, *Drager*, Anesthesia Ventilator
a_{23}	14AG885, *Carina Home*, *Drager*, Intensive Care Ventilator
a_{24}	14AD329, *Evita 4 Edition*, *Drager*, Intensive Care Ventilator
a_{25}	14AD358, *Evita 4 Edition*, *Drager*, Intensive Care Ventilator
a_{26}	14AD376, *Evita 4 Edition*, *Drager*, Intensive Care Ventilator
a_{27}	14AD704, *Evita 4 Edition*, *Drager*, Intensive Care Ventilator
a_{28}	14AG848, *Evita 4 Edition*, *Drager*, Intensive Care Ventilator
a_{29}	14AG867, *Evita 4 Edition*, *Drager*, Intensive Care Ventilator
a_{30}	14AG893, *Evita 4 Edition*, *Drager*, Intensive Care Ventilator
a_{31}	14AI116, *Evita 4 Edition*, *Drager*, Intensive Care Ventilator
a_{32}	14AI132, *Evita 4 Edition*, *Drager*, Intensive Care Ventilator
a_{33}	14AD381, *Evita XL*, *Drager*, Intensive Care Ventilator
a_{34}	14AA275, *Babylog 8000 Plus*, *Drager*, Neonatal Ventilator
a_{35}	14AE065, *Babylog 8000 Plus*, *Drager*, Neonatal Ventilator
a_{36}	14AA289, *Fabian*, *Acutronic*, Neonatal Ventilator
a_{37}	14AB111, *Infant Flow SIPAP*, *Carefusion*, Neonatal Ventilator
a_{38}	14AE058, *Infant Flow SIPAP*, *Carefusion*, Neonatal Ventilator
a_{39}	14AE067, *Infant Flow SIPAP*, *Carefusion*, Neonatal Ventilator

5.3.2 Criteria Tree

In the co-construction of the MCDA model, the establishment of criteria for the classification of medical ventilators was done in view of the concerns raised by the DM in their interaction with the analyst. As noted earlier, this constitutes a crucial moment that influences the remainder of the DA process.

For this case study, five fundamental points of view (FPV) were created to capture the primary concerns expressed by the DM for the assessment of ventilators. With each of these, the subcriteria or consequences were identified by the analyst, by investigating the dimensions from that point of view that were valued by the DM and that were able to influence the preference of one action over the other. Then, these were arranged in a coherent family of criteria, allowing the operationalization of the information associated with the subcriteria and taking into account the logical requirements of exhaustiveness, cohesiveness and nonredundancy. It is important to note that, regarding the value dimensions involved in each criterion, these can have one dimension or be built-in criteria, the latter being multidimensional and having more than one subcriterion associated (Bana e Costa and Beinat, 2005).

It was then possible to construct the criteria tree in Table 5.2, providing a visual representation of these components of the DA process. This result of the problem formulation systemized the data available and simplified the process of understanding and interpreting the elements for the DM.

The description of each element of the criteria tree is presented in Table 5.2, with the fundamental points of view FPV$_i$, for $i = 1, \ldots, 5$, the criteria g_n, for $n = 1, \ldots, 12$ and the subcriteria.

Table 5.2: Criteria Tree regarding the classification of medical ventilators in *Hospital da Luz Lisboa*. The set of Fundamental Points of View, Criteria and Subcriteria are presented.

Fundamental Points of View	Criteria	Subcriteria
FPV1 Technical	g_1 Technology level (max)	$g_{1,1}$ Technical features
		$g_{1,2}$ Upgrade level
		$g_{1,3}$ Interoperability
		$g_{1,4}$ Remote assistance
FPV2 Quality	g_2 Reliability (max)	
	g_3 Lifetime ratio (min)	
	g_4 Utilization (min)	
	g_5 Visual condition (max)	
	g_6 Preventive maintenance commitment (max)	
	g_7 Adaptability (max)	$g_{7,1}$ Access of healthcare services
		$g_{7,2}$ Portability
		$g_{7,3}$ Accessories and consumables' standardization
	g_8 Safety (max)	$g_{8,1}$ Integrated safety functions
		$g_{8,2}$ Cybersecurity
FPV3 Clinical usability	g_9 Professionals' satisfaction (max)	
	g_{10} User friendliness (max)	$g_{10,1}$ Ease of use
		$g_{10,2}$ Ease of daily routine
FPV4 Financial	g_{11} Maintenance costs (min)	$g_{11,1}$ Equipment maintenance factor
		$g_{11,2}$ New functionalities expenses
FPV5 Environmental	g_{12} Environmental sustainability (max)	$g_{12,1}$ Ecofriendly production Process
		$g_{12,2}$ Ecoefficiency of the equipment

FPV1: Technical

This fundamental point of view expressed the concern of the DM regarding the inherent properties of the ventilator. Thereby, it allowed for the assessment of the built-in features of one ventilator and analyzed the degree to which the ventilator contributed to the fulfilment of the hospital's mission to the commitment to excellence and innovation.

Technology level, $\mathbf{g}_1$

Measured the overall technology level of the ventilator. It can range from state-of-the-art to obsolete due to technological developments. The preference increases with the maximization of the performance on the criterion.

- **Technical features, $\mathbf{g}_{1,1}$:** emphasized on characteristics of the equipment that are considered key in the technical assessment of the ventilator, for instance, the treatment delivery, the display and the functioning options;
- **Interoperability, $\mathbf{g}_{1,2}$:** measured the integration of the device in the network and capability of working with other products or systems;
- **Upgrade level, $\mathbf{g}_{1,3}$:** evaluated the upgradability of the medical device;
- **Remote assistance, $\mathbf{g}_{1,4}$:** assessed the possibility of the manufacturer to remotely connect to the ventilator, for potential monitoring and solving of complications with the equipment.

FPV2: Quality

This point of view aimed to evaluate the performance of the medical ventilators in *Hospital da Luz Lisboa*, according to the hospital, health professionals and patient's demands. It also took into consideration the wear level of each ventilator at the date.

Reliability, $\mathbf{g}_2$

Quantified the malfunction/failure events, which served as a measure of how reliable a medical equipment was. Given that zero failures are always the users' target, the preference direction is minimization.

Lifetime ratio, $\mathbf{g}_3$

Evaluated the degree of deterioration of a ventilator according to the ratio of its age and the expected lifetime of the product. The criterion's preference increases when this ratio is minimized.

Utilization, $\mathbf{g}_4$

Calculated the amount of use a piece of equipment had, once it influences its wear and overall service. Hence, the preference direction is minimization.

Visual condition, g_5

Inspection of the visual condition of the medical device, which the aim is to be maximized.

Preventive maintenance commitment, g_6

Extent of the commitment of the hospital to a preventive maintenance strategy, which was determined by the degree of fulfilment of the preventive maintenance plan and whether it was done by the manufacturer or by other representatives. Since the preventive maintenance procedures are expected to prolong the life of the equipment, the commitment should be maximized.

Adaptability, g_7

The adaptability of the ventilator can be examined by studying its ability to adjust to the hospital's various needs, which ought to be maximized. Accessories and consumables' standardization was a dimension included in this criterion once a higher degree of standardization is translated into more adaptable equipment within the hospital.

- **Access of healthcare services, $g_{7,1}$:** evaluated the capacity of a ventilator to be used in diverse patient types. For instance, it is analyzed if a medical ventilator is able to ventilate any patient, including neonates, pediatrics, adults and even more debilitated patients with more complex procedures or morbidly obese patients.

- **Portability, $g_{7,2}$:** evaluated the degree of portability of the equipment in the hospital, which can also be translated into the flexibility level of the hardware.

- **Accessories and consumables' standardization, $g_{7,3}$:** assessed the homogeneity of the accessories and consumables required by each ventilator in *Hospital da Luz Lisboa*.

Safety, g_8

Measured the way the ventilator was able to minimize the risks for the patient, maximizing the overall safety. This involved not only the safety features associated with its utilization but also concerning cybersecurity issues, both capable of potentially impacting the safety and effectiveness of the device.

- **Integrated safety functions, $g_{8,1}$:** examined the way the equipment was able to prevent adverse situations that can happen during a patient utilization of the ventilator, such as utilization errors by the health professionals and other unexpected complications.

- **Cybersecurity, $g_{8,2}$:** contemplated whether the device had features that allowed to maximize the protection of systems, networks and programs from digital attacks.

FPV3: Clinical Usability

Zhang and Walji (2011) consider that usability appraises "how useful, usable, and satisfying a system is for the intended users to accomplish goals in the work domain by performing certain sequences of tasks". Applying to the clinical context, this criterion intended to include the user's judgments regarding the clinical and operational impact that the ventilator created in the hospital setting. Therefore, although it was the DM that provided the final judgements for the assignment of a performance value to each medical ventilator, the views of the health professionals (doctors and nurses from *Hospital da Luz Lisboa*, specifically) were a determining factor.

Professionals' satisfaction, $\mathbf{g}_9$

Included the health professionals' perspective on the suitability of the medical equipment for the needs of the patients and its overall performance. Its preference direction is maximization.

User friendliness, $\mathbf{g}_{10}$

Appraised the overall user friendliness of the medical equipment, including the intuitiveness of the interface, operational system and daily routine procedure. The preference increases in the direction of maximization of the performance according to this criterion.

- **Ease of use, $\mathbf{g}_{10,1}$:** assessed the easiness of handling the ventilator's user interface and operational system, by including the user's point of view.
- **Ease of daily routine, $\mathbf{g}_{10,2}$:** each ventilator requires a daily maintenance procedure done by a health professional. Therefore, including the users' point of view in the assessment of the speed and facility of the daily maintenance served as an important measure of the user friendliness of the medical ventilator.

FPV4: Financial

A measure of the financial impact that the maintenance of the ventilator entailed. This measure was important because the financial aspect can influence the decision of when a failure occurs, repairing the medical equipment or buying a new one, taking into account the economic consequences that such a decision may have on the organization.

Maintenance costs, $\mathbf{g}_{11}$

Included the cost associated with repairing a ventilator, buying parts or adding new functionalities to it, which were financial burdens that had to be considered by the hospital management and should ultimately be minimized.

- **Equipment maintenance factor, $\mathbf{g}_{11,1}$:** measured the cumulative expenses encountered in performing preventive and corrective maintenances to the medical device, in relation to its acquisition price.

– **New functionalities expenses, $g_{11,2}$:** measured the costs associated with the addition of new functionalities and updates to the ventilator.

FPV5: Environmental

Measured the way one particular equipment contributed to the hospital's environmental sustainability.

Environmental sustainability, g_{12}

As a topic that receives plenty of attention from different governmental departments and from the media, it should be introduced in the classification of ventilators. Its preference direction is maximization.

– **Ecofriendly production process, $g_{12,1}$:** assessed whether the supplier of the ventilator employed sustainable practices in the production of the equipment, such as reduction of waste, reduction of energy use, water-efficient practices or favoring of sustainable materials (Sachidananda et al., 2016).

– **Eco-efficiency of the equipment, $g_{12,2}$:** concerned the level to which the use of the ventilator in the hospital reduced environmental impact. This reduction can be done if the equipment includes "green" features that bear in mind resources depletion, waste levels, environmental noise, the consumption of energy, water and other substances (Akadiri et al., 2012).

5.4 Evaluation Model

At this point, the analyst had the material required to proceed to the third step of the DA process, the construction of an evaluation model. By organizing the information gathered on the first two steps, the problem statement and formulation, it was possible to compose a model to obtain a formal answer to the problem. This step involves not only the development of scales for each criterion but also the definition the criteria weights. With these data, the performances of the actions according to all criteria were assigned. Furthermore, the set of predefined and ordered categories for this case study was presented, as well as the respective reference actions and the thresholds considered in the model.

5.4.1 Criteria Scales

A criterion scale provides a way to assess performance, yielding a score to each action in regard to one criterion. Turning to the problem in question, the criteria defined previously are either one dimensional or built-in criteria. In the first case, the criteria scales are built considering the necessary levels to represent a single dimension. For the second case, the criteria scales must incorporate all dimensions of a criterion, by combining them into a single ordered set of possible performances. Similarly to prior, the definition of the subcriteria scales, the aggregation of subcriteria and the subsequent definition of the criterion scales was performed in proximity with the DM, so as to capture all significant aspects and the combinations of subcriteria that comply with the DM's convictions. Bearing the aforementioned in mind, the criteria scales and their description are presented below.

Technology Level, g_1

This criterion incorporates four dimensions: 'Technical features' ($g_{1,1}$), 'Interoperability' ($g_{1,2}$), 'Upgrade level' ($g_{1,3}$) and 'Remote assistance' ($g_{1,4}$). Each of these subcriteria has a qualitative, discrete and constructed scale, displayed in Table 5.3, 5.4, 5.5 and 5.6.

Considering the four subcriteria and their respective scales, the possible combinations for the construction of the criterion scale summed up to 48. Analyzing all the possible combinations, the number of levels for 'Technology level' (g_1) was reduced to five levels, presented in Table 5.7. According to the DM, these levels provided a complete and accurate representation of all the dimensions associated with the criterion.

Table 5.3: Subcriterion scale exhibiting the levels, description and abbreviation concerning 'Technical features'.

Technical features, $g_{1,1}$		
Levels	**Description**	**Abbreviation**
3	The ventilator presents a high number of treatment, display and functioning options.	High
2	The ventilator presents a medium number of treatment, display and functioning options.	Medium
1	The ventilator presents a low number of treatment, display and functioning options.	Low

Table 5.4: Subcriterion scale exhibiting the levels, description and abbreviation concerning 'Interoperability'.

Interoperability, $g_{1,2}$		
Levels	**Description**	**Abbreviation**
4	Potential bidirectional communication between the ventilator and the patient. Moreover, possibility of connection of the ventilator to a central registry system, as well as to other devices.	Very high Interoperability
3	The ventilator is connected to a central registry system and allows for communication to other devices.	High Interoperability
2	The ventilator is connected to a central registry system or allows for communication to other devices.	Moderate Interoperability
1	The ventilator works in a stand-alone system, given that it is not connectable to other devices or a central registry system.	Low Interoperability

Table 5.5: Subcriterion scale exhibiting the levels, description and abbreviation concerning 'Upgrade level'.

Upgrade level, $g_{1,3}$		
Levels	**Description**	**Abbreviation**
2	The ventilator allows for possible upgrading procedures.	Upgradable
1	The ventilator cannot not undergo any upgrading procedures.	Not Upgradable

Table 5.6: Subcriterion scale exhibiting the levels, description and abbreviation concerning 'Remote assistance'.

Remote assistance, $g_{1,4}$		
Levels	**Description**	**Abbreviation**
2	The manufacturer is able to remotely access the ventilator, possibly detecting and solving emerging problems.	Effective
1	The manufacturer is not able to remotely access the ventilator.	Not Effective

Table 5.7: Criterion scale for 'Technology level', presenting the four subcriteria aggregated: 'Technical features', 'Upgrade level', 'Interoperability' and 'Remote assistance'.

Technology Level, g_1					
Preference direction: Maximization					
	Levels	**Technical features**	**Interoperability**	**Remote assistance**	**Upgrade level**
5	State-of-the-art	High	Very High Interoperability	Effective	Upgradable
4	Greatly Advanced	High	Very High Interoperability	(...)	(...)
			High Interoperability	(...)	(...)
3	Moderately Advanced	High	Moderate Interoperability	(...)	(...)
		Medium	Very High Interoperability	(...)	(...)
			High Interoperability	(...)	(...)
			Moderate Interoperability	(...)	(...)
2	Minimally Advanced	High	Low Interoperability	(...)	(...)
		Medium	Low Interoperability	(...)	(...)
		Low	Very High Interoperability	(...)	(...)
			High Interoperability	(...)	(...)
1	Obsolete	Low	Moderate Interoperability	(...)	(...)
			Low Interoperability	(...)	(...)

Reliability, g_2

Aiming to determine how dependable each ventilator in the analysis is, this criterion took into consideration the malfunctions/failure events it has suffered. Using a quantitative, continuous and indirect descriptor of performance, this criterion is operationalized by using the following indicator:

Number of failure events

Preference direction: Minimization

Lifetime ratio, g_3

This criterion utilizes a ratio of the age of the ventilator and its expected lifetime to examine the deterioration of the equipment, employing a quantitative, continuous and direct descriptor:

$$\frac{\text{Age}}{\text{Expected Product Life}} \tag{5.1}$$

Preference direction: Minimization

Utilization, g_4

Similarly to g_3, this criterion operates with a quantitative, continuous and direct descriptor. Here, the utilization of each ventilator is measured by the indicator below.

Total hours of utilization

Preference direction: Minimization

Visual condition, g_5

Regarding this one dimensional criterion, a qualitative, discrete and constructed scale was created, as observed in Table 5.8.

Table 5.8: Criterion scale exhibiting the levels, description and abbreviation concerning 'Visual condition'.

Visual condition, g_5		
Preference direction: Maximization		
Levels	**Description**	**Abbreviation**
2	The ventilator appears to be in overall good visual condition, with no visible deterioration marks.	Good Condition
1	The ventilator presents several visible deterioration marks.	Poor Condition

Preventive Maintenance Commitment, g_6

Analogously to g_5, the qualitative, discrete and constructed scale in Table 5.9 evaluates, for each medical equipment, the commitment to the preventive maintenance plan.

Table 5.9: Criterion scale exhibiting the levels, description and abbreviation concerning 'Preventive maintenance commitment'.

Preventive maintenance commitment, g_6		
Preference direction: Maximization		
Levels	**Description**	**Abbreviation**
4	The preventive maintenance procedures have been performed by the manufacturer and according to the periodicities defined.	Excellent
3	The preventive maintenance procedures were not carried out by the manufacturer but have been performed according to the periodicities defined.	Good
2	The preventive maintenance procedures were carried out by the manufacturer, but the established periodicities were not respected.	Acceptable
1	The preventive maintenance procedures were not carried out by the manufacturer and the established periodicities were not respected.	Poor

Adaptability, g_7

This criterion is operationalized by combining three subcriteria: 'Access of healthcare services' ($g_{7,1}$), 'Portability' ($g_{7,2}$) and 'Accessories and consumables' standardization' ($g_{7,3}$). Each of these subcriteria has a qualitative, discrete and constructed scale, displayed on Tables 5.10, 5.11 and 5.12.

Even though the total number possible combinations were 12, the DM proposed the aggregation of levels, resulting in a six level scale, presented in Table 5.13.

Table 5.10: Subcriterion scale exhibiting the levels, description and abbreviation concerning 'Access of healthcare services'.

Access of healthcare services, $g_{7,1}$		
Levels	**Description**	**Abbreviation**
2	The ventilator is able to ventilate and perform to the needs of most patients.	Overarching
1	The ventilator is limited to the type of patient and complexity of the procedures.	Specific

Table 5.11: Subcriterion scale exhibiting the levels, description and abbreviation concerning 'Portability'.

Portability, $g_{7,2}$		
Levels	**Description**	**Abbreviation**
3	The ventilator is cart mounted.	Cart mounted
2	Although the ventilator is fixed, it allows some flexibility in its usage or it is possible to buy an accessory to enhance portability.	Fixed yet flexible
1	The ventilator is strictly fixed.	Fixed

Table 5.12: Subcriterion scale exhibiting the levels, description and abbreviation concerning 'Accessories and consumables' standardization'.

Accessories and consumables' standardization, $g_{7,3}$		
Levels	**Description**	**Abbreviation**
2	The ventilator requires accessories and consumables that are homogeneous when considering the ones used in other equipment in the hospital.	Homogeneous
1	The ventilator requires accessories and consumables that are uncommon when considering the ones used in other equipment in the hospital.	Heterogeneous

Table 5.13: Criterion scale for 'Adaptability', presenting the three subcriteria aggregated: 'Access of healthcare services', 'Portability' and 'Accessories and consumables' standardization'.

Adaptability, g_7				
Preference direction: Maximization				
Levels		**Portability**	**Accessories and consumables' standardization**	**Access of healthcare services**
6	Excellent Adaptability	Cart Mounted	Homogeneous	Overarching
5	Very Good Adaptability	Cart Mounted	Homogeneous	Specific
4	Good Adaptability	Cart Mounted	Heterogeneous	(...)
		Fixed yet flexible	Homogeneous	(...)
3	Moderate Adaptability	Fixed yet flexible	Heterogeneous	(...)
2	Low Adaptability	Fixed	Homogeneous	(...)
			Heterogeneous	Overarching
1	Unadaptable	Fixed	Heterogeneous	Specific

Safety, g_8

When it comes to 'Safety' (g_8), two dimensions are featured: 'Integrated safety functions' ($g_{8,1}$) and 'Cybersecurity' ($g_{8,2}$). Each of these subcriteria has a qualitative, discrete and constructed scale, displayed on Tables 5.14 and 5.15.

Taking into consideration the subcriteria and their respective scales, a total of six combinations was possible. However, the DM concluded that with only the four levels presented in Table 5.16, a comprehensive description of the aspects included in the criterion was produced.

Table 5.14: Subcriterion scale exhibiting the levels, description and abbreviation concerning 'Integrated safety functions'.

Integrated safety functions, $g_{8,1}$		
Levels	**Description**	**Abbreviation**
3	The ventilator has a satisfatory amount of safety functions.	Satisfactory
2	The ventilator includes the basic safety functions.	Basic
1	The ventilator includes an insufficient amount of safety functions.	Insufficient

Table 5.15: Subcriterion scale exhibiting the levels, description and abbreviation concerning 'Cybersecurity'.

Cybersecurity, $g_{8,2}$		
Levels	**Description**	**Abbreviation**
2	The ventilator contains features that allow the protection of systems, networks and programs from digital attacks.	Yes
1	The ventilator does not contain features that allow the protection of systems, networks and programs from digital attacks.	No

Table 5.16: Criterion scale for 'Safety', presenting the two subcriteria aggregated: 'Integrated safety functions' and 'Cybersecurity'.

Safety, g_8			
Preference direction: Maximization			
Levels		**Integrated safety functions**	**Cybersecurity**
4	Safe ventilator	Satisfatory	Yes
3	Medium Safety	Satisfatory	No
		Basic	Yes
2	Low Safety	Basic	No
		Insufficient	Yes
1	Ventilator not safe	Insufficient	No

Professional's satisfaction, g_9

With the qualitative, discrete and constructed scale in Table 5.17, the DM considered it to be possible to assess the health professionals' perspective on the performance of the medical ventilators in *Hospital da Luz Lisboa*.

Table 5.17: Criterion scale exhibiting the levels, description, abbreviation and code concerning 'Professionals' satisfaction'.

Professionals' satisfaction, g_9		
Preference direction: Maximization		
Levels	**Description**	**Abbreviation**
5	The ventilator's overall functioning exceeds the expectations of the health professionals.	Very Satisfactory
4	The health professionals are satisfied with the overall functioning of the ventilator.	Satisfactory
3	The health professionals have a neutral opinion regarding the overall functioning of the ventilator.	Neutral
2	The health professionals are dissatisfied with the overall functioning of the ventilator.	Dissatisfactory
1	The health professionals consider that the overall functioning of the ventilator is far from meeting the standards of healthcare.	Very Dissatisfactory

User friendliness, g_{10}

Criterion g_{10}, 'User friendliness' incorporates two subcriteria, 'Ease of use' ($g_{10,1}$) and 'Ease of daily routine' ($g_{10,2}$). Each of these subcriteria has a qualitative, discrete and constructed scale, displayed on Tables 5.18 and 5.19.

Once again, it was a decision of the DM to take the six possible combinations of the subcriteria and construct a scale (see Table 5.20) with only five representative levels of the aspects in question.

Table 5.18: Subcriterion scale exhibiting the levels, description and abbreviation concerning 'Ease of use'.

Ease of use, $g_{10,1}$		
Levels	**Description**	**Abbreviation**
3	Friendly user interface and overall intuitive operational system.	Easy
2	Challenging operational system and user interface.	Somewhat Difficult
1	Inconvenient operational system and user interface that imposes strong difficulties to the healthcare professionals.	Quite Difficult

Table 5.19: Subcriterion scale exhibiting the levels, description and abbreviation concerning 'Ease of daily routine'.

Ease of daily routine, $g_{10,2}$		
Levels	**Description**	**Abbreviation**
3	The ventilator has daily maintenance routine assisted functions that make the process faster and simple to the health professional.	Easy
2	The ventilator's daily maintenance routine procedure is somewhat inconvenient and tiresome to the health professional.	Somewhat Difficult
1	The ventilator's daily maintenance routine procedure is time-consuming and complex to the health professional.	Quite Difficult

Table 5.20: Criterion scale for 'User friendliness', presenting the two subcriteria aggregated: 'Ease of use' and 'Ease of daily routine'.

User friendliness, g_{10}			
Preference direction: Maximization			
Levels		**Ease of Use**	**Ease of daily routine**
5	User Friendly	Easy	Easy
4	Friendly to use except for daily routine	Easy	Somewhat difficult
		Easy	Quite difficult
3	Not friendly to use except for daily routine	Somewhat difficult	Easy
		Quite difficult	Easy
2	Low User friendliness	Somewhat difficult	Somewhat difficult
1	Not User Friendly	Somewhat difficult	Quite difficult
		Quite difficult	Somewhat difficult
		Quite difficult	Quite difficult

Maintenance costs, g_{11}

This criterion includes two aspects: 'Equipment maintenance factor' ($g_{11,1}$) and 'New functionalities expenses' ($g_{11,2}$). In this situation, a quantitative, continuous and direct descriptor is employed, using the sum of these ratios, as described below.

$$\frac{\text{Expenses in maintenance (preventive and corrective)}}{\text{Acquisition price of the product}} + \frac{\text{Expenses in new functionalities}}{\text{Acquisition price of the product}} \tag{5.2}$$

Preference direction: Minimization

Environmental sustainability, g_{12}

Environmental sustainability concerns both 'Ecofriendly production process' ($g_{12,1}$) and 'Eco-efficiency of the equipment' ($g_{12,2}$). Each of these subcriteria has a qualitative, discrete and constructed scale, displayed on Tables 5.21 and 5.22.

The total number of possible combinations was six, yet the DM carefully formed a new scale of four levels, which described both dimensions appropriately (see Table 5.23).

Table 5.21: Subcriterion scale exhibiting the levels, description and abbreviation concerning 'Ecofriendly production process'.

Ecofriendly production process, $g_{11,1}$		
Levels	**Description**	**Abbreviation**
2	The manufacturer employs sustainable practices in the production of the equipment.	Ecofriendly
1	The manufacturer does not employ sustainable practices in the production of the equipment.	Not Ecofriendly

Table 5.22: Subcriterion scale exhibiting the levels, description and abbreviation concerning 'Eco-efficiency of the equipment'.

Eco-efficiency of the equipment, $g_{11,2}$		
Levels	**Description**	**Abbreviation**
3	The ventilator includes "green features" and is recognized for reducing the environmental impact of the hospital.	Eco-efficient
2	The ventilator does not include features that make it stand out either in a negative or positive environmental perspective.	Neutral
1	The ventilator is recognized by the hospital to have a negative environmental impact.	Environmentally hazardous

Table 5.23: Criterion scale for 'Environmental sustainability', presenting the two subcriteria aggregated: 'Ecofriendly production process' and 'Eco-efficiency of the equipment'.

Environmental sustainability, g_{12}			
Preference direction: Maximization			
	Levels	**Eco-efficiency of the equipment**	**Ecofriendly production process**
4	Sustainable	Eco-efficient	Ecofriendly
3	Some level of environmental awareness	Eco-efficient	Not Ecofriendly
		Neutral	Ecofriendly
2	Low Sustainability	Neutral	Not Ecofriendly
1	Environmental Hazardous	Environmental Hazardous	(. . .)

5.4.2 Criteria performance tables

Having defined the ventilators to be featured in the analysis, the criteria for their assessment and the scales, it was possible to evaluate the performance of each action according to each criterion.

For criteria such as 'Reliability', 'Lifetime ratio', 'Utilization', 'Visual condition', 'Preventive maintenance commitment', 'Adaptability' and 'Maintenance costs' the DM, in interaction with the analyst, had to meticulously analyze the operation of the medical ventilators from *Hospital da Luz Lisboa* individually

to decide on the performance values. On the other hand, for the 'Technology level', 'Safety', 'Professionals' satisfaction', 'User friendliness' and 'Environmental sustainability', the DM concluded that the performance in these criteria did not vary within the same model of equipment. In this last case, an analysis for each of the selected medical ventilators' models was performed and the performances were determined as a consequence.

As mentioned earlier, the DM had the final word on the performance of the actions on the different criteria, despite relying on data collected along the process. In particular, regarding the 'Reliability' and the 'Maintenance costs', a data processing procedure was carried out from the hospital's failure occurrence computerized list to obtain the number of failure events and the cumulative expenses in preventive maintenance, corrective maintenance and new functionalities for each medical ventilator. It should be noted that the records available contained data from 2011 to 2019. This implies that it was not possible to obtain data for every year since *Hospital da Luz Lisboa* started its activity, resulting in presumably lower values for the performance of the ventilators on these criteria than true ones. Besides, for 'Lifetime ratio', in accordance with World Health Organization et al. (2011a), intensive care ventilators and neonatal ventilators had an eight year typical product life whereas anesthesia ventilators have an eight to 10 year typical product life. It was the DM's ruling to consider an eight year expected lifetime for all ventilators in the study, except for the model *Fabius MRI*, which was marked as having 10 years of expected product life. With respect to the inclusion of judgments from the users in the assignment of the ventilator's performance, health professionals (doctors and nurses) from diverse functional areas of *Hospital da Luz Lisboa* were invited to participate in an online survey available from July to August 2020 (see Appendix A). The respondents commented on the ease of use, ease of daily routine and the overall satisfaction with the models of medical ventilators in the hospital and these observations were taken into account by the DM when providing the final judgements for the criteria 'Professionals' satisfaction' and 'User friendliness'.

The final assignment of the performance of the actions in each of the criteria and subcriteria was performed at the date of August 6, 2020, as part of the co-construction process between the analyst and the DM. Firstly, subcriteria performance tables were constructed for the built-criteria (see tables B.1, B.2, B.3, B.4, B.5 and B.6 in Appendix B). Then, the criteria performance table of the study was completed (see Table B.7, Appendix B), constituting an input for the model execution.

5.4.3 Definition of criteria weights

In a DA context, determining the relative importance of the different criteria motivates another important interaction between the analyst and the DM. Several techniques can be used within the ELECTRE family of methods, nonetheless, the one employed in this case study is the *revised Simos' procedure* (Figueira et al., 2011). This technique is well accepted once it is intuitive for any DM, not necessarily familiarized with MCDA (Figueira and Roy, 2002).

Proposed by Simos and revised by Figueira and Roy, the *revised Simos' procedure* was used to define the medical ventilator's criteria weights according to the following steps (Figueira and Roy, 2002): firstly, the analyst provided the DM with a deck of cards, where 12 cards had the names of the criteria

and the remaining were blank cards. Then, it was asked for the DM to regroup the 12 cards from the least important criterion to the most important criterion. It was also mentioned that it is possible for some criteria to have equal importance. Afterward, the DM quantified the difference between two successive criteria by inserting a desired number of blank cards between them. The answer given by the DM to the following question was also registered, in order to establish the Z value: "How many times is the criteria assigned with the highest ranking more attractive than the one with the lowest ranking?". Figure 5.1 displays the ranking of the criteria, the number of blank cards inserted between criteria and the Z value defined by the DM.

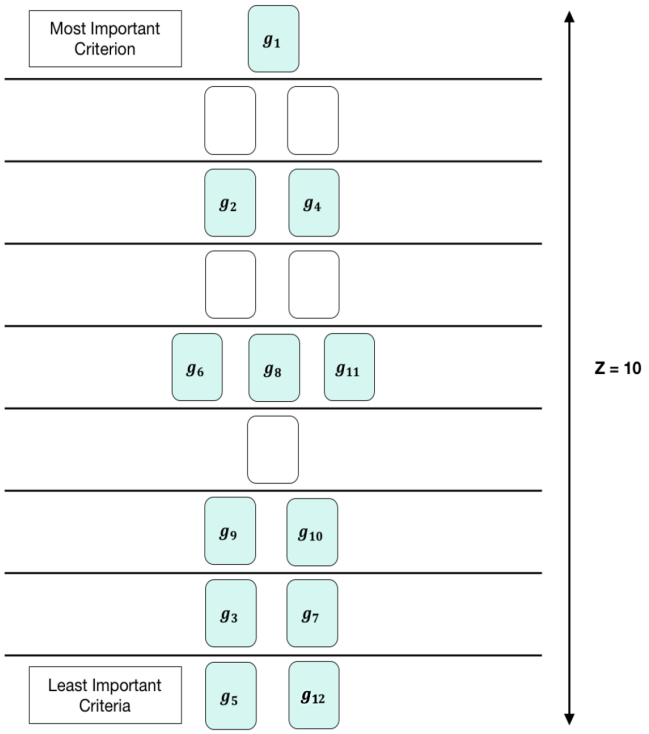

Figure 5.1: Illustration of the *revised Simos' procedure*: Ranking of the cards with the criteria, the white cards and the Z value.

The information gathered in the interaction between the analyst and the DM was posteriorly introduced in a web-based platform, DECSPACE [1], where the DCM-SRF method was selected. This way, the normalized and non-normalized weights for the family of criteria in question were obtained (see Table 5.24).

Table 5.24: Normalized and non-normalized ventilator's classification criteria weights.

Weights	**Criteria**											
	$\mathbf{g}_1$	$\mathbf{g}_2$	$\mathbf{g}_3$	$\mathbf{g}_4$	$\mathbf{g}_5$	$\mathbf{g}_6$	$\mathbf{g}_7$	$\mathbf{g}_8$	$\mathbf{g}_9$	$\mathbf{g}_{10}$	$\mathbf{g}_{11}$	$\mathbf{g}_{12}$
Non-normalized weight	10.1	7.3	1.9	7.3	1.0	4.6	1.9	4.6	2.8	2.8	4.6	1.0
Normalized weight (%)	20.1	14.7	3.8	14.7	2.0	9.2	3.8	9.2	5.6	5.6	9.3	2.0

[1] http://app.decspacedev.sysresearch.org (Accessed on August 6, 2020)

5.4.4 Definition of categories, reference actions and thresholds

Going back to the actions already defined, a group of medical ventilators from *Hospital da Luz Lisboa*, they are critical life support equipment used for neonates, pediatrics and adults. With the significance these devices carry in *Hospital da Luz Lisboa*, the categories for their sorting were defined by the DM bearing in mind the generation of the most appropriate and efficient classification system possible. The set of predefined and ordered categories for this case study was:

- C_5, Excellent
- C_4, Very Good
- C_3, Good
- C_2, Adequate
- C_1, Poor

For each category, the characterization was done by delineating one or more reference actions. For instance, regarding category C_5, the DM was asked by the analyst: "Take a medical ventilator that is classified as 'Excellent'. For each criterion, around what values do you consider the performance of that ventilator to be placed?". By doing the same procedure for all the categories, the DM was able to define the characteristic reference actions, exposed in Table 5.25.

Table 5.25: Performance of the characteristic reference actions on each criterion for the five categories considered in the model.

Category	Reference Action	Criteria											
		$\mathbf{g}_1$	$\mathbf{g}_2$	$\mathbf{g}_3$	$\mathbf{g}_4$	$\mathbf{g}_5$	$\mathbf{g}_6$	$\mathbf{g}_7$	$\mathbf{g}_8$	$\mathbf{g}_9$	$\mathbf{g}_{10}$	$\mathbf{g}_{11}$	$\mathbf{g}_{12}$
C_5	b_5^1	5	5	0.5	100	2	4	6	4	5	5	0.5	4
	b_5^2	4	5	0.5	250	2	3	5	4	4	5	0.3	4
C_4	b_4^1	4	6	0.6	1000	2	3	4	4	4	5	0.3	4
C_3	b_3^1	3	8	0.8	3000	2	3	4	3	3	4	0.4	3
C_2	b_2^1	2	12	0.8	8000	1	2	3	3	2	3	0.5	3
C_1	b_1^1	1	15	1.0	15000	1	2	2	2	1	2	0.6	2

In the collection of the judgments from the DM by the analyst, it was possible to confirm the arbitrariness and subjectivity associated with the definition of criteria and the uncertainty regarding the information. As mentioned in section 4.2, ELECTRE TRI-NC copes with this imperfect nature of data by introducing discriminating thresholds. This way, two thresholds were established for each criterion g_j: an indifference threshold q_j and a preference threshold p_j, presented in Table 5.26.

Moreover, when asked if, for any of the criteria in the model, there was a difference in performance by two actions a and a' that would lead to a veto of the assertion that "a outranks a'", the DM felt the need to include a veto threshold in three of the 12 criteria considered. These are presented in Table 5.27.

Lastly, the minimum credibility level, λ, accepted by the DM also needed to be defined. The importance of this method parameter should be highlighted, since it allows for the validation (or not) of

Table 5.26: Indifference and preference thresholds for each criterion considered in the model.

Thresholds	Criteria											
	$\mathbf{g}_1$	$\mathbf{g}_2$	$\mathbf{g}_3$	$\mathbf{g}_4$	$\mathbf{g}_5$	$\mathbf{g}_6$	$\mathbf{g}_7$	$\mathbf{g}_8$	$\mathbf{g}_9$	$\mathbf{g}_{10}$	$\mathbf{g}_{11}$	$\mathbf{g}_{12}$
q	1	1	0.001	1	1	1	1	1	1	1	0.01	1
p	1	5	0.001	200	1	1	1	1	1	1	0.10	1

Table 5.27: Veto thresholds for each criterion considered in the model.

Threshold	Criteria											
	$\mathbf{g}_1$	$\mathbf{g}_2$	$\mathbf{g}_3$	$\mathbf{g}_4$	$\mathbf{g}_5$	$\mathbf{g}_6$	$\mathbf{g}_7$	$\mathbf{g}_8$	$\mathbf{g}_9$	$\mathbf{g}_{10}$	$\mathbf{g}_{11}$	$\mathbf{g}_{12}$
v	-	-	-	-	-	-	4	-	3	3	-	-

outranking relations and influences the application of the ascending and descending rules for the assignment procedure. For a clear understanding, it can be compared, in a way, to the majority level in voting theory (Figueira et al., 2011). The chosen credibility level, which was validated by the DM, was $\lambda = 0.60$.

5.5 Final recommendation

The final recommendation consisted on taking the output of the evaluation model and translating it back into a format that is accessible for the DM. In addition, the analyst had to check the output for its theoretical soundness, operational completeness and legitimation. This final step of the DA process is presented in the next chapter, where the results of the model are obtained.

5.6 Summary

This chapter presented the four main steps of the DA process applied to the case study of this dissertation. Firstly, an identification and representation of the problem statement was obtained, identifying the DM of the decision process and describing their concerns regarding the classification of medical ventilators in *Hospital da Luz Lisboa*. In fact, most of these concerns were sustained by the ventilator assessment criteria found in the literature reviewed in Chapter 3. From there, it was possible for the analyst to translate the problem statement into decision support language and, in interaction with the DM, identify the appropriate problem formulation. As a result, 39 medical ventilators were identified as the actions of the decision process and a criteria tree was built, with five FPV, their respective criteria and subcriteria. The third step of the DA process was the construction of the evaluation model, for later obtaining a formal answer to the problem. Here, the criteria scales were assembled, bearing in mind that, for the case of built-in criteria, the aggregation of levels was required.

Once the previous steps were followed, a performance table was obtained and the relative importance of the different criteria was accessed by introducing the *revised Simos' procedure* to obtain the

criteria weights. The five categories for the classification of ventilators and their respective reference actions were also established, as well as the preference, indifference and veto thresholds to be considered for each criterion in ELECTRE TRI-NC. The minimum credibility level to be introduced in the model was also defined. Finally, the last step of the DA process, the final recommendation, was introduced, even though its complete exploration will only be performed in the next chapter.

Chapter 6

Results, Analysis and Discussion

The present chapter is dedicated to the results of the execution of the sorting methodology to support the maintenance management of medical equipment in *Hospital da Luz Lisboa*. Firstly, the *MCDA-ULaval* implementation is explored and from there, the final recommendation is proposed to the DM and scrutinized in interaction with the analyst. Posteriorly, the robustness of the model is tested and the consequences of the model in *Hospital da Luz Lisboa* and in the operations of the maintenance department, in particular, are discussed.

6.1 *MCDA-ULaval* implementation and model execution

Having thoroughly explored the present case study and developed a model to obtain a formal answer to the problem at hand, it is possible to turn the focus to its implementation in the software introduced in section 4.2.4., *MCDA-ULaval*.

A *MCDA-ULaval* project has different types of objects and takes as input multiple sets of data: the alternatives (corresponding to the actions of the model, the selected medical ventilators of *Hospital da Luz Lisboa*), the criteria, the performance tables and the decision configurations, including the criterion and method parameters, the categories, the reference alternatives and the performance tables of reference alternatives. It should be noted that this free software programmed in *Java* is also able to take into account existing interactions between criteria, even though these were not considered for this particular project.

After the creation of the project in *MCDA-ULaval*, the second stage consisted of its initialization by importing the alternative set, the criteria set and the performance table from a *CSV* file. From that point, the inserted objects appeared on the navigation tree on the left column of the workspace, as portrayed in Figures 6.1, 6.2, 6.3 and 6.4. By clicking on different items on the navigation tree, a window on the right column of the workspace opened, allowing the user to view and make changes to the inserted data.

When selecting the *Alternative Set* item, the window illustrated in the right column of Figure 6.1 was exhibited and the buttons exposed on top of such window allowed for alternatives to be deleted, added and reordered. Each alternative name and its description could also be edited and subsets of alternatives created.

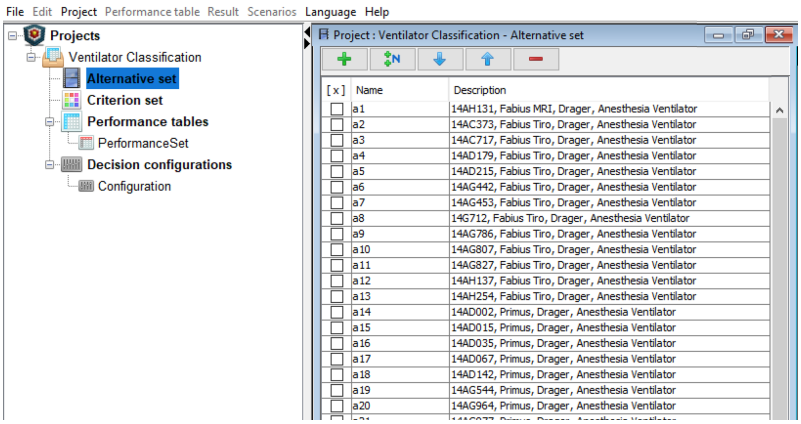

Figure 6.1: Action Set window displayed in MCDA-ULAVAL.

Moreover, the *Criteria Set* window featured on the right column of Figure 6.2 displays the criteria considered in this model as well as their description and type of scale, which can be cardinal or ordinal for quantitative and qualitative scales, respectively. Similarly to the *Alternative Set*, changes to the data can be made and buttons on the top of this window may be employed. However, in this case, an additional edit button was present, that allowed the user to specify the desired precision for quantitative criteria (by establishing the decimals) and the number of levels for qualitative criteria.

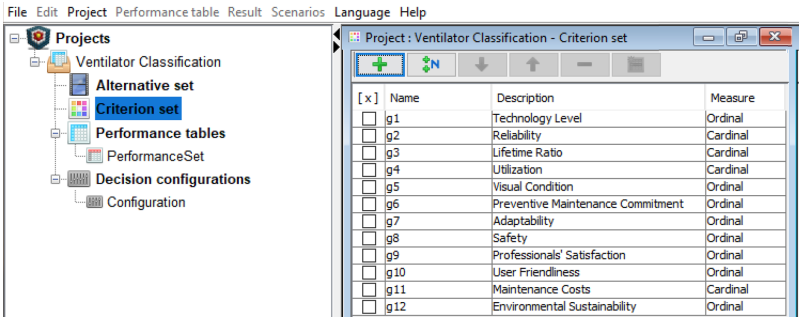

Figure 6.2: Criterion Set window displayed in *MCDA-ULaval*.

The performance table of the project is presented in the right column of Figure 6.3. Here, each entry of the table contains the value corresponding to the performance of each ventilator on each criterion. It was possible for the user to edit the values indicated on the table (by selecting an entry).

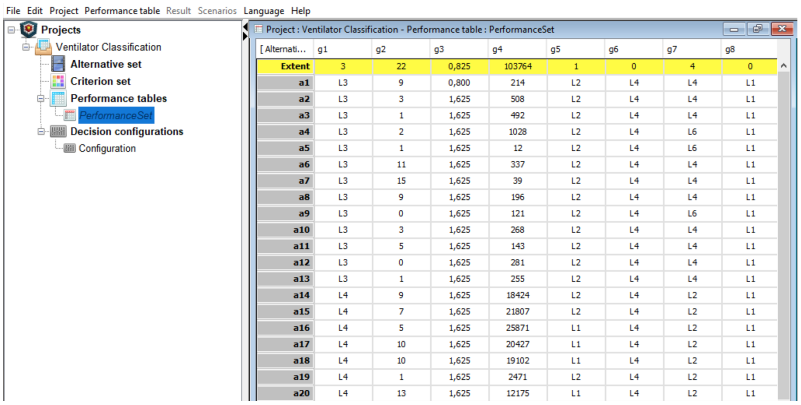

Figure 6.3: Performance table window displayed in *MCDA-ULaval*.

The next phase was the generation of the decision configuration, where firstly, the ELECTRE TRI-NC method was selected. Then, as observed in Figure 6.4, for each criterion, parameters such as the preference threshold, the indifference threshold, the veto threshold, the weight of the criterion and the direction in which preference increases were defined, according to what had already been detailed in the previous chapter. Regarding the method parameters, the value of the minimum credibility level was also entered. In addition, the model's ordered categories and reference actions were introduced and the performance table of the reference actions was imported. Once again, the software allowed the editing of the data inserted and provided buttons that enabled the possible addition, deletion and reordering of these decision configurations.

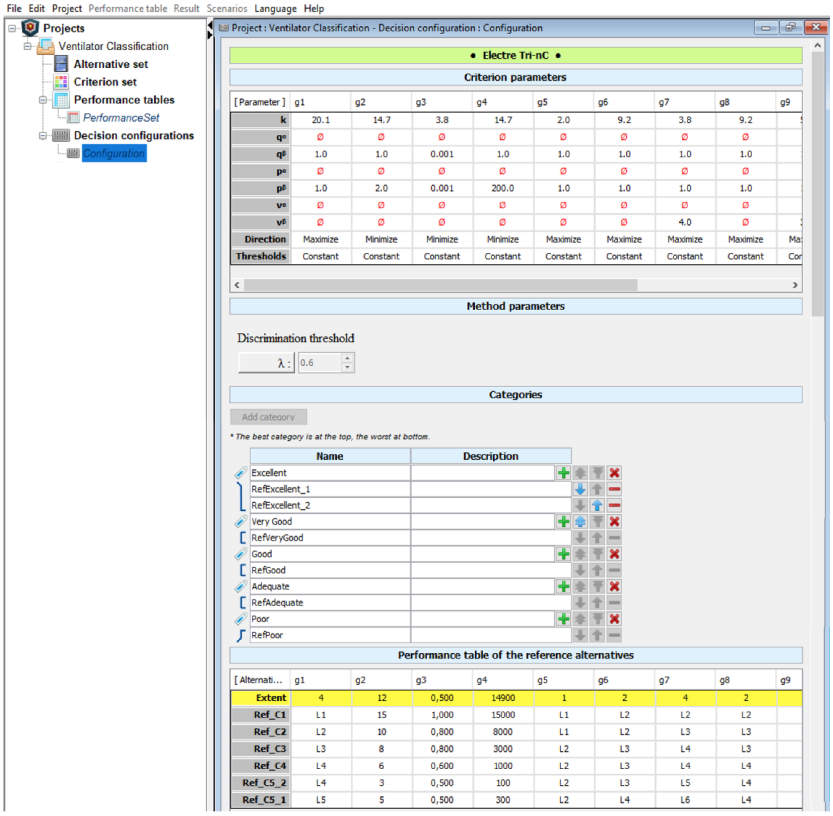

Figure 6.4: Decision configurations window displayed in *MCDA-ULaval*.

As the software requires all the inserted parameters to be valid, the existence of any invalid ones precludes the execution of a project and an error message informs the user of the value that needs to be changed. Provided all parameters were validated, the final step in the application of the model for the classification of medical ventilators was the execution of the project, by pressing the *Execute* command in *MCDA-ULaval*. In doing so, a results window opened, displaying the assignment of each action to a category or an interval of categories. The results of the model execution are presented in the upcoming sections and, additionally, a scenario analysis with modified parameters is performed to test the robustness of the model. The managerial implications of the results in *Hospital da Luz Lisboa* are also analyzed.

6.2 Results

The application of a multicriteria method should be succeeded by a presentation and analysis of the obtained results. In this case study, the model execution resulted in the sorting of the medical ventilators from *Hospital da Luz Lisboa* to one or more of the five predefined categories. In line with what was discussed in section 4.2.2, this sorting procedure is based, primarily, on the construction of preference relations through the validation of outranking relations, by taking the performance of an action on the different criteria. After, as outlined in section 4.2.3, an assignment procedure occurs, where two joint rules, the ascending and descending rules, elect the lowest and highest categories, respectively, which are potentially adequate to receiving an action. The output of the model execution is presented in Table 6.1 and in Figure 6.5 a plot displays the assignment of the actions to the possible categories, providing a visual representation of the same results.

Table 6.1: Results of the model execution in *MCDA-ULaval* for the 39 selected medical ventilators from *Hospital da Luz Lisboa*.

Action	Description	Minimum	Maximum
a_1	14AH131, *Fabius MRI*, *Drager*, Anesthesia Ventilator	C_2 Adequate	C_3 Good
a_2	14AC373, *Fabius Tiro*, *Drager*, Anesthesia Ventilator	C_3 Good	C_3 Good
a_3	14AC717, *Fabius Tiro*, *Drager*, Anesthesia Ventilator	C_3 Good	C_3 Good
a_4	14AD179, *Fabius Tiro*, *Drager*, Anesthesia Ventilator	C_3 Good	C_3 Good
a_5	14AD215, *Fabius Tiro*, *Drager*, Anesthesia Ventilator	C_3 Good	C_3 Good
a_6	14AG442, *Fabius Tiro*, *Drager*, Anesthesia Ventilator	C_2 Adequate	C_3 Good
a_7	14AG453, *Fabius Tiro*, *Drager*, Anesthesia Ventilator	C_2 Adequate	C_3 Good
a_8	14AG712, *Fabius Tiro*, *Drager*, Anesthesia Ventilator	C_2 Adequate	C_3 Good
a_9	14AG786, *Fabius Tiro*, *Drager*, Anesthesia Ventilator	C_3 Good	C_3 Good
a_{10}	14AG807, *Fabius Tiro*, *Drager*, Anesthesia Ventilator	C_3 Good	C_3 Good
a_{11}	14AG827, *Fabius Tiro*, *Drager*, Anesthesia Ventilator	C_3 Good	C_3 Good
a_{12}	14AH137, *Fabius Tiro*, *Drager*, Anesthesia Ventilator	C_3 Good	C_3 Good
a_{13}	14AH254, *Fabius Tiro*, *Drager*, Anesthesia Ventilator	C_3 Good	C_3 Good
a_{14}	14AD002, *Primus*, *Drager*, Anesthesia Ventilator	C_3 Good	C_3 Good
a_{15}	14AD015, *Primus*, *Drager*, Anesthesia Ventilator	C_3 Good	C_4 Very Good
a_{16}	14AD035, *Primus*, *Drager*, Anesthesia Ventilator	C_3 Good	C_4 Very Good
a_{17}	14AD067, *Primus*, *Drager*, Anesthesia Ventilator	C_2 Adequate	C_2 Adequate
a_{18}	14AD142, *Primus*, *Drager*, Anesthesia Ventilator	C_2 Adequate	C_2 Adequate
a_{19}	14AG544, *Primus*, *Drager*, Anesthesia Ventilator	C_3 Good	C_4 Very Good
a_{20}	14AG964, *Primus*, *Drager*, Anesthesia Ventilator	C_2 Adequate	C_2 Adequate
a_{21}	14AG977, *Primus*, *Drager*, Anesthesia Ventilator	C_3 Good	C_3 Good
a_{22}	14AD051, *Zeus*, *Drager*, Anesthesia Ventilator	C_1 Poor	C_3 Good
a_{23}	14AG885, *Carina Home*, *Drager*, Intensive Care Ventilator	C_3 Good	C_3 Good
a_{24}	14AD329, *Evita 4 Edition*, *Drager*, Intensive Care Ventilator	C_2 Adequate	C_3 Good
a_{25}	14AD358, *Evita 4 Edition*, *Drager*, Intensive Care Ventilator	C_2 Adequate	C_3 Good
a_{26}	14AD376, *Evita 4 Edition*, *Drager*, Intensive Care Ventilator	C_2 Adequate	C_3 Good
a_{27}	14AD704, *Evita 4 Edition*, *Drager*, Intensive Care Ventilator	C_2 Adequate	C_3 Good
a_{28}	14AG848, *Evita 4 Edition*, *Drager*, Intensive Care Ventilator	C_2 Adequate	C_3 Good
a_{29}	14AG867, *Evita 4 Edition*, *Drager*, Intensive Care Ventilator	C_2 Adequate	C_3 Good
a_{30}	14AG893, *Evita 4 Edition*, *Drager*, Intensive Care Ventilator	C_3 Good	C_3 Good
a_{31}	14AI116, *Evita 4 Edition*, *Drager*, Intensive Care Ventilator	C_2 Adequate	C_3 Good
a_{32}	14AI132, *Evita 4 Edition*, *Drager*, Intensive Care Ventilator	C_2 Adequate	C_3 Good
a_{33}	14AD381, *Evita XL*, *Drager*, Intensive Care Ventilator	C_2 Adequate	C_4 Very Good
a_{34}	14AA275, *Babylog 8000 Plus*, *Drager*, Neonatal Ventilator	C_4 Very Good	C_5 Excellent
a_{35}	14AE065, *Babylog 8000 Plus*, *Drager*, Neonatal Ventilator	C_4 Very Good	C_5 Excellent
a_{36}	14AA289, *Fabian*, *Acutronic*, Neonatal Ventilator	C_4 Very Good	C_5 Excellent
a_{37}	14AB111, *Infant Flow SIPAP*, *Carefusion*, Neonatal Ventilator	C_3 Good	C_3 Good
a_{38}	14AE058, *Infant Flow SIPAP*, *Carefusion*, Neonatal Ventilator	C_3 Good	C_3 Good
a_{39}	14AE067, *Infant Flow SIPAP*, *Carefusion*, Neonatal Ventilator	C_3 Good	C_3 Good

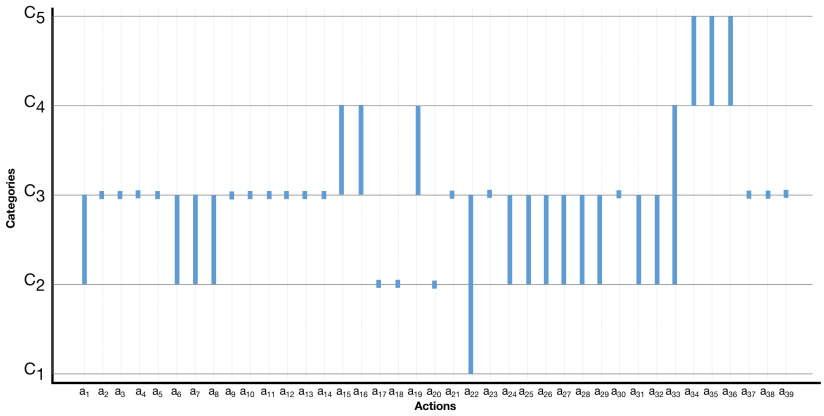

Figure 6.5: Assignment procedure results from *MCDA-ULaval*.

These results constitute the final recommendation in the present DA process, which should be validated by the DM. In this process, there is a need for a thorough interpretation underlying the values obtained and a critical analysis of their significance. For this reason, a statistical analysis is performed and presented in Table 6.2, expressed in number and percentage of actions assigned per interval of categories.

Table 6.2: Statistics concerning the assignment procedure, expressed in number and approximate percentage of actions assigned per interval of categories.

Category Assignment		**Number of Actions**	**Percentage of Actions (%)**
Minimum	**Maximum**		
C_1	C_3	1	2
C_2	C_2	3	8
C_2	C_3	12	31
C_2	C_4	1	2
C_3	C_3	16	41
C_3	C_4	3	8
C_4	C_5	3	8

Firstly, according to what was expected, one of three cases is observed: the ascending and descending views select the same category, consecutive categories or non-consecutive categories (or an interval of categories). In the first case, the medical ventilator is assigned, without ambiguity, to a single category whereas in the second and third cases, the action's category is considered ill-determined (Figueira et al., 2011). Analysing Table 6.2, it is found that the first case of assignment procedure is the most common among the actions in the study. With the λ chosen by the DM ($\lambda = 0,60$), 19 among the 39 medical ventilators were assigned to a single category (approximately 49%), 18 were assigned to two consecutive categories (nearly 46%) and three were assigned to an interval of three categories (only about 5%). Recall that the objective of this DA sorting model is to give a recommendation to the DM regarding the maintenance condition of each of the selected medical ventilators from *Hospital da Luz Lisboa*, given the five predefined categories considered. Therefore, we can consider that the λ utilized yielded an unambiguous final recommendation for the majority of the medical ventilators in the study,

providing valuable help for the DM in determining a definitive decision.

Moreover, it can also be noted that the highest number of actions was assigned to the category Good (C_3), with a percentage of approximately 41%. In fact, considering the representation of the individual categories potentially adequate to receiving an action in Table 6.2, C_3 was identified for the possible assignment of 33 out of the 39 actions and C_2 for the assignment of 17. The category Very Good (C_4) had 7 out of 39 actions that could be assigned to it, whilst the extreme categories Excellent (C_5) and Poor (C_1) had only three and one, respectively.

When presented with the abovementioned statistics, the DM expressed these were in agreement with what was expected, validating the results obtained. Given the recommendation from *MCDA-ULaval*, the DM was confronted with the final decision regarding the choice of category for each medical ventilator. A pessimist and an optimist view were presented by the analyst as possible options, in which the minimum and the maximum categories would be chosen for the assignment of each action, respectively. The statistical analyses of the results that both options would yield are exhibited in Tables 6.3 and 6.4.

Table 6.3: Pessimist view for the assignment of actions to categories, expressed in number and approximate percentage of actions assigned per interval of categories.

Category	Number of actions	Percentage of Actions (%)
C_1, Poor	1	3
C_2, Adequate	16	41
C_3, Good	19	49
C_4, Very Good	3	8
C_5, Excellent	0	0

Table 6.4: Optimist view for the assignment of actions to categories, expressed in number and approximate percentage of actions assigned per interval of categories.

Category	Number of actions	Percentage of Actions (%)
C_1, Poor	0	0
C_2, Adequate	3	8
C_3, Good	29	74
C_4, Very Good	4	10
C_5, Excellent	3	8

Yet again, the context of the application of this model had to be factored in. As a leading healthcare provider, *Hospital da Luz Lisboa* is conscious of the uncertainty and complexity of the health sector and, as a consequence, the rigor that is required in decision-making processes. Regarding the maintenance management of critical equipment such as medical ventilators, the importance it carries in achieving both efficiency and high quality of care can hardly be overemphasized. Thereby, the DM decided to consider the worst-case scenario provided by *MCDA-ULaval*, the pessimist view, for the assignment of each medical ventilator to a category. From this point forward, the completion of the analysis of the results will be performed considering this decision.

Examining the results of particular actions, the three actions assigned to a better category were a_{34} (14AA275, *Babylog 8000 Plus*, *Drager*, Neonatal Ventilator), a_{35} (14AE065, *Babylog 8000 Plus*, *Drager*, Neonatal Ventilator) and a_{36} (14AA289, *Fabian*, *Acutronic*, Neonatal Ventilator), selected to the category Very Good (C_4). The action that yielded the worst category assignment was a_{22} (14AD051, *Zeus*, *Drager*, Anesthesia Ventilator), selected to the category Poor (C_1).

The DM expressed that these findings are in line with what was expected. With the level of dependence between the performance determination of each ventilator and its model, the DM was able to justify that, for the action a_{22}, the "inflexible system", characteristic of the *Zeus* model from *Drager* might explain the results. At the same time, possible higher flexibility in several features of the models *Babylog*

8000 Plus from *Drager* and *Fabian* from *Acutronic* may have yielded positive results for actions a_{34}, a_{35} and a_{36}. For the remaining models, the DM considered the attribution of a category range between C_2 and C_3 to be adequate and mentioned that, between these consecutive categories, the distinction may arise from the separate specifications of the functional area of *Hospital da Luz Lisboa* where each medical ventilator is inserted.

6.3 Robustness Analysis

After the application of an MCDA methodology, it is pivotal to perform a test over the inherent robustness of the model utilized for the classification of the maintenance condition of the medical ventilators in *Hospital da Luz Lisboa*, particularly considering the characteristics of the present study, its innovative nature and the uncertainties underlying the data employed. With the objective of understanding in what way changes in the assumptions used for the construction of the model yield distinct results, a robustness analysis should entail the creation of comprehensive and meaningful scenarios. In this process, components of the model can be further examined, the influence of parameters can be assessed, premises can be questioned and associations between elements can be appraised. Additionally, if conducted in proximity with the DM, adjustments and modifications can be made, possibly leading towards a more comprehensive and improved model.

In the development of different scenarios, the analyst was faced with a multiplicity of parameters that could potentially be varied within the healthcare context of the application of the model. In accordance with the DM, the focus was turned to the points of hesitation and difficulties encountered during the course of the DA process by the DM. Taking into account the realistic variation that the considered parameters may endure in *Hospital da Luz Lisboa*, the values for the modification of each parameter were established and scenarios were created. This way, the different scenarios included a simultaneous change on the Z value defined in the *revised Simos' procedure* for the determination of the criteria weights, the minimum credibility level, λ, accepted by the DM and the veto thresholds, v_7, v_9 and v_{10}, for the criteria 'Adaptability' (g_7), 'Professionals' satisfaction' (g_9) and 'User friendliness' (g_{10}).

Table 6.5 resumes the parameters considered in the present robustness analysis, their initial assigned value for the model execution in the previous section and their respective variations that resulted in the scenarios that were obtained.

Table 6.5: Parameters considered for the robustness analysis, their initial values assigned in the model execution and the new values to be tested.

Parameter	Assigned Value	New values
Z	10	8, 9, 11, 12
λ	0.60	0.55, 0.65
v_7	4	3, 5
v_9	3	4
v_{10}	3	4

With five considered values for Z, three different values for λ and 12 possible combinations of seven different veto thresholds, 180 scenarios were developed, for a total of 7020 assignments. For the reason stated in the section above, the choice of pessimist view has been established by the DM and the results, in Table C.1 (Appendix B), as well as the analysis of the distinct scenarios consider only the minimum category possible for the assignment of each medical ventilator.

Firstly, when changing the Z value, the repercussions were expected to occur on the level of the criteria weights. For lower values of Z, the differences between the most and least preferred criteria are decreased whereas, with increased values of Z, the differences between the most and least preferred criteria are accentuated. In a robust model, the considered alterations of Z value should not significantly impact the outputs.

Effectively, in the total of the scenarios analyzed, the variations of Z presented no implications in the results in Table C.1.

On the other hand, the minimum credibility level λ influences the definition of outranking relations and the application of the descending and ascending rules. With an increasing value for λ, there is a growing likelihood that the minimum and maximum categories assigned converged into the same category, whereas a decrease of λ can lead to the selection of a wider interval of categories. The scenarios in Table C.1 display only the worst possible category for the assignment of each action and so, by increasing λ, the tendency is for the ascending rule to select an equal or higher category for the assignment of medical ventilators in comparison with lower values of λ. This way, it was expected that for $\lambda = 0.55$, the minimum category assigned would be equal or lower to the one assigned for $\lambda = 0.60$, whereas for $\lambda = 0.65$, an equal or higher category would be selected.

The analysis of Table C.1 validates the mentioned expectations. Changing from $\lambda = 0.60$ to $\lambda = 0.55$, there is a decrease in the assignment of five actions by one category, resulting in adjustments 4% of the total assignments. Alternatively, when the λ value is altered from $\lambda = 0.60$ to $\lambda = 0.65$, an increase in the assignment of 15 actions by one category is verified, with a total variation of 14% of the assignments. It is important to mention that the considered alterations of λ influence the assignments of the actions that were previously considered as the best and the worst, according to the set of predefined categories.

Lastly, the influence of a modification of veto thresholds in the outcomes was analyzed. In the present study, the DM introduced veto power to three of the 12 criteria: 'Adaptability' (g_7), 'Professionals' satisfaction' (g_9) and 'User friendliness' (g_{10}). This way, if one action outranks another in a majority of the criteria and one or more of the abovementioned criteria are out of this majority, their veto thresholds are evaluated before drawing a final conclusion.

The fact is, observing Table C.1 and focusing uniquely on the modification of veto thresholds, the alteration of v_{10} is the only one that has repercussions on the classification of the medical ventilators. By changing v_{10}, from three to four, three actions are assigned to category C_4 instead of C_3, changing 1% of the total number of assignments.

Furthermore, the combination of the alteration of v_{10}, from three to four, and λ, from $\lambda = 0.60$ to $\lambda = 0.60$, yielded the alteration in the assignment procedure, from C_3 to C_4 and from C_3 to C_5 in seven and two actions, respectively, a 3% change in the total assignments. This last variation is noteworthy

in particular, once it leads to the assignment of actions to the best possible category, Excellent (C_5), which had not previously been achieved. In this case, the actions that are deemed as exhibiting the best maintenance condition change.

In general, with a variety of 180 scenarios tested, 22% of the total assignments suffered alterations, from which less than 1% constituted changes by more than one category. Looking at the results of this analysis, the DM alluded to the fact that the model *Fabius Tiro* from *Drager* was the only model of medical ventilators for which the variations yield significant differences in the results. It should be pointed out that, in the construction of this model, a comprehensive approach was used, so that it could yield an appropriate assessment of different types and models of medical ventilators in the hospital. This way, with the consistency obtained for the remaining models, the robustness of the model was proven and the MCDA approach, in particular, the ELECTRE TRI-NC method were found to be a suitable option in the context of the classification of the maintenance condition of the selected medical ventilators from *Hospital da Luz Lisboa*.

6.4 Managerial Implications

Currently, companies are faced with a multiplicity of decision-making situations which have led to the increasing adoption of decision support tools. Regarding the health sector in particular, its complex, fast-changing and highly competitive nature requires organizations to follow an efficient costs and assets management strategy, that maximizes both the available resources and the healthcare provision. As a reference in the health sector, *Luz Saúde* and, in particular, *Hospital da Luz Lisboa* are aware of the importance of developing ingenious approaches to optimize processes that occur in the daily operations within a hospital. Aligning with goals such as 'Excellence in healthcare', 'Technology and innovation' and 'Talent and training', the hospital features specialized services with sophisticated and front-line medical equipment. The introduction of a model in *Hospital da Luz Lisboa* for the classification of medical ventilators intended to serve as a support to the maintenance management, by minimizing cost implications, reducing variability and improving patient outcomes.

Given the context where the model is applied, in order for proper implementation of this valuable tool for the hospital, certain conditions need to be verified. The commitment to active inventory management in the hospital must act as the base for storing important medical equipment data. Indeed, it is essential that the sourcing and collection of data are performed consistently, continually and in a rigorous manner, according to the inherent characteristics of each device and the functional area of the hospital where it is inserted. Regarding the assessment of the performance of inventoried items, the inclusion of professionals from diverse areas originates a variety of views that result in a more comprehensive and strengthen model. Therefore, the involvement of health professionals such as doctors, nurses as well as engineers, technicians and the managers from *Hospital da Luz Lisboa* in the maintenance management of medical equipment should be encouraged. Moreover, the possibility of implementing MCDA methodologies for the assessment of other medical devices or even, to alternative decision processes in the hospital should be considered.

The monitoring of the maintenance condition of the medical ventilators in *Hospital da Luz Lisboa* should be performed with a periodic application of the DA model to the selected medical equipment and, eventually, to new ones that may be acquired. The critical analysis of the model is also a crucial aspect, as a regular review of both the model and criteria parameters as well as elements such as criteria and criteria scales is a requirement in determining whether updates or changes to the model should be executed.

In the aftermath of the model application in *Hospital da Luz Lisboa*, the maintenance strategy for a medical ventilator differs according to the categories selected by *MCDA-ULaval*. These consequences are always based on the previous application of the model and were defined by the DM in interaction with the analyst for each of the possible categories. For instance, the DM considered that, for categories C_3, C_2 and C_1, more detailed control measures should be established in comparison with higher categories. For a visual representation of the consequences for the assignment of medical ventilators to each category, a decision tree was built and is displayed in Figure 6.6.

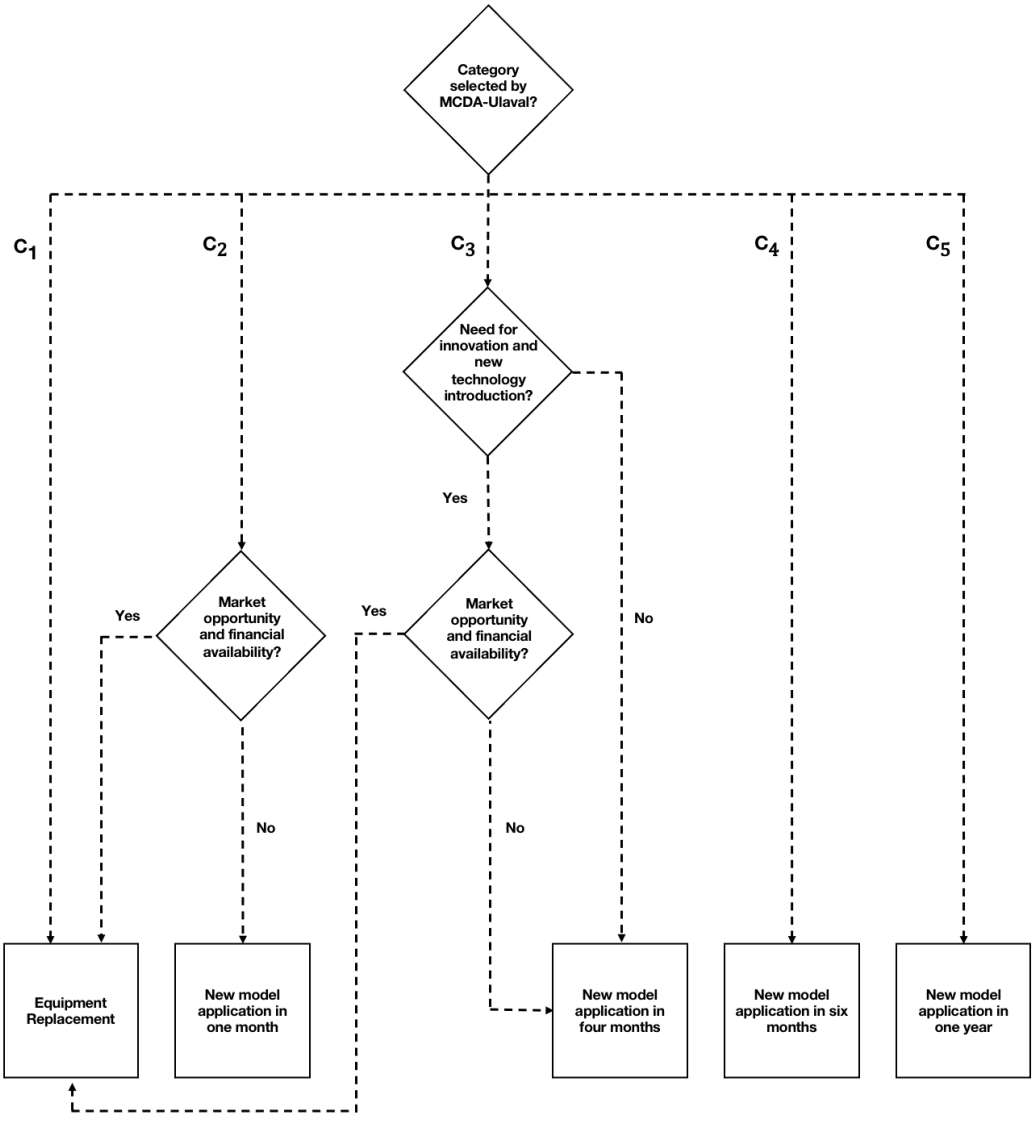

Figure 6.6: Decision tree for the consequences of the assignment of medical ventilators to each category in *Hospital da Luz Lisboa*.

Firstly, the equipment that is assigned to the category Poor (C_1) is pointed out and signaled for replacement. If, however, the medical ventilator is assigned to the category Adequate (C_2), an assessment of the market opportunities and financial availability should be performed. In the case where market opportunities are present and *Luz Saúde* is able to handle the financial burden, the equipment is replaced. If not, a new model application is scheduled for two months from the previous application, with a review of the model and criteria parameters. Alternatively, when an equipment is assigned to the category Good (C_3), an evaluation of the need for innovation and the introduction of new technologies in the hospital should be carried out. From there, if the responsible parties from *Hospital da Luz Lisboa* consider that the innovation and technology are at the required level, then a new model application is scheduled for four months from the previous application, with a review of the model and criteria parameters. Otherwise, if the responsible parties in the hospital are looking to invest in medical ventilators, then a second analysis is performed to understand whether market opportunities are emerging and if there is financial availability at the moment. If the analysis turns out positive, the equipment is replaced. If not, a new model application is scheduled for four months from the previous application, with a review of the model and criteria parameters. What is more, in the case where the category Very Good (C_4) is selected, the next model application is scheduled for one semester from the previous application, at which time the model and criteria parameters are reviewed. Lastly, when the category Excellent (C_5) is assigned to a medical ventilator, the next model application to that equipment is scheduled for one year from the previous application and the model and criteria parameters should be reviewed at that point.

The implications for the assignment of consequences to the possible categories were established according to the DM's judgments and bearing in mind that periodic monitorization of results is a permanent condition for appropriate model implementation. In addition, it was suggested that moments such as the establishment or reviewing of budgetary policies for medical equipment and for innovation in *Hospital da Luz Lisboa* may constitute opportune moments for a model application.

6.5 Summary

This chapter focused on the presentation and analysis of the results of the *MCDA-ULaval* implementation and model execution. With an overview of the *MCDA-ULaval* software, the results were obtained for the classification of the maintenance condition of 39 medical ventilators from *Hospital da Luz Lisboa*.

As expected, for each action, one of three cases occurred: the ascending and descending views selected the same category, consecutive categories or non-consecutive categories (or an interval of categories) to assign to that action. Moreover, in the obtained results, 41% of the actions were assigned to the category Good (C_3). When confronted with the final decision regarding the choice of category for each medical ventilator, the DM decided to always chose the pessimist option and assign the minimum category provided by *MCDA-ULaval* to each action. This way, no ventilators were assigned to the best possible category Excellent (C_5) and the best assignments were made for three actions, a_{34}, a_{35} and a_{36} to the category Very Good (C_4). On the other end of the spectrum, action a_{22} was assigned to the worst possible category, Poor (C_1). The DM expressed that these findings are in line with what was expected.

When testing the robustness of the model, 180 scenarios were created. The variation of the Z value and veto thresholds v_7 and v_9 had no influence in the assignment procedure. On the other hand, the adjustments of minimum credibility level, λ and veto threshold v_{10} lead to alterations to the results. From these, it is important to highlight the modification in the assignment of the actions that had been previously defined as the best and worst actions, as well as the assignment of two actions to the best possible category, Excellent (C_5), which had not been achieved previously.

Overall, the alterations that were observed for the different scenarios were explained by the general character of the model and still allowed for the validation of the model in the classification of the maintenance condition of the selected medical ventilators from *Hospital da Luz Lisboa*.

Regarding the model application in the hospital, the consequences of the assignment procedure differed for the five considered categories. In the interaction of the analyst with the DM, a decision tree was built exposing the consequences of the assignment to each category in *Hospital da Luz Lisboa*, emphasizing the periodic monitoring of the maintenance conditions of the medical ventilators and the stricter measures for categories C_3, C_2 and C_1.

Chapter 7

Conclusions

In the last chapter of this dissertation, the conclusions of the work developed are presented. Primarily, the achievements are examined for the hospital where the constructed model was applied. From there, a limitation analysis is carried out, to understand the areas for improvement of this study and lastly, the possibilities for future extensions of this work are investigated.

7.1 Achievements

As I stand today, the world is at the early stages of responding to the outbreak of a global pandemic that has affected more than 40 million people around the globe (Worldometers, 2020). With the potential of overwhelming health systems, *COVID-19* has forced healthcare organizations to rapidly adapt to the latest protocols, adopt new strategies to manage limited resources, accommodate new technologies and leverage existing ones (Buchholz and Briggs, 2020). In this respect, the comprehensive management of healthcare technologies, in particular medical equipment, by introducing innovative methods and tools takes on further relevance. Moreover, as critical medical equipment in the provision of respiratory assistance and, in particular, key devices in the fight against *COVID-19*, medical ventilators have been at the forefront of healthcare conversations worldwide.

For *Luz Saúde*, the awareness of the importance of investing in new methodologies that support decision-making processes and that contribute to increase efficiency and healthcare quality is nothing new. In *Hospital da Luz Lisboa* in particular, the complexity associated with the maintenance management of medical equipment was seen as an opportunity for improving the assessment of equipment functionality, by introducing a DA tool. What is more, the stakeholders in the hospital recognized the benefits that such a tool could bring, from the prevention of equipment failure to the maximization of equipment performance and the achievement of higher staff satisfaction levels.

It was in this context that the present dissertation was inserted, introducing a classification model for a selected group of medical ventilators from *Hospital da Luz Lisboa*, in order to assess their maintenance condition. An MCDA sorting methodology was followed, utilizing ELECTRE TRI-NC, and the evolution of every phase of the DA process was dependent on the interaction between the analyst and the DM, two biomedical engineers and members of DIME in *Hospital da Luz Lisboa*.

The first phase of the study consisted on the examination of *Luz Saúde* and the hospital in which

the model would be applied, *Hospital da Luz Lisboa*, in search of the values, necessities, demands and all the relevant characteristics of one of the biggest healthcare providers in Portugal. In this process, medical ventilators stood out as the medical equipment that made the most sense for this analysis.

Afterward, the required data was gathered and processed, making it possible to start the co-construction of the model, identifying the actions, defining the criteria, building the criteria scales and establishing the necessary parameters for the model execution.

In the application of the model to the medical ventilators, the *MCDA-ULaval* software was utilized and with the intervention of the DM, each of the actions was assigned to a maintenance condition category. According to what was expected by the DM, with the choice of the pessimist option (assigning the minimum category provided by *MCDA-ULaval*), the majority of the actions were assigned to either the category Adequate (C_2) or the category Good (C_3). With the obtained results, a test of the robustness level of the model was carried out and the operational consequences for the hospital were explored. For 180 created scenarios, few were the variations of parameters that lead to significant alterations in the results, allowing for the validation of the model in the classification of the maintenance condition of the selected medical ventilators from *Hospital da Luz Lisboa*.

Collectively, the initial objectives of this dissertation were achieved. With the methodology utilized and the model created, a new tool for the assessment of the maintenance condition of the medical ventilators of *Hospital da Luz Lisboa* was successfully introduced.

7.2 Study Limitations

Medical equipment maintenance management is an intricate topic, that requires a constantly high level of quality, safety and efficacy in the clinical context. With implications on people's health, the examination of the points for possible improvement of this methodology constitutes a crucial part of this study.

The first important aspect worth mentioned is the lack of specific literature concerning multicriteria models for the assessment of medical ventilators. As stated in Chapter 3, in the life cycle planning and management of medical equipment that should be implemented in healthcare organizations, decision processes for acquisition, assessment and replacement are featured, among others. Considering ventilator specific literature, the only studies that were found concerned purchasing decisions. Even though this posed a difficulty in the comprehensive analysis of the subject, it also assured the innovative character of the present approach.

Another point is that, as the entity that provides the judgments for the case study at hand, the choice of DM is most likely to impact the obtained results. Although the DM provided a multidimensional view of the problem, it cannot be guaranteed that a complete overview of the features for the assessment of medical ventilators and their maintenance condition was provided. Furthermore, under the circumstances imposed by the global pandemic during the course of this dissertation, the presential interactions between the analyst and the DM were reduced, which might have affected the process.

Moreover, even though the objective of this study was the construction of a general model for the medical ventilators of *Hospital da Luz Lisboa*, these medical equipment present distinct characteristics

according to their type, model or the functional area where they are inserted. Therefore, while the level of specificity of the model was maximized within the scope of medical ventilators, some elements that would be pertinent for the classification of a particular subgroup of medical ventilators were not featured in this study.

When it comes to the construction of the qualitative criteria scales by the analyst in interaction with the DM, the objective description of the levels was sometimes, difficult to achieve. Even though this process could have perhaps been performed in a more rigorous way, the analyst and the DM considered that the most intuitive approach was utilized and that the model accuracy was assured.

A different remark is related to the independence between criteria assumed throughout the study. For instance, the possible interactions between the criteria 'Utilization' and 'Lifetime ratio', as well as between the criteria 'Reliability' and 'Maintenance costs' should be questioned.

What is more, the fact that some records of *Hospital da Luz Lisboa* contained data from 2011 to 2019 resulted in an imprecise performance assignment for the criteria 'Reliability' and 'Maintenance costs'. Although this flaw was not deemed significant by the DM, it constitutes a limitation that should be recognized.

7.3 Future Work

Medical technology is a dynamic industry, that works to "save and improve lives" by transforming ideas into solutions for the healthcare sector (Boisseau et al., 2020). Concerning the work developed in this dissertation, future investigations should be conducted for diverse aspects of the study, in the creation of possible adaptations or simply curiosity.

For the strengthening and expansion of the results of this study, a deeper analysis of some criteria, their respective scales and interactions between criteria might yield noteworthy conclusions, that should be followed by the testing of new scenarios under these conditions. Furthermore, the managerial implications of the action assignment to categories in *Hospital da Luz Lisboa* may be increasingly detailed.

With the aforementioned impact of the DM is the results, the adaptability of the model could be evaluated, by the introduction of other relevant actors. Besides, with the commitment to a periodic application of the model to the existing medical ventilators of *Hospital da Luz Lisboa* and to new ones that may be acquired, the DM must also preserve a critical thinking and a tech-driven spirit, that will allow them to provide accurate judgments in light of current technological advances.

All in all, the work developed in this dissertation represents an important first step in the implementation of MCDA methodologies for supporting decision processes in *Hospital da Luz Lisboa*. With that in mind, the model executed for this case study may be employed as a guideline for the construction of new proposals for the hospital. Both the classification of other medical equipment from *Hospital da Luz Lisboa* and the possible generalization of the model for the development of a maintenance prioritization system for the hospital constitute interesting options.

Regarding medical ventilators specifically, a natural extension of this analysis concerns the classi-

fication of medical ventilators from other healthcare units, considering their inherent specifications and adjusting parameters if necessary. Another line of research that could be pursued would be the adaptation of the present model for other parts of the life cycle planning and managing of medical ventilators, for instance, purchasing decisions. Also, an adaptation of the model could also be considered for alternative decision processes in *Luz Saúde*.

As a final note, *COVID-19* has exceedingly increased the demand for medical ventilators worldwide. As a result, the maintenance of these medical equipment has been the focus of growing attention in healthcare organizations, that urgently aim to assure the dependability of these equipment and the prevention of unexpected events. This way, the exploration of this method's potentialities may generate unprecedented contributions that are, in today's world, more significant than ever.

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Appendix A

Online Survey to Health Professionals

Appendix A presents the online surveys in which the health professionals (doctors and nurses) from *Hospital da Luz Lisboa* were invited to participate. The objective of the application of these surveys was to provide insights for the DM and to facilitate the assignments of performance for the medical ventilators on the criteria 'Professionals' satisfaction' (g_9) and 'User friendliness' (g_{10}).

Moreover, it is worth noting that, for 'User friendliness', both dimensions of the criterion were assessed: 'Ease of use' ($g_{10,1}$) and 'Ease of daily maintenance ($g_{10,2}$).

A.1 Survey for Doctors and Nurses from *Hospital da Luz Lisboa*

A.1.1 Introduction

This form appears as part of a dissertation project to obtain the master's degree in Biomedical Engineering at *Instituto Superior Técnico*, with the objective of applying multicriteria modeling to support the maintenance management of medical equipment. More precisely, this dissertation focuses on the creation of a method for classifying medical ventilators at *Hospital da Luz Lisboa*.

The purpose of this questionnaire is to collect data regarding the opinion of health professionals for the ease of use, the ease of daily routine and the overall satisfaction level with the medical ventilators from *Hospital da Luz Lisboa*. The data collected is confidential. If you have any questions or suggestions about the project, we leave a space at the end so you can leave a comment.

To answer the following questions, consider the medical ventilators present in *Hospital da Luz Lisboa*.

Thank you for collaborating.

A.1.2 Anesthesia Ventilators

Fabius MRI - Drager

Figure A.1: *Fabius MRI*. Note: Adapted May 20, 2020 from Drager (n.d.), Fabius MRI.

Personal satisfaction: Evaluation of the suitability of the ventilator for the needs of the patients and its overall performance.

A. According to the levels below, classify your level of satisfaction with the ventilator *Fabius MRI*.

1. Very Dissatisfactory - The overall functioning of the ventilator is far from meeting the standards of healthcare.
2. Dissatisfactory - Dissatisfaction with the overall functioning of the ventilator.
3. Neutral - Neutral opinion regarding the overall functioning of the ventilator.
4. Satisfactory - Satisfaction with the overall functioning of the ventilator.
5. Very Satisfactory - The ventilator's overall functioning exceeds the expectations.
6. I don't know how to answer.

Ease of use: Assessment of the easiness of handling the medical ventilator's user interface and operational system.

B. According to the levels below, classify the easiness of use of the ventilator *Fabius MRI*.

1. Quite Difficult - The ventilator has an inconvenient operational system and user interface that imposes strong difficulties in its utilization.
2. Somewhat Difficult – The ventilator has a challenging operational system and user interface.
3. Easy – The ventilator has a friendly user interface and overall intuitive operational system.
4. I don't know how to answer.

Ease of daily routine: Assessment of the speed and facility of the daily routine performed in the medical ventilator.

C. According to the levels below, classify the easiness of the daily routine of the ventilator *Fabius MRI*.

1. Quite Difficult - The ventilator's daily maintenance routine procedure is time-consuming and complex.
2. Somewhat Difficult – The ventilator's daily maintenance routine procedure is somewhat inconvenient and tiresome.
3. Easy – The ventilator has daily maintenance routine assisted functions that make the process fast and simple.
4. I don't know how to answer.

Fabius Tiro - Drager

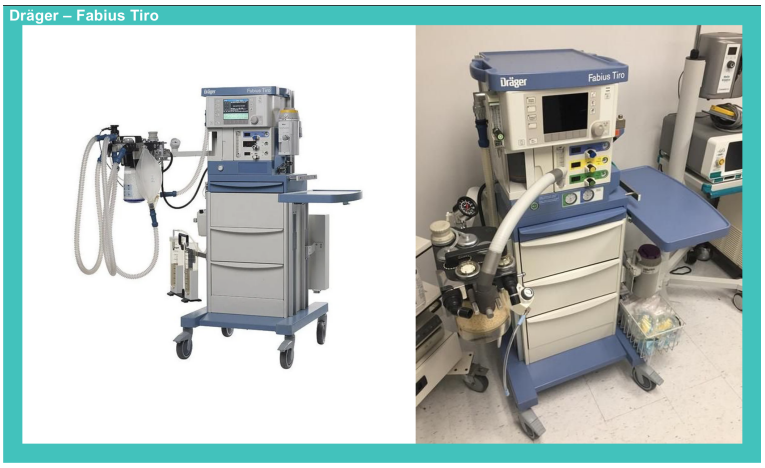

Figure A.2: *Fabius Tiro*. Note: Adapted May 20, 2020 from Drager (n.d.), Fabius Tiro.

Personal satisfaction: Evaluation of the suitability of the ventilator for the needs of the patients and its overall performance.

A. According to the levels below, classify your level of satisfaction with the ventilator *Fabius Tiro*.

1. Very Dissatisfactory - The overall functioning of the ventilator is far from meeting the standards of healthcare.
2. Dissatisfactory - Dissatisfaction with the overall functioning of the ventilator.
3. Neutral - Neutral opinion regarding the overall functioning of the ventilator.
4. Satisfactory - Satisfaction with the overall functioning of the ventilator.
5. Very Satisfactory - The ventilator's overall functioning exceeds the expectations.
6. I don't know how to answer.

Ease of use: Assessment of the easiness of handling the medical ventilator's user interface and operational system.

B. According to the levels below, classify the easiness of use of the ventilator *Fabius Tiro*.

1. Quite Difficult - The ventilator has an inconvenient operational system and user interface that imposes strong difficulties in its utilization.
2. Somewhat Difficult – The ventilator has a challenging operational system and user interface.

3. Easy – The ventilator has a friendly user interface and overall intuitive operational system.
4. I don't know how to answer.

Ease of daily routine: Assessment of the speed and facility of the daily routine performed in the medical ventilator.

C. According to the levels below, classify the easiness of the daily routine of the ventilator *Fabius Tiro*.

1. Quite Difficult - The ventilator's daily maintenance routine procedure is time-consuming and complex.
2. Somewhat Difficult – The ventilator's daily maintenance routine procedure is somewhat inconvenient and tiresome.
3. Easy – The ventilator has daily maintenance routine assisted functions that make the process fast and simple.
4. I don't know how to answer.

Primus - Drager

Figure A.3: *Primus*. Note: Adapted May 20, 2020 from Drager (n.d.), Primus.

Personal satisfaction: Evaluation of the suitability of the ventilator for the needs of the patients and its overall performance.

A. According to the levels below, classify your level of satisfaction with the ventilator *Primus*.

1. Very Dissatisfactory - The overall functioning of the ventilator is far from meeting the standards of healthcare.
2. Dissatisfactory - Dissatisfaction with the overall functioning of the ventilator.
3. Neutral - Neutral opinion regarding the overall functioning of the ventilator.
4. Satisfactory - Satisfaction with the overall functioning of the ventilator.
5. Very Satisfactory - The ventilator's overall functioning exceeds the expectations.
6. I don't know how to answer.

Ease of use: Assessment of the easiness of handling the medical ventilator's user interface and operational system.

B. According to the levels below, classify the easiness of use of the ventilator *Primus*.

1. Quite Difficult - The ventilator has an inconvenient operational system and user interface that imposes strong difficulties in its utilization.
2. Somewhat Difficult – The ventilator has a challenging operational system and user interface.
3. Easy – The ventilator has a friendly user interface and overall intuitive operational system.
4. I don't know how to answer.

Ease of daily routine: Assessment of the speed and facility of the daily routine performed in the medical ventilator.

C. According to the levels below, classify the easiness of the daily routine of the ventilator *Primus*.

1. Quite Difficult - The ventilator's daily maintenance routine procedure is time-consuming and complex.
2. Somewhat Difficult – The ventilator's daily maintenance routine procedure is somewhat inconvenient and tiresome.
3. Easy – The ventilator has daily maintenance routine assisted functions that make the process fast and simple.
4. I don't know how to answer.

Zeus - Drager

Figure A.4: *Zeus*. Note: Adapted May 20, 2020 from Drager (n.d.), Zeus.

Personal satisfaction: Evaluation of the suitability of the ventilator for the needs of the patients and its overall performance.

A. According to the levels below, classify your level of satisfaction with the ventilator *Zeus*.

1. Very Dissatisfactory - The overall functioning of the ventilator is far from meeting the standards of healthcare.

2. Dissatisfactory - Dissatisfaction with the overall functioning of the ventilator.
3. Neutral - Neutral opinion regarding the overall functioning of the ventilator.
4. Satisfactory - Satisfaction with the overall functioning of the ventilator.
5. Very Satisfactory - The ventilator's overall functioning exceeds the expectations.
6. I don't know how to answer.

Ease of use: Assessment of the easiness of handling the medical ventilator's user interface and operational system.

B. According to the levels below, classify the easiness of use of the ventilator *Zeus*.

1. Quite Difficult - The ventilator has an inconvenient operational system and user interface that imposes strong difficulties in its utilization.
2. Somewhat Difficult – The ventilator has a challenging operational system and user interface.
3. Easy – The ventilator has a friendly user interface and overall intuitive operational system.
4. I don't know how to answer.

Ease of daily routine: Assessment of the speed and facility of the daily routine performed in the medical ventilator.

C. According to the levels below, classify the easiness of the daily routine of the ventilator *Zeus*.

1. Quite Difficult - The ventilator's daily maintenance routine procedure is time-consuming and complex.
2. Somewhat Difficult – The ventilator's daily maintenance routine procedure is somewhat inconvenient and tiresome.
3. Easy – The ventilator has daily maintenance routine assisted functions that make the process fast and simple.
4. I don't know how to answer.

A.1.3 Intensive Care Ventilators

Carina Home - Drager

Figure A.5: *Carina Home*. Note: Adapted May 20, 2020 from Drager (n.d.), Carina Home.

Personal satisfaction: Evaluation of the suitability of the ventilator for the needs of the patients and its overall performance.

A. According to the levels below, classify your level of satisfaction with the ventilator *Carina Home*.

1. Very Dissatisfactory - The overall functioning of the ventilator is far from meeting the standards of healthcare.
2. Dissatisfactory - Dissatisfaction with the overall functioning of the ventilator.
3. Neutral - Neutral opinion regarding the overall functioning of the ventilator.
4. Satisfactory - Satisfaction with the overall functioning of the ventilator.
5. Very Satisfactory - The ventilator's overall functioning exceeds the expectations.
6. I don't know how to answer.

Ease of use: Assessment of the easiness of handling the medical ventilator's user interface and operational system.

B. According to the levels below, classify the easiness of use of the ventilator *Carina Home*.

1. Quite Difficult - The ventilator has an inconvenient operational system and user interface that imposes strong difficulties in its utilization.
2. Somewhat Difficult – The ventilator has a challenging operational system and user interface.
3. Easy – The ventilator has a friendly user interface and overall intuitive operational system.
4. I don't know how to answer.

Ease of daily routine: Assessment of the speed and facility of the daily routine performed in the medical ventilator.

C. According to the levels below, classify the easiness of the daily routine of the ventilator *Carina Home*.

1. Quite Difficult - The ventilator's daily maintenance routine procedure is time-consuming and complex.
2. Somewhat Difficult – The ventilator's daily maintenance routine procedure is somewhat inconvenient and tiresome.
3. Easy – The ventilator has daily maintenance routine assisted functions that make the process fast and simple.
4. I don't know how to answer.

Evita 4 Edition - Drager

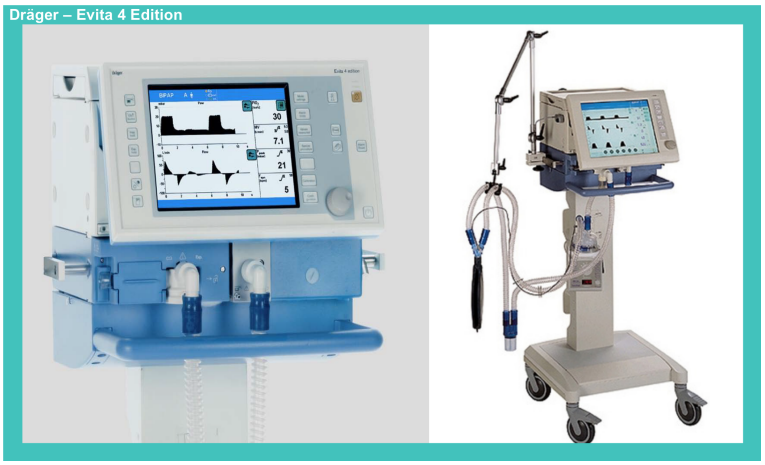

Figure A.6: *Evita 4 Edition*. Note: Adapted May 20, 2020 from Drager (n.d.), Evita 4 Edition.

Personal satisfaction: Evaluation of the suitability of the ventilator for the needs of the patients and its overall performance.

A. According to the levels below, classify your level of satisfaction with the ventilator *Evita 4 Edition*.

1. Very Dissatisfactory - The overall functioning of the ventilator is far from meeting the standards of healthcare.
2. Dissatisfactory - Dissatisfaction with the overall functioning of the ventilator.
3. Neutral - Neutral opinion regarding the overall functioning of the ventilator.
4. Satisfactory - Satisfaction with the overall functioning of the ventilator.
5. Very Satisfactory - The ventilator's overall functioning exceeds the expectations.
6. I don't know how to answer.

Ease of use: Assessment of the easiness of handling the medical ventilator's user interface and operational system.

B. According to the levels below, classify the easiness of use of the ventilator *Evita 4 Edition*.

1. Quite Difficult - The ventilator has an inconvenient operational system and user interface that imposes strong difficulties in its utilization.
2. Somewhat Difficult – The ventilator has a challenging operational system and user interface.

3. Easy – The ventilator has a friendly user interface and overall intuitive operational system.
4. I don't know how to answer.

Ease of daily routine: Assessment of the speed and facility of the daily routine performed in the medical ventilator.

C. According to the levels below, classify the easiness of the daily routine of the ventilator *Evita 4 Edition*.

1. Quite Difficult - The ventilator's daily maintenance routine procedure is time-consuming and complex.
2. Somewhat Difficult – The ventilator's daily maintenance routine procedure is somewhat inconvenient and tiresome.
3. Easy – The ventilator has daily maintenance routine assisted functions that make the process fast and simple.
4. I don't know how to answer.

Evita XL - Drager

Figure A.7: *Evita XL*. Note: Adapted May 20, 2020 from Drager (n.d.), Evita XL.

Personal satisfaction: Evaluation of the suitability of the ventilator for the needs of the patients and its overall performance.

A. According to the levels below, classify your level of satisfaction with the ventilator *Evita XL*.

1. Very Dissatisfactory - The overall functioning of the ventilator is far from meeting the standards of healthcare.
2. Dissatisfactory - Dissatisfaction with the overall functioning of the ventilator.
3. Neutral - Neutral opinion regarding the overall functioning of the ventilator.
4. Satisfactory - Satisfaction with the overall functioning of the ventilator.
5. Very Satisfactory - The ventilator's overall functioning exceeds the expectations.
6. I don't know how to answer.

Ease of use: Assessment of the easiness of handling the medical ventilator's user interface and operational system.

B. According to the levels below, classify the easiness of use of the ventilator *Evita XL*.

1. Quite Difficult - The ventilator has an inconvenient operational system and user interface that imposes strong difficulties in its utilization.
2. Somewhat Difficult – The ventilator has a challenging operational system and user interface.
3. Easy – The ventilator has a friendly user interface and overall intuitive operational system.
4. I don't know how to answer.

Ease of daily routine: Assessment of the speed and facility of the daily routine performed in the medical ventilator.

C. According to the levels below, classify the easiness of the daily routine of the ventilator *Evita XL*.

1. Quite Difficult - The ventilator's daily maintenance routine procedure is time-consuming and complex.
2. Somewhat Difficult – The ventilator's daily maintenance routine procedure is somewhat inconvenient and tiresome.
3. Easy – The ventilator has daily maintenance routine assisted functions that make the process fast and simple.
4. I don't know how to answer.

A.1.4 Neonatal Ventilators

Babylog 8000 Plus - Drager

Figure A.8: *Babylog 8000 Plus*. Note: Adapted May 20, 2020 from Drager (n.d.), Babylog 8000 Plus.

Personal satisfaction: Evaluation of the suitability of the ventilator for the needs of the patients and its overall performance.

A. According to the levels below, classify your level of satisfaction with the ventilator *Babylog 8000 Plus*.

1. Very Dissatisfactory - The overall functioning of the ventilator is far from meeting the standards of healthcare.
2. Dissatisfactory - Dissatisfaction with the overall functioning of the ventilator.
3. Neutral - Neutral opinion regarding the overall functioning of the ventilator.
4. Satisfactory - Satisfaction with the overall functioning of the ventilator.
5. Very Satisfactory - The ventilator's overall functioning exceeds the expectations.
6. I don't know how to answer.

Ease of use: Assessment of the easiness of handling the medical ventilator's user interface and operational system.

B. According to the levels below, classify the easiness of use of the ventilator *Babylog 8000 Plus*.

1. Quite Difficult - The ventilator has an inconvenient operational system and user interface that imposes strong difficulties in its utilization.
2. Somewhat Difficult – The ventilator has a challenging operational system and user interface.
3. Easy – The ventilator has a friendly user interface and overall intuitive operational system.
4. I don't know how to answer.

Ease of daily routine: Assessment of the speed and facility of the daily routine performed in the medical ventilator.

C. According to the levels below, classify the easiness of the daily routine of the ventilator *Babylog 8000 Plus*.

1. Quite Difficult - The ventilator's daily maintenance routine procedure is time-consuming and complex.
2. Somewhat Difficult – The ventilator's daily maintenance routine procedure is somewhat inconvenient and tiresome.
3. Easy – The ventilator has daily maintenance routine assisted functions that make the process fast and simple.
4. I don't know how to answer.

Fabian - Acutronic

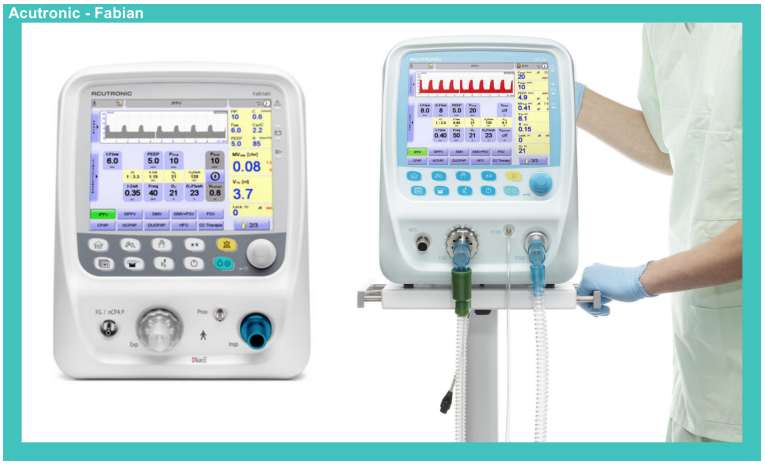

Figure A.9: *Fabian*. Note: Adapted May 20, 2020 from Acutronic (n.d.), The Fabian Family.

Personal satisfaction: Evaluation of the suitability of the ventilator for the needs of the patients and its overall performance.

A. According to the levels below, classify your level of satisfaction with the ventilator *Fabian*.

1. Very Dissatisfactory - The overall functioning of the ventilator is far from meeting the standards of healthcare.
2. Dissatisfactory - Dissatisfaction with the overall functioning of the ventilator.
3. Neutral - Neutral opinion regarding the overall functioning of the ventilator.
4. Satisfactory - Satisfaction with the overall functioning of the ventilator.
5. Very Satisfactory - The ventilator's overall functioning exceeds the expectations.
6. I don't know how to answer.

Ease of use: Assessment of the easiness of handling the medical ventilator's user interface and operational system.

B. According to the levels below, classify the easiness of use of the ventilator *Fabian*.

1. Quite Difficult - The ventilator has an inconvenient operational system and user interface that imposes strong difficulties in its utilization.
2. Somewhat Difficult – The ventilator has a challenging operational system and user interface.

3. Easy – The ventilator has a friendly user interface and overall intuitive operational system.
4. I don't know how to answer.

Ease of daily routine: Assessment of the speed and facility of the daily routine performed in the medical ventilator.

C. According to the levels below, classify the easiness of the daily routine of the ventilator *Fabian*.

1. Quite Difficult - The ventilator's daily maintenance routine procedure is time-consuming and complex.
2. Somewhat Difficult – The ventilator's daily maintenance routine procedure is somewhat inconvenient and tiresome.
3. Easy – The ventilator has daily maintenance routine assisted functions that make the process fast and simple.
4. I don't know how to answer.

Infant Flow SIPAP - Carefusion

Figure A.10: *Infant Flow SIPAP*. Note: Adapted May 20, 2020 from Pulmocor (n.d.), Ventilation CPAP Infant Flow.

Personal satisfaction: Evaluation of the suitability of the ventilator for the needs of the patients and its overall performance.

A. According to the levels below, classify your level of satisfaction with the ventilator *Infant Flow SIPAP*.

1. Very Dissatisfactory - The overall functioning of the ventilator is far from meeting the standards of healthcare.
2. Dissatisfactory - Dissatisfaction with the overall functioning of the ventilator.
3. Neutral - Neutral opinion regarding the overall functioning of the ventilator.
4. Satisfactory - Satisfaction with the overall functioning of the ventilator.
5. Very Satisfactory - The ventilator's overall functioning exceeds the expectations.
6. I don't know how to answer.

Ease of use: Assessment of the easiness of handling the medical ventilator's user interface and operational system.

B. According to the levels below, classify the easiness of use of the ventilator *Infant Flow SIPAP*.

1. Quite Difficult - The ventilator has an inconvenient operational system and user interface that imposes strong difficulties in its utilization.
2. Somewhat Difficult – The ventilator has a challenging operational system and user interface.
3. Easy – The ventilator has a friendly user interface and overall intuitive operational system.
4. I don't know how to answer.

Ease of daily routine: Assessment of the speed and facility of the daily routine performed in the medical ventilator.

C. According to the levels below, classify the easiness of the daily routine of the ventilator *Infant Flow SIPAP*.

1. Quite Difficult - The ventilator's daily maintenance routine procedure is time-consuming and complex.
2. Somewhat Difficult – The ventilator's daily maintenance routine procedure is somewhat inconvenient and tiresome.
3. Easy – The ventilator has daily maintenance routine assisted functions that make the process fast and simple.
4. I don't know how to answer.

Appendix B

Performance Tables

In Appendix B, the performance tables of the study are presented. Firstly, for each of the built-in criteria, the subcriteria performance tables are displayed, considering the 39 medical ventilators from *Hospital da Luz Lisboa*. Then, the criteria performance table of this case study is shown, again for the 39 medical ventilators from *Hospital da Luz Lisboa* considered and the 12 criteria.

B.1 Built-in Criteria's Subcriteria Performance Tables

Table B.1: Subcriterion performance tables for 'Technology level', presenting the four subcriteria: 'Technical features', 'Upgrade Level', 'Interoperability' and 'Remote assistance'.

	$g_{1,1}$	$g_{1,2}$	$g_{1,3}$	$g_{1,4}$
a_1	2	2	2	1
a_2	2	2	2	1
a_3	2	2	2	1
a_4	2	2	2	1
a_5	2	2	2	1
a_6	2	2	2	1
a_7	2	2	2	1
a_8	2	2	2	1
a_9	2	2	2	1
a_{10}	2	2	2	1
a_{11}	2	2	2	1
a_{12}	2	2	2	1
a_{13}	2	2	2	1
a_{14}	3	3	1	1
a_{15}	3	3	1	1
a_{16}	3	3	1	1
a_{17}	3	3	1	1
a_{18}	3	3	1	1
a_{19}	3	3	1	1
a_{20}	3	3	1	1
a_{21}	3	3	1	1
a_{22}	3	3	1	1
a_{23}	1	1	1	1
a_{24}	2	2	1	1
a_{25}	2	2	1	1
a_{26}	2	2	1	1
a_{27}	2	2	1	1
a_{28}	2	2	1	1
a_{29}	2	2	1	1
a_{30}	2	2	1	1
a_{31}	2	2	1	1
a_{32}	2	2	1	1
a_{33}	2	2	1	1
a_{34}	2	1	1	1
a_{35}	2	1	1	1
a_{36}	2	1	1	1
a_{37}	1	1	1	1
a_{38}	1	1	1	1
a_{39}	1	1	1	1

Table B.2: Subcriterion performance tables for 'Adaptability', presenting the three subcriteria: 'Access of healthcare services', 'Portability' and 'Accessories and consumables' standardization'.

	$g_{7,1}$	$g_{7,2}$	$g_{7,3}$
a_1	2	3	1
a_2	2	2	2
a_3	2	2	2
a_4	2	3	2
a_5	2	3	2
a_6	2	2	2
a_7	2	2	2
a_8	2	2	2
a_9	2	3	2
a_{10}	2	2	2
a_{11}	2	2	2
a_{12}	2	2	2
a_{13}	2	2	2
a_{14}	2	1	2
a_{15}	2	1	2
a_{16}	2	1	2
a_{17}	2	1	2
a_{18}	2	1	2
a_{19}	2	1	2
a_{20}	2	1	2
a_{21}	2	1	2
a_{22}	2	2	2
a_{23}	1	3	2
a_{24}	2	2	1
a_{25}	2	2	1
a_{26}	2	2	1
a_{27}	2	2	1
a_{28}	2	2	1
a_{29}	2	2	1
a_{30}	2	3	1
a_{31}	2	2	1
a_{32}	2	2	1
a_{33}	2	2	1
a_{34}	2	3	1
a_{35}	2	3	1
a_{36}	2	3	1
a_{37}	1	3	1
a_{38}	1	3	1
a_{39}	1	3	1

Table B.3: Subcriterion performance tables for 'Safety', presenting the two subcriteria: 'Integrated safety functions' and 'Cybersecurity'.

	$g_{8,1}$	$g_{8,2}$
a_1	3	1
a_2	3	1
a_3	3	1
a_4	3	1
a_5	3	1
a_6	3	1
a_7	3	1
a_8	3	1
a_9	3	1
a_{10}	3	1
a_{11}	3	1
a_{12}	3	1
a_{13}	3	1
a_{14}	3	2
a_{15}	3	2
a_{16}	3	2
a_{17}	3	2
a_{18}	3	2
a_{19}	3	2
a_{20}	3	2
a_{21}	3	2
a_{22}	3	2
a_{23}	2	1
a_{24}	3	2
a_{25}	3	2
a_{26}	3	2
a_{27}	3	2
a_{28}	3	2
a_{29}	3	2
a_{30}	3	2
a_{31}	3	2
a_{32}	3	2
a_{33}	3	2
a_{34}	3	1
a_{35}	3	1
a_{36}	3	1
a_{37}	2	1
a_{38}	2	1
a_{39}	2	1

Table B.4: Subcriterion performance tables for 'User friendliness', presenting the two subcriteria: 'Ease of use' and 'Ease of daily routine'.

	$g_{10,1}$	$g_{10,2}$
a_1	3	1
a_2	3	1
a_3	3	1
a_4	3	1
a_5	3	1
a_6	3	1
a_7	3	1
a_8	3	1
a_9	3	1
a_{10}	3	1
a_{11}	3	1
a_{12}	3	1
a_{13}	3	1
a_{14}	3	2
a_{15}	3	2
a_{16}	3	2
a_{17}	3	2
a_{18}	3	2
a_{19}	3	2
a_{20}	3	2
a_{21}	3	2
a_{22}	3	3
a_{23}	3	2
a_{24}	2	3
a_{25}	2	3
a_{26}	2	3
a_{27}	2	3
a_{28}	2	3
a_{29}	2	3
a_{30}	2	3
a_{31}	2	3
a_{32}	2	3
a_{33}	3	2
a_{34}	3	3
a_{35}	3	3
a_{36}	3	2
a_{37}	3	3
a_{38}	3	3
a_{39}	3	3

Table B.5: Subcriterion performance tables for 'Maintenance costs', presenting the two subcriteria: 'Equipment maintenance factor' and 'New functionalities expenses'.

	$g_{11,1}$	$g_{11,2}$
a_1	0,32	0
a_2	0,26	0
a_3	0,26	0
a_4	0,26	0
a_5	0,26	0
a_6	0,26	0
a_7	0,26	0
a_8	0,33	0
a_9	0,26	0
a_{10}	0,26	0
a_{11}	0,26	0
a_{12}	0,26	0
a_{13}	0,26	0
a_{14}	0,36	0
a_{15}	0,37	0
a_{16}	0,36	0
a_{17}	0,37	0
a_{18}	0,37	0
a_{19}	0,36	0
a_{20}	0,36	0
a_{21}	0,36	0
a_{22}	0,21	0
a_{23}	0,35	0
a_{24}	0,41	0
a_{25}	0,41	0
a_{26}	0,41	0
a_{27}	0,41	0
a_{28}	0,41	0
a_{29}	0,41	0
a_{30}	0,41	0
a_{31}	0,41	0
a_{32}	0,41	0
a_{33}	0,41	0
a_{34}	0,26	0
a_{35}	0,26	0
a_{36}	0,30	0
a_{37}	0,33	0
a_{38}	0,40	0
a_{39}	0,51	0

Table B.6: Subcriterion performance tables for 'Environmental sustainability', presenting the two subcriteria: 'Ecofriendly production process' and 'Ecoefficiency of the equipment'.

	$g_{12,1}$	$g_{12,2}$
a_1	2	2
a_2	2	2
a_3	2	2
a_4	2	2
a_5	2	2
a_6	2	2
a_7	2	2
a_8	2	2
a_9	2	2
a_{10}	2	2
a_{11}	2	2
a_{12}	2	2
a_{13}	2	2
a_{14}	2	2
a_{15}	2	2
a_{16}	2	2
a_{17}	2	2
a_{18}	2	2
a_{19}	2	2
a_{20}	2	2
a_{21}	2	2
a_{22}	2	3
a_{23}	2	2
a_{24}	2	2
a_{25}	2	2
a_{26}	2	2
a_{27}	2	2
a_{28}	2	2
a_{29}	2	2
a_{30}	2	2
a_{31}	2	2
a_{32}	2	2
a_{33}	2	2
a_{34}	2	2
a_{35}	2	2
a_{36}	2	2
a_{37}	2	2
a_{38}	2	2
a_{39}	2	2

B.2 Criteria Performance Table

Table B.7: Criteria performance table for the 39 medical ventilators from *Hospital da Luz Lisboa* considered in the study and the 12 criteria.

Actions	Criteria											
	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	g_{11}	g_{12}
a_1	3	9	0,800	214	2	4	4	3	2	4	0,32	3
a_2	3	3	1,625	268	2	4	4	3	2	4	0,26	3
a_3	3	1	1,625	268	2	4	4	3	2	4	0,26	3
a_4	3	2	1,625	1028	2	4	6	3	2	4	0,26	3
a_5	3	1	1,625	12	2	4	6	3	2	4	0,26	3
a_6	3	11	1,625	337	2	4	4	3	2	4	0,26	3
a_7	3	15	1,625	39	2	4	4	3	2	4	0,26	3
a_8	3	9	1,625	196	2	4	4	3	2	4	0,33	3
a_9	3	0	1,625	121	2	4	6	3	2	4	0,26	3
a_{10}	3	3	1,625	268	2	4	4	3	2	4	0,26	3
a_{11}	3	5	1,625	143	2	4	4	3	2	4	0,26	3
a_{12}	3	0	1,625	268	2	4	4	3	2	4	0,26	3
a_{13}	3	1	1,625	268	2	4	4	3	2	4	0,26	3
a_{14}	4	7	1,625	18537	2	4	2	4	4	4	0,36	3
a_{15}	4	5	1,625	21807	2	4	2	4	4	4	0,37	3
a_{16}	4	4	1,625	25871	1	4	2	4	4	4	0,36	3
a_{17}	4	8	1,625	20427	1	4	2	4	4	4	0,37	3
a_{18}	4	8	1,625	19102	1	4	2	4	4	4	0,37	3
a_{19}	4	1	1,625	2471	2	4	2	4	4	4	0,36	3
a_{20}	4	13	1,625	12175	1	4	2	4	4	4	0,36	3
a_{21}	4	8	1,625	24909	2	4	2	4	4	4	0,36	3
a_{22}	4	22	1,625	18537	1	4	4	4	5	5	0,21	4
a_{23}	1	3	1,625	200	2	4	5	2	2	4	0,35	3
a_{24}	3	0	1,625	52900	2	4	3	4	4	3	0,41	3
a_{25}	3	5	1,625	52900	2	4	3	4	4	3	0,41	3
a_{26}	3	4	1,625	52900	2	4	3	4	4	3	0,41	3
a_{27}	3	2	1,625	52900	2	4	3	4	4	3	0,41	3
a_{28}	3	1	1,625	12543	2	4	3	4	4	3	0,41	3
a_{29}	3	2	1,625	93285	2	4	3	4	4	3	0,41	3
a_{30}	3	0	1,625	2714	2	4	4	4	4	3	0,41	3
a_{31}	3	2	1,625	52900	2	4	3	4	4	3	0,41	3
a_{32}	3	3	1,625	103059	2	4	3	4	4	3	0,41	3
a_{33}	3	1	1,625	103776	2	4	3	4	4	4	0,41	3
a_{34}	2	0	1,625	200	2	4	4	3	5	5	0,26	3
a_{35}	2	1	1,625	200	2	4	4	3	5	5	0,26	3
a_{36}	2	2	1,625	200	2	4	4	3	4	4	0,30	3
a_{37}	1	0	1,625	200	2	4	4	2	4	5	0,33	3
a_{38}	1	3	1,625	200	2	4	4	2	4	5	0,40	3
a_{39}	1	3	1,625	200	2	4	4	2	4	5	0,51	3

Appendix C

Robustness Analysis Data-sheets

Appendix C displays the results of the Robustness Analysis presented in section 6.3. Here, the variation of the parameters, according to Table 6.5, yielded the development of 180 scenarios. From these, the choice of pessimist view was established by the DM. Thus, Table C.1 shows only the distinct scenarios obtained, considering only the minimum category possible for the assignment of each medical ventilator.

Table C.1: Results for the variations of Z value, minimum credibility level, λ and veto thresholds v_7, v_9 and v_{10}, presenting only the minimum category assigned by *MCDA-ULaval*.

Action	$Z=8$						$Z=9$						$Z=10$						$Z=11$						$Z=12$					
	$\lambda=0.55$		$\lambda=0.60$		$\lambda=0.65$		$\lambda=0.55$		$\lambda=0.60$		$\lambda=0.65$		$\lambda=0.55$		$\lambda=0.60$		$\lambda=0.65$		$\lambda=0.55$		$\lambda=0.60$		$\lambda=0.65$		$\lambda=0.55$		$\lambda=0.60$		$\lambda=0.65$	
	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$	$(v_7=3 \vee v_7=4 \vee v_7=5) \wedge (v_9=3 \vee v_9=4) \wedge v_{10}=4$
a_1	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2
a_2	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4
a_3	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4
a_4	C_3	C_3	C_3	C_4	C_3	C_4	C_3	C_3	C_3	C_4	C_3	C_4	C_3	C_3	C_3	C_4	C_3	C_4	C_3	C_3	C_3	C_4	C_3	C_4	C_3	C_3	C_3	C_4	C_3	C_4
a_5	C_3	C_3	C_3	C_4	C_3	C_5	C_3	C_3	C_3	C_4	C_3	C_5	C_3	C_3	C_3	C_4	C_3	C_5	C_3	C_3	C_3	C_4	C_3	C_5	C_3	C_3	C_3	C_4	C_3	C_5
a_6	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2
a_7	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2
a_8	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2
a_9	C_3	C_3	C_3	C_4	C_3	C_5	C_3	C_3	C_3	C_4	C_3	C_5	C_3	C_3	C_3	C_4	C_3	C_5	C_3	C_3	C_3	C_4	C_3	C_5	C_3	C_3	C_3	C_4	C_3	C_5
a_{10}	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4
a_{11}	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4
a_{12}	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4
a_{13}	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4	C_3	C_3	C_3	C_3	C_3	C_4
a_{14}	C_2	C_2	C_3	C_3	C_3	C_3	C_2	C_2	C_3	C_3	C_3	C_3	C_2	C_2	C_3	C_3	C_3	C_3	C_2	C_2	C_3	C_3	C_3	C_3	C_2	C_2	C_3	C_3	C_3	C_3
a_{15}	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3
a_{16}	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3
a_{17}	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2
a_{18}	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2
a_{19}	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3
a_{20}	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2	C_2
a_{21}	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3
a_{22}	C_1	C_1	C_1	C_1	C_2	C_2	C_1	C_1	C_1	C_1	C_2	C_2	C_1	C_1	C_1	C_1	C_2	C_2	C_1	C_1	C_1	C_1	C_2	C_2	C_1	C_1	C_1	C_1	C_2	C_2
a_{23}	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3
a_{24}	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3
a_{25}	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3
a_{26}	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3
a_{27}	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3
a_{28}	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3
a_{29}	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3
a_{30}	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3
a_{31}	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3
a_{32}	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3
a_{33}	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3	C_2	C_2	C_2	C_2	C_3	C_3
a_{34}	C_3	C_3	C_4	C_4	C_4	C_4	C_3	C_3	C_4	C_4	C_4	C_4	C_3	C_3	C_4	C_4	C_4	C_4	C_3	C_3	C_4	C_4	C_4	C_4	C_3	C_3	C_4	C_4	C_4	C_4
a_{35}	C_3	C_3	C_4	C_4	C_4	C_4	C_3	C_3	C_4	C_4	C_4	C_4	C_3	C_3	C_4	C_4	C_4	C_4	C_3	C_3	C_4	C_4	C_4	C_4	C_3	C_3	C_4	C_4	C_4	C_4
a_{36}	C_3	C_3	C_4	C_4	C_4	C_4	C_3	C_3	C_4	C_4	C_4	C_4	C_3	C_3	C_4	C_4	C_4	C_4	C_3	C_3	C_4	C_4	C_4	C_4	C_3	C_3	C_4	C_4	C_4	C_4
a_{37}	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3
a_{38}	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3	C_3
a_{39}	C_2	C_2	C_3	C_3	C_3	C_3	C_2	C_2	C_3	C_3	C_3	C_3	C_2	C_2	C_3	C_3	C_3	C_3	C_2	C_2	C_3	C_3	C_3	C_3	C_2	C_2	C_3	C_3	C_3	C_3