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

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November 2020

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

1. Introduction

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, 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). 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 medical equipment from *Hospital da Luz Lisboa*, the biggest hospital in the *Hospital da Luz* network. Consequently, the present study is developed, aiming to provide a tool for the classification of the maintenance condition of a group of medical ventilators selected by the Infrastructures, Maintenance and Equipment Department (DIME). 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 the *COVID-19* global pandemic.

The introduction of a sorting method is made resorting to a Multicriteria Decision Aiding approach (MCDA), called 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*.

2. Literature Review

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). Regarding medical equipment maintenance management, Song et al. (2020) stated that 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.

The fact is, along the medical equipment life cycle, healthcare entities are responsible for taking decisions on acquisition, maintenance, utilization and replacement, usually associated with limited capital available (Dondelinger, 2004; Ouda et al., 2010). When organizations fail to invest in technology evaluation, technical complications may arise, such as device failures at critical times, the presence of obsolete medical equipment, demotivation from health professionals, among others (Clark, 2020).

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 analysis. This is done by resorting to a model developed for medical ventilators, life support type of equipment that possess characteristics that must be taken into account.

– Medical Ventilators

A medical ventilator, or as it can also be designated, a breathing machine or a 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, 2020). In its utilization, the aim of a medical ventilator can be to assist the breathing process of a patient or to completely control it (Elsevier Interactive Patient Education, 2020).

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. Moreover, based on 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 (World Health Organization, 2020; World Health Organization et al., 2011a). On the other hand, even though anesthesia ventilators integrate several aspects of the ICU ventilators, they are usually utilized in operating room settings (Jain and Swaminathan, 2013). 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 (World Health Organization, 2020).

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 optimal maintenance strategies for these devices should be a priority within healthcare facilities (Poor, 2018).

– Medical Ventilator Assessment Criteria

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.

Starting the analysis with the DA models for the acquisition of medical equipment, several criteria were considered.

Ramírez and Calil (2007) expressed concerns regarding clinical, financial, quality, safety and technical aspects. Lindgreen et al. (2009) introduced sustainability related dimensions. Pecchia et al. (2013) focused on performance, patient safety, usability and technical issues in the development of a model for the acquisition of a computerized tomography (CT) scanner. Barrios et al. (2016) added to the previous model the following: 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.

Sloane et al. (2003) explored the necessary factors for buying an intensive care ventilator and came up with cost, safety, biomedical engineering and clinical factors. Chatburn and Primiano (2001) proposed a model to purchase intensive care ventilators, where a cost, customer service analysis and technical evaluation were carried out.

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.

Fennigkoh (1992) introduced a model that considered the criteria 'Equipment Service and Support', 'Equipment Function', 'Cost Benefits' and 'Clinical Efficacy'. Dondelinger (2004) divided the criteria into objective and subjective ones, including features such as the failure rate, the repair cost factor, the advancements in technology and the evaluation of how well the replacement of one particular item would fit into the organization's five-year plan. For Rajasekaran (2005), the construction of a replacement model should be based on technical, safety and financial rules. Taylor and Jackson (2005) added to the previous study the mission critically. 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) considered technical, financial and safety criteria. Jamshidi et al. (2015) based the model construction 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 and an analysis of the consequences of failures for patient safety, the device operator and maintenance personnel, economic loss and the meantime to repair the equipment. Lastly, Clark (2020) detailed a list of factors to be included, such as age, risk, support status, reliability, condition assessment, regulation, as well as safety issues among recalls and alerts, adverse events, user errors, problem found work orders, equipment's status, 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 incorporated 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.

Regarding the establishment of a risk-based inventory for determining the medical equipment to be included in a preventive maintenance, different algorithms were studied, such as the *Fennigkoh and Smith Algorithm* (Biomedical Instrumentation & Planning, 2013), the *World Health Organization Modification* (World Health Organization et al., 2011b), the *Clinical Evaluation Modification* (Sen Salinas, 2015), the *Modification of Preventive Maintenance Index* (Rodríguez et al., 2001), the *Wang and Levenson's Algorithm and its modification* (Gaitán, 2015).

3. Case Study

– Methodology

MCDA can provide structure to processes that involve not only multiple aspects to be considered but also that deal with imperfect information and diverse perspectives from the decision makers (DM) (Roy, 1999). To this extent, it is natural that these methodologies are being considered when it comes to decision-making in healthcare, a sector involving not only a great deal of uncertainty but also an enormous diversity of possible outcomes. In this research work, the aim is to apply an MCDA method to a sorting problematic related with medical equipment management (medical ventilators, specifically). 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 method that is employed is ELECTRE TRI-nC. In this method, $A = \{a_1, a_2, \dots, a_i, \dots\}$ 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 $C = \{C_1, \dots, C_h, \dots, C_q\}$ 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 $F = \{g_1, \dots, g_j, \dots, g_m\}$ 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). Introducing the set of characteristic reference actions, $B = \{B_1, \dots, B_h, \dots, B_q\}$, these are responsible for defining the categories.

ELECTRE TRI-nC is composed of two main

procedures: an *aggregation procedure*, which comprises the construction of one or more outranking relations, and an *exploitation procedure*, which assigns a category to each of the possible actions (Greco et al., 2016).

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.

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

Concordance concerns "the strength of the coalition of criteria being in favor of the outranking relation aS_ja'" and is modeled using a comprehensive concordance index, $c(a, a')$ (Figueira et al., 2013). 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. 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.

The discordance concept is applied to those criteria that oppose to the assertion "a outranks a'" and so, have a veto power, taken into account by a partial discordance index (Almeida-Dias et al., 2012).

The introduction of a minimal degree of credibility, λ, should be established by the DM in order to validate or not the outranking relation aS_ja' and allows for the definition of the binary relations:

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

The ELECTRE TRI-nC method's assignment procedure is composed of two joint rules, the ascending and descending rules, that are used conjointly to highlight the highest category and the lowest category which can appear potentially adequate to receive an action (Almeida-Dias et al., 2010). The minimal credibility level, λ, is also responsible for influencing the results of these rules.

Both the ascending and descending 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). Their definitions 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.
- 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.

The application of the ELECTRE TRI-nC method was performed with the use of *MCDA-ULaval*, a software developed in the *Université Laval*, in Quebec (Verdasca, 2016).

– Problem Formulation

In translating the problem statement into decision support language, 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. A data selection procedure resulted in a total of 39 medical ventilators, with 22 anesthesia ventilators, 11 intensive care ventilators and six neonatal ventilators.

For the co-construction of the MCDA model, the establishment of criteria was done in view of the concerns raised by the DM in their interaction with the analyst. Five fundamental points of view (FPV) were created to capture the primary concerns expressed by the DM for the assessment of ventilators and from there, a criteria tree was defined with the criteria and subcriteria for each FPV (see Table 1).

– Evaluation Model

The construction of a model to obtain a formal answer to the problem involved the development of scales for the criteria. A criterion scale provides a way to assess performance, yielding a score to each action in regard to one criterion. Here, the

Table 1: Criteria Tree regarding the classification of medical ventilators in *Hospital da Luz Lisboa*.

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

operationalization of the information for the criteria associated dimensions is required.

Turning to the problem in question, the criteria defined 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.

Moreover, in MCDA, different types of scales can be adopted (Bana e Costa and Beinat, 2005). While for the criteria 'Technology level', 'Visual condition', 'Preventive maintenance commitment', 'Adaptability', 'Safety', 'Professionals' satisfaction', 'User friendliness' and 'Environmental sustainability' a qualitative, discrete and constructed descriptor is employed, for the criteria 'Reliability', 'Lifetime ratio', 'Utilization' and 'Maintenance Costs' a quantitative and continuous descriptor is used.

With this data, it was possible to assign the performances of the actions according to all criteria.

In a DA context, several techniques can be used to determine the relative importance of the different criteria. The one employed in this case study is the *revised Simos' procedure* (Figueira et al., 2011), a well accepted technique that is intuitive for any DM (Figueira and Roy, 2002). This way, the normalized and non-normalized weights for the family of criteria in question were obtained (see Table 2).

The set of ordered categories for the sorting of the medical ventilators of *Hospital da Luz Lisboa* were also established by the DM and the reference actions for each category were defined (see Table 3).

Table 2: Normalized and non-normalized ventilator's classification criteria weights.

Weights	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	g_{11}	g_{12}
Non-normalized	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

Table 3: Performance of the characteristic reference actions on each criterion for the five categories considered in the model.

Category	Reference Action	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	g_{11}	g_{12}
C_5, Excellent	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, Very Good	b_4^1	4	6	0.6	1000	2	3	4	4	4	5	0.3	4
C_3, Good	b_3^1	3	8	0.8	3000	2	3	4	3	3	4	0.4	3
C_2, Adequate	b_2^1	2	12	0.8	8000	1	2	3	3	2	3	0.5	3
C_1, Poor	b_1^1	1	15	1.0	15000	1	2	2	2	1	2	0.6	2

To cope with the imperfect nature of data, discrimination thresholds were introduced in ELECTRE TRI-nC: an indifference threshold q_j and a preference threshold p_j, presented in Table 4.

Table 4: Indifference and preference thresholds for each criterion considered in the model.

Thresholds	g_1	g_2	g_3	g_4	g_5	g_6	g_7	g_8	g_9	g_{10}	g_{11}	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

The DM also felt the need to include a veto threshold in three of the 12 criteria considered: $v_7 = 4$, $v_9 = 3$ and $v_{10} = 3$. Lastly, the chosen minimum credibility level validated by DM was $\lambda = 0.60$.

4. Results and discussion

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 the results of the model implementation in *MCDA-ULaval*.

The output of the model execution corresponds to the sorting of the medical ventilators from *Hospital da Luz Lisboa* to one or more of the five ordered categories. For a visual representation, Figure 1 displays the assignment of the actions to the possible categories.

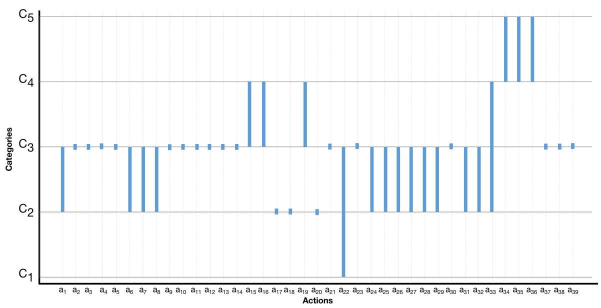

Figure 1: Assignment procedure results from *MCDA-ULaval*.

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.

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. 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%).

Moreover, in the obtained results, 41% of the actions were assigned to the single category Good (C_3). In fact, considering the representation of the individual categories in the maximum and minimum categories potentially adequate to receiving an action, C_3 was identified for the possible assignment of 33 out of the 39 actions.

When presented with the abovementioned statistics, the DM expressed that 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. 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. 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). 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.

– Robustness Analysis

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 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 parameters may endure in *Hospital da Luz Lisboa*, 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 existing veto thresholds, v_7, v_9 and v_{10}, for the criteria 'Adaptability' (g_7), 'Professionals' satisfaction' (g_9) and 'User friendliness' (g_{10}).

For the 180 scenarios 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.

Furthermore, 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 methodology and, in particular, ELECTRE TRI-nC 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*.

– Managerial Implications

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. The introduction of the present 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 organization's commitment to active inventory management must act as the base for storing important medical equipment data. Besides, the inclusion of professionals from diverse areas originates a variety of views that result in a more comprehensive and strengthen model. Lastly, 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 crucial, as a regular review of both the model and criteria parameters as well as elements such as criteria and 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 2.

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.

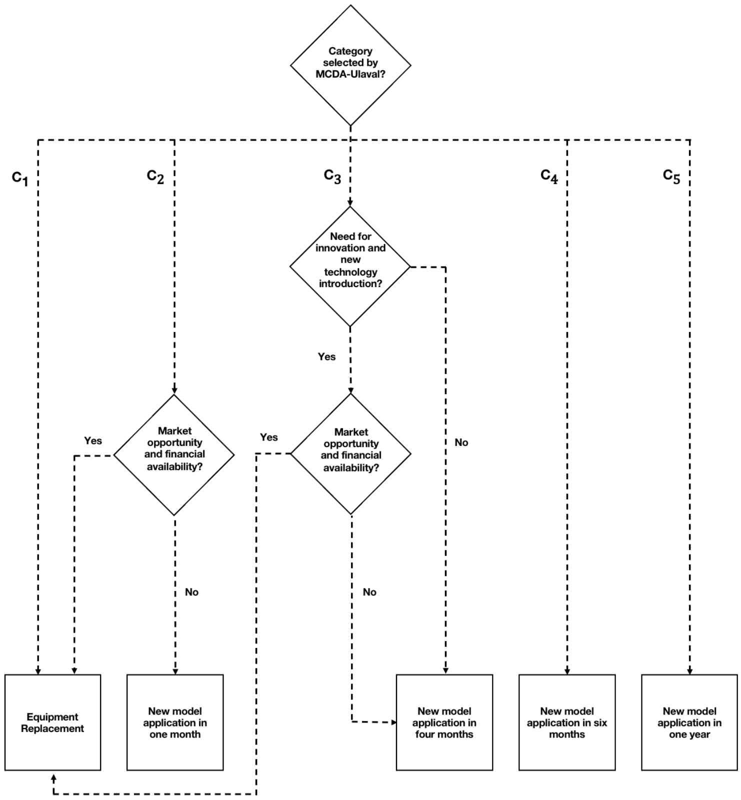

Figure 2: Decision tree for the consequences of the assignment of medical ventilators to each category in *Hospital da Luz Lisboa*.

5. Conclusions and Future Work

With the potential of overwhelming health systems, the *COVID-19* pandemic 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 takes on further relevance. 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.

In this context, a classification model for a selected group of medical ventilators from *Hospital da Luz Lisboa* was inserted, in order to assess their maintenance condition. An MCDA sorting methodology was followed, utilizing ELECTRE TRI-nC.

Collectively, the objectives of this study were achieved, as a new tool for the assessment of the maintenance condition of the medical ventilators of *Hospital da Luz Lisboa* was successfully introduced.

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. Furthermore, the managerial consequences of the action assignment to categories in *Hospital da Luz Lisboa* may be increasingly detailed.

The adaptability of the model could also be evaluated, by the introduction of other relevant actors.

The work developed represents a first step in the implementation of MCDA methodologies for supporting decision processes in *Hospital da Luz Lisboa*. With that in mind, the model for this case study may be employed as a guideline for both the classification of other medical equipment or the possible generalization of the model for the development of a maintenance prioritization system for the hospital. Regarding medical ventilators specifically, a natural extension of this analysis concerns the classification of medical ventilators from other healthcare units as well as 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 increased the demand for medical ventilators worldwide. As a result, their maintenance has been the focus of growing attention in healthcare organizations, that urgently aim to assure the dependability of these devices 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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