MCDA approach for the supplier selection in the healthcare units in Portugal: the case of heavy medical equipment

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ABSTRACT: Medical devices, in particular the heavy set, are equipment with very high technological levels, which contributes significantly to the quality of healthcare services in medical diagnosis, monitoring and even therapeutics. This creates the need to incorporate new, safer and complex technologies in order to guarantee safety, quality and medical efficacy, which is reflected in a significant evolution of medical equipment over the years. In this context, the focus is on the sustainable supplier selection, in order to select the equipment that best meets the requirements of a given service. For such purpose, a value based MCDA approach is used adapting the Choquet integral to assess criteria interactions. The proposed methodology includes the following two main steps: Firstly, assigning numerical values to the capacities of the Choquet integral, by constructing a ratio scale. Secondly, to construct interval scales that reflect the utility values to the criteria performances. Based on the criteria previously identified, in the end, this application resulted in a set of ranking alternatives, ordered by preference, with the objective of identifying, and subsequently select, the supplier (or his equipment) with the highest overall score. The results were consistent with those expected and analysis was carried out to prove the robustness of the model constructed as well as to study other variations in the parameters considered.

KEYWORDS: Supplier selection, Heavy medical equipment, Multicriteria analysis, Choquet integral; Deck of cards method.

1. INTRODUCTION

Technology is constantly being innovated [1]. In the health sector, the adequate implementation of technological innovation contributes to an improvement in the quality of healthcare provided [2], since it is very dependent on the use of medical equipment in different areas, such as diagnosis of pathologies, medical monitoring or therapy [3].

In recent years there has been a significant evolution in medical equipment, due to the need to incorporate new, safer, more complex technologies and also taking into account the requirements of safety, maintenance, performance of the equipment itself and even cost reduction [4]. There is thus a great need to ensure medical safety, quality and efficacy.

At the same time, there has been a development of the hospital network, which implies a growth in the inventory of the equipment in question. However, unsustainable purchases of medical equipment and in an unjustified manner may jeopardize their use, in the case of not being used optimally. It is extremely important, in this context, to have knowledge of the existing equipment, the operating time they have and their differentiation, in order to correctly support the expenditures in this field [5]. On the other hand, the competitiveness of the health sector tends to increase, so that health system entities also need differentiation and innovation, which is possible through the use of newer and more innovative medical technologies [6].

In addition to all this, with new technologies and increasing complexity over time, there is a greater need to have experienced health professionals capable of amplifying their knowledge and experience, in order to reduce the risk of accidents and other complications [1]. These aspects make it increasingly relevant to create and implement evaluation technologies as well as manage existing technologies.

In order to reduce the sample of health system suppliers and the previous facts, this work will focus on a set of equipment called heavy medical equipment (HME). This group of biomedical equipment presents, among other factors, significantly higher costs, which leads to a greater need of studying their acquisition as well as the sustainability associated with this same process. The main objective is to achieve a better rationalization and standardization of quality and of the cost in the various health units.

The study will be performed for the health services units belonging to the Portuguese National Health System (NHS). The main goal of this dissertation is the application of a multicriteria decision support methodology in the selection of heavy medical equipment in the NHS health units.

2. PROBLEM CONTEXT

The supplier selection of heavy medical equipment for healthcare units belonging to the NHS is the focus of this dissertation. First of all, it becomes necessary to define the concept of supplier.

In the literature, the supplier (individual or organization) is the company that supplies the product and usually refers to the distribution company responsible for delivering the product [7]. In fact, the supplying company does not necessarily correspond to the manufacturing company, and these two processes (supply and manufacturing) are carried out by different entities. There is a need, in this context, to adapt this concept, considering supplier the entity responsible for the equipment, and therefore the manufacturer.

In this section, an introduction will be made to the concept of heavy medical equipment which contains not only its definition but also the type of equipment in this category. The process of how these devices is acquired in the healthcare units of the NHS is therefore explained.

2.1. Heavy medical equipment (HME)

Before defining what is meant by Heavy Medical Equipment (EMP) it is important to do a framework of the context in a more comprehensive domain and to mention which equipment belong to this subset.

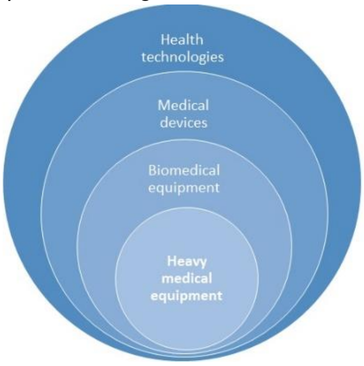

Figure 1: Framework of heavy medical equipment (adapted from Penedo et al.[5])

The term of Health Technologies is defined by the World Health Organization as the application of skills and knowledge in the form of devices, medicines, vaccines, procedures and systems developed with the objective of improving the quality of life and solving health problems [8].

It is important to highlight, from the various subsets of health technologies, in the scope of this work, medical devices. These comprise any apparatus, instrument, equipment, software, material, implant or other similar items which are intended for diagnostic and therapeutic purposes for humans and whose main effect is not achieved by pharmacological, metabolic or immunological resources. These devices are intended to prevent, diagnose and treat or alleviate an illness as well as an injury or disability. They also aim at the study, alteration or replacement of the anatomy or physiological process. Sterilization of medical devices, design control and collection of information through in vitro studies of human samples for medical or diagnostic purposes are also targets to be achieved by manufacturers of medical devices [9].

Within the group of medical devices can also be highlighted the category of biomedical equipment. This subset excludes sterile, implantable and consumable medical devices, drugs, reagents or elements from the human body (such as blood, tissues, among others). Except for these, biomedical equipment generally corresponds to equipment whose functions are to perform curative actions, follow-up, diagnostic and therapeutic activities [5].

It is finally in this group of biomedical devices that are included the heavy medical equipment (HME). According to Penedo et al.[5] HME is defined as "any equipment used for diagnostic and/or therapeutic purposes, subject to regular quality controls and whose human resources are specialized and monitored for possible harmful exposure arising from the exercise of the profession (if applicable)." In addition, they must meet at least two criteria among the following:

- High cost of acquisition or maintenance (to be defined by a member of the Government and in own dispatch);
- Fixed equipment with specific installation essential to its use;
- Characteristics of the equipment (physical) that imply specific infrastructures and licensed for its operation.

Table 1: Medical equipment covered by the definition of heavy medical equipment

Nuclear medicine	**Radioncology**
Gamma camera	Linear accelerator
Gamma camera-CT	High dose brachytherapy
Cyclotron	Cyber-knife
PET	Gamma-knife
PET-CT	Simulator
PET-MR	
Radiology	**Hyperbaric medicine**
Computed Tomography (CT)	Hyperbaric chamber
Magnetic resonance (MR)	Tomotherapy
Angiograph	

After definition of the concept, the equipment considered in this category of HME are shown in Table 1.

2.2. Acquisition process of HME in Portugal

The process of acquiring EMP in Portugal is a complex process and where several entities are involved. The Services of Facilities and Equipment (SFE) in some healthcare unit are entities responsible for the maintenance and conservation of existing equipment, as well as all hospital structures, except for network and computer equipment, from the user's perspective. Thus, they play a key role not only in the maintenance of heavy hospital equipment, but also in their acquisition, whether through innovation or replacement.

There are several factors that can lead to a process of replacement or acquisition of new medical equipment in the healthcare sector. If the equipment presents a fault or a serious technical problem, where its maintenance entails very high costs, or even if it is not possible to correct the faults, then it is indicated to proceed for a replacement. The lifetime of the equipment can also be a decisive factor, or even because, due to the current technology, these can be considered obsolete, being necessary to improve their functionalities and characteristics that are missing and that are necessary for the service. Also, even if a substitution is not performed, there may also be the acquisition of a new equipment by necessity of the hospital service, to fill some gaps, or even the intention to invest in, for example, a new room or space.

Identification of this need and subsequent request for substitution or acquisition is usually given by the service director physicians, coordinating technicians, or other health care professionals in the hospital service where the need was felt.

In a first step, and after identification of the need, a communication is made to the SFE that carries out an evaluation of this request for replacement/acquisition. Subsequently, this service confirms the need for change, following up the process. The Board of Directors of the proposing entity then becomes aware of the process and is responsible for its evaluation, having to accept or reject the request in question.

Since this is a group of medical equipment with very specific characteristics such as high costs, an investment authorization is carried out at this stage which, depending on the budget, is evaluated by different entities (internal or external). This budget is assessed and determined by the SFE, which performs a prior market analysis.

In the end, the purchase of equipment involves the opening of a public tender on a digital platform with the creation of specifications required for the new equipment and this procedure is available for any industry that wishes to compete. The requirements set out in the tender specifications are dictated by professionals who work directly with the equipment, such as medical service directors, coordinating technicians or SFE professionals.

In short, the initiative to purchase or replace equipment is a political-administrative decision of the health service provider, which ends with the opening of a public tender for suppliers in the sector.

3. LITERATURE REVIEW

A literature review was conducted with the purpose of identifying the supplier selection studies in the healthcare area and more specifically, in the selection of heavy medical equipment, based on multicriteria approaches. Multicriteria decision support methods (MCDA) appear as a branch of operational research, whose purpose is (as the name implies) to support the resolution of issues associated with decision making and taking into account several criteria in its analysis (Keeney, 1992).

In this section are presented some applications of MCDA methods found in literature and used in a context of supplier selection and in health sector, specifically in the selection of medical devices.

Although there are several studies on supplier selection, literature is still limited in the specific context of health and medical devices [10].

Currently, there are several criteria in MCDA to evaluate and select suppliers. However, these may not be the most appropriate in the health area and medical devices. In this specific context, unlike other areas of action, it is indispensable to take into account the fact that health is an irreplaceable good that affects individuals directly [11]. Decisions cannot be made solely with the management of the supply chair, since the health and life of patients are also fundamental aspects to be taken into account in the analysis [12].

Santos and Garcia [13] proposed an integrated approach of AHP (Analytic Hierarchy Process), MAFMA (Multi-Attribute Failure Mode Analysis) and ELECTRE (ELimination and Choice Translating REality). The main goal was to create a model to select and acquire a medical device, specifically for primary care stations, based on decision making, technology assessment health technology.

Beşkese and Evecen [12] developed a decision model using AHP to evaluate supplier selection in healthcare sector. The criteria considered in the analysis were costs, services, supplier profile and risk. In this study, quality was considered an exclusion factor, due to its extreme importance. Service was the most important criteria, followed by costs and then risk.

Pecchia et al. [14] suggested an approach also based on AHP method, in order to select a computed tomography equipment (CT). In the evaluation process, authors take into account performance, patient security, functionality and technical aspects. Performance and security were considered the most important criteria.

Ghadimi and Heavy [10] proposed a ranking method based on fuzzy inference systems (FIS) with application to the sustainable supplier selection in the medical industry. Several criteria were analyzed, associated with the three dimensions of sustainability – social, environmental and economics.

Kulak et al. [15] developed a methodology using fuzzy axiomatic design (FAD). The equipment is evaluated from the models but presents as main focus only the costs and technical aspects of the medical devices, not being considered other sustainability characteristics to acquire the same.

A more detailed review can be seen at M. Prazeres (2018) [16].

4. METHODOLOGY

The objective is to develop a multicriteria model to select suppliers of heavy medical equipment for health facilities in Portugal, and it should be possible to apply to any public tender and for any type of equipment in this set.

The public tender that will be analyzed is for the acquisition and installation of a 3T Magnetic Resonance equipment and its accessories and complementary elements for the Radiology Service of the Portuguese Oncology Institute of Lisbon Dr. Francisco Gentil, E.P.E. (IPOFLG, E.P.E.).

In this public tender, CP nr 100/2015, three suppliers compete. For reasons of confidentiality of information, they will not be identified, assigning to each one the denominations: alternative 1 (a1), alternative 2 (a2) and alternative 3 (a3). For this specific case, the decision maker (DM) will not be an individual person, but rather a group of individuals directly related to the acquisition of equipment in the hospital in question.

4.1. Problem structuring

The problem structuring is the first point of this methodology. Within this topic, it is necessary to distinguish two distinct phases: firstly, the identification of the problem, through the collection of information; and secondly the problem formulation, which encompasses the interpretation and processing all the information. It is fundamental to have a good structuring of the problem to follow the process.

Semi-structured interviews were conducted with the purpose of identifying the different concerns of actors involved in the process, to later make possible the construction of a cognitive map with the information collected. The construction of this maps, in this context, helps in problem structuring, since it facilitates the visualization of the problem and represents the thinking and the concerns of the actors in a clear and intuitive way [17].

From the collection and treatment of the data, the criteria that are part of this methodology were constructed and will be the base of the evaluation of the alternatives under analysis. These criteria are subdivided into four major areas addressed in the concepts of sustainability: socio-environmental dimension, economic-financial, quality and more recently, governance. Table 2 summarizes all the elements to be considered in this methodology. In addition, a set of sub-criteria or elementary consequences, from which the criteria are constructed, is also identified, allowing later its operationalization.

4.2. Evaluation model

In the previous section, a coherent family of criteria was defined, through which the alternatives will be evaluated and compare. In the model construction is necessary to proceed to the operationalization of these criteria, which include the aggregation of the different elementary consequences identified. For this, a set of dimensions is

Table 2: *Fundamental points of view (FPV), criteria and elementary consequences for the supplier selection of HME*

FPV	Criteria		Elementary consequences
FPV1 **Socio environ--ment**	g_1 Practice health professionals (max)		c_1 Training (qualitative)
			c_2 Disciplinary and security practices (qualitative)
	g_2 Supplier profile (max)		c_3 Social responsibility (qualitative)
			c_4 Supplier reputation (qualitative)
	g_3 Environ--mental expertise (max)		c_5 Process of production *ecofriendly* (qualitative)
			c_6 Ecoefficiency of equipment (qualitative)
FPV2 **Economic & financial**	g_4 Costs (min)		c_7 Acquisition (euros, €)
			c_8 Operation (euros, €)
			c_9 Maintenance (euros, €)
FPV3 **Quality**	g_5 Technological capability (max)	$g_{5.1}$ Performance/ Obsolescence	c_{10} Durability (year)
			c_{11} Technology & innovation (qualitative)
			c_{12} Operational availability (percentage)
			c_{13} Upgrades possibility (qualitative)
			c_{14} Robustness (qualitative)
	g_6 Services & delivery (max)		c_{15} Technical support (assists, per year)
			c_{16} Responsiveness (qualitative)
			c_{17} Warranty (years)
			c_{18} Delivery time (qualitative)
	g_7 Control (max)		c_{19} Internal audit (audits, per year)
FPV4 **Governance**	g_8 Transparency of info (max)		c_{20} Disclosure of documents (qualitative)
			c_{21} Clarity of information (qualitative)
	g_9 Supplier reliability (max)		c_{22} Similar equipment in operation (qualitative)

created, which encompasses the elementary consequences as well as an associated scale, which contain a set of different levels, in order to map each of the alternatives [18].

In practice, for the model implementation, there are two steps to be performed: the assignment of numerical values to the capabilities of the Choquet integral for each of the criteria and the construction of interval scales with the purpose of assigning utility values to the performance of the criteria , on a common ratios scale [19].

4.2.1. <u>Operationalization of criteria</u>

Due to the extension of this topic, an example of operationalization will be given for the most appreciated criterion, g_5 (technological capacity). This criterion depends on a sub-criterion related to performance and another (also an elementary consequence) related with robustness.

For the aggregation of the 4 dimensions belonging to the sub-criterion $g_{5.1}$, a profile tree was elaborated in order to analyze the possible combinations between all the scales. The related ones, for each elementary consequence, were designed as follows:

$E_{c_{10}} = \{Acceptable\ value\ for\ the\ lifetime;\ Low\ value\}$;

$E_{c_{11}} = \{Equipment\ has\ all\ the\ requirements\ with\ additional\ technical\ aspects;\ Equipment\ has\ all\ the\ requirements;\ equipment\ does\ not\ fullfil\ the\ needs\}$;

$E_{c_{12}} = \{Acceptable\ percentual\ values\ for\ operational\ availability;\ Low\ percentual\ values\}$;

$E_{c_{13}} = \{Possibility\ of\ upgrades;\ upgrades\ not\ possible\}$.

For the aggregation of the levels obtained through the profile tree, we considered the following:

- Level "Very Strong" is represented by the combination that presents maximum quotation in all the analyzed consequences.
- The "Strong" level includes levels that have the four consequences with positive parameters, or three positive parameters if an "excellent" is included in them;
- The "Moderate" level encompasses levels that have three consequences with positive parameters, or only two if an "excellent" is included in them;
- The level "Weak" encompasses levels that have three consequences with positive parameters, or only one if this parameter is "excellent ";
- Level "Very Weak" includes all levels that present only one positive parameter, or that are classified in elemental consequence 11 as the lower level.

Thus, the respective scale is given by:

$E_{g_{5.1}} = \{Very\ strong;\ Strong;\ Moderate;\ Weak; Very\ weak\}$

For the elementary consequence robustness (c_{14}), the following scale of 3 levels was considered: $E_{c_{14}} = \{Highly\ robust;\ Moderatly\ robust; Slightly\ robust\ \}$;

Once again, a profile tree was added to aggregate the several levels from both scales ($c_{14};\ g_{5.1}$), finally obtaining a final scale for the criterion g_5 which presents the following levels: $E_{g_5} = \{Very\ strong;\ Strong;\ Moderate;\ Weak;\ Very\ weak; Insatisfatory\}$.

The other scales are constructed in a similar way from the elementary consequences associated, with the following scales:

$E_{g_1} = \{Very\ strong;\ Strong;\ Moderate;\ Weak;\ Very\ weak\}$;

$E_{g_2} = \{Strong;\ Moderate;\ Weak\}$;

$E_{g_3} = \{Excellent; Very\ strong;\ Strong;\ Moderate;\ Weak;\ Very\ weak;\ Insatisfatory\}$;

$E_{g_6} = \{Excellent; Very\ strong;\ Strong;\ Moderate;\ Weak;\ Very\ weak\}$;

$E_{g_7} = \{Ideal;\ Good;\ Average; Bad\}$;

$E_{g_8} = \{Excellent; Very\ strong;\ Strong;\ Moderate;\ Weak;\ Very\ weak;\ Insatisfatory\}$;

$E_{g_9} = \{High;\ Moderate;\ Low; None\}$.

4.2.2. Choquet integral

Differently from the weighted-sum methods, Choquet integral, which define the weighting that each criterion will have for the final scores associated with each alternative to be evaluated, Choquet integral allows possible interactions between criteria. Thus, this method is considered a non-additive model [20], being the best known in the literature today [19].

The Choquet integral is an aggregation function based on the concept of capacity (diffuse measure) that joins the weights of each subset of criteria rather than a single criterion.

Let A be a set of m, where $A = \{a_1, \dots, a_j, \dots, a_m\}$ and G a set of n criteria, with $G = \{g_1, \dots, g_i, \dots, g_n\}$. For a given action and for a given criterion $g_i(a)$ can be defined as the performance of an action a on a given criterion g_i and $u_i(g_i(a))$ as the utility of that performance. In simplicity, it is also possible to identify the criteria by their indexes. For simplicity, $u_i(g_i(a)) \equiv u_i(a)$ can be considered.

More precisely, the capacity of the various criteria in G is a function such that $\mu : 2^G \to [0,1]$ (that is, the set of all subsets of G), which can be interpreted as the weight of each criterion of set G. This setting must satisfy the following properties:

(i) $\mu(\emptyset) = 0; \mu(G) = 1$ (boundary conditions)

(ii) $\forall\ S \subseteq T \subseteq G$, $\mu(S) \leq \mu(T)$ (monotonicity condition)

Intuitively, for each subset $T \subseteq G$, the value, $\mu(T)$, represents the value of the capacity (or weight) of the criterion belonging to the subset T.

Given a capacity $\mu : 2^G$ and an action $a \in A$, Choquet integral can be defined as:

$$C_\mu(a) = \sum_{i=1}^{n} (u_{(i)}(a) - u_{(i-1)}(a))\mu(G_i) \quad (1)$$

where $u_{(i)} = \{u_{(1)}, \dots, u_{(n)}\}$ represent the utility functions (or utilities) of the set criteria G in such a way that $u_{(1)}(a) \leq \dots \leq u_{(n)}(a)$ and $G_i = \{(i), \dots, (n)\}$ for $i = 1, \dots, n$ and $u_{(0)}(a) = 0$. It should be noted that the Choquet integral guarantees the commensurability between criteria [19].

In this context the concept of the Möbius transform is introduced and the Choquet integral is reformulated according to this transformation. Thus, given the capacity μ in 2^G, its representation of Möbius is a function m: $m : 2^G \to \mathbb{R}$, such that for any subset $S \subseteq G$,

$$\mu(S) = \sum_{T \subseteq S} m(T) \quad (2)$$

where the transformation can be given by the values:

$$m(S) = \sum_{T \subseteq S} (-1)^{|S-T|} \mu(T) \quad (3)$$

The Choquet integral can be rewritten with respect to the Möbius representation m of the capacity μ as shown below,

$$C_\mu(a) = \sum_{T \subseteq G} m(T) \min_{i \in T}\{u_i(a)\} \quad (4)$$

where the properties mentioned in (i) and (ii) are reformulated as follows:

(i') $m(\emptyset) = 0; \sum_{T \subseteq S} m(T) = 1$.

(ii') $\forall\, i \in G$ and $\forall\, R \subseteq G\backslash\{i\}$,
$m(\{i\}) + \sum_{T\subseteq R} m(T \cup \{i\}) \geq 0$;

and thus,

$$\mu(S) = \sum_{i\in S} m(\{i\}) + \sum_{\{i,j\}\subseteq S, \{i,j\}\in O} m(\{i,j\}) \tag{5}$$

$$\mu(G) = \sum_{i\in G} m(\{i\}) + \sum_{\{i,j\}\in O} m(\{i,j\}) = 1 \tag{6}$$

while the integral of Choquet is reformulated as,

$$C_\mu(a) = \sum_{i\in G} m(\{i\}) u_i(a) + \sum_{\{i,j\}\in O} m(\{i,j\}) \min\{u_i(a), u_j(a)\} \tag{7}$$

Only the interaction between pairs of criteria will be considered, often used in applications with the Choquet integral, since interactions with a higher number of criteria significantly increase the complexity of the model. It should be noted that equation (5) and following correspond to the specific case of use of the mentioned bi-additive capacity, which was proposed by Grabisch in 1997 [21].

When considering a pair of criteria g_i and g_j, one of the three cases can occur:

- There is no interaction between the two criteria, in which case $\mu(\{g_i, g_j\}) = \mu(\{g_i\}) + \mu(\{g_j\})$;
- There is a mutual-strengthening effect, also called synergy, between the 2 criteria g_i and g_j where $\mu(\{g_i, g_j\}) > \mu(\{g_i\}) + \mu(\{g_j\})$;
- There is a mutual-weakening effect, or redundancy, where $\mu(\{g_i, g_j\}) < \mu(\{g_i\}) + \mu(\{g_j\})$

For $\{i,j\} \in O$, there is a mutual-strengthening effect between i and j if $m(\{i,j\}) > 0$ and mutual-weakening if $m(\{i,j\}) < 0$.

Hereafter, m_i will be used instead of $m(\{i\})$ as well as m_{ij} in the place of $m(\{i,j\})$. The same will apply to the concepts of capacities (μ_i and μ_{ij}).

In this study, the following interactions were considered:

- Mutual-strengthening effect between g_1 (practice of health professionals) and g_6 (services &delivery);
- Mutual-weakening effect between g_1 (practice of health professionals) and g_2 (supplier profile).

In discussion with the team of decision makers (DM) on the interactions between the evaluation criteria, for the first interaction, an alternative that presents good practices and good levels of service and delivery is greatly appreciated. Consequently, the overall weight of the pair of criteria should be greater than the sum of their individual weights [22].

In fact, for the second interaction considered, an alternative that presents a good evaluation in the practice of technicians is often also a good assessment of the supplier profile. In this way, the overall weight of the pair of criteria will be less than the sum of their individual capacities.

After the identification of the individual criteria and the interactions between pairs, the model based on the Choquet integral is applied. This requires the realization of two fundamental steps, which can be described as the construction of interval scales and the determination of capacities (weights).

4.2.3. Determining the capacities

We opted to apply the deck of cards method as a methodology to support the construction of this problem. This method was proposed by Jean Simos, in 1994, and later, Figueira and Roy [23] proposed an adaptation to this model, in order to construct ratio scales as well as interval scales.

For the determination of capacities by application of the Choquet integral and using the deck of cards method, it is essential that there is a dialogue between the analyst and the DM. This process should contain the following steps:

1. The analyst provides the DM with a first set of cards, which present the name of each object (criterion). It is also provided another set containing only blank cards.
2. The DM must order the cards of the first set from the projects he considers less important to the one of greater importance. Note that if there are two tie cards, they must be considered at the same level.
3. Consecutive levels in the ranking may be more or less close (equidistance is not mandatory). The DM is then asked to model this difference between the levels with white cards, placing the number of cards he finds sufficient between consecutive positions.
4. Finally, the analyst must obtain the ratio *z*, which represents how many times the capacity of the criterion in the highest position is greater than the capacity of the criterion in the lowest position.

It is considered a specific set of objects, which is called (fictitious) projects. Its set comprises n projects (as many as the number of criteria) and |O| (as many as the number of interactions between pairs of criteria.

The cards for the n projects should present utilitiy 1 for the most preferential level for the criterion concerned and the least preferred level for the remaining ones. In the case of interactions, projects should present the level more preferably in both of the interacting criteria.

Given the criteria and interactions, the finite set of reference projects is considered: $P = \{p_1, p_2, p_3, p_4, p_5, p_6, p_7, p_8, p_9, p_{16}, p_{12}\}$. After ordering the cards according to the preferences of the decision makers, a ranking was obtained $\mathrm{R} = \{\mathrm{R}_1, \ldots, \mathrm{R}_v\}$, which includes the number of white cards e_h between each of the levels.

We can consider the ranking with the following structure: $X = [R_1(\mathrm{e}_1);\ R_2(\mathrm{e}_2); \ldots; R_8(\mathrm{e}_8); R_9]$. Hence, the ranking made by the DM is given by a vector like: $[\{\mathrm{p}_3, p_8\}(0); \{p_2, p_7\}(0); p_9(0);\ p_1(0); p_{12}(1); p_6(3); p_{16}(1);\ p_4(0); p_5]$

It is verified that project p_5 was considered the most important and p_3 and p_8, were considered the least important. The DM considered a value of 15 for the z-ratio.

Subsequently, the SRF software (Simos-Roy-Figueira acronym) was used to obtain the values corresponding to the capacities for each criterion and interactions between pairs of criteria [23]. It is necessary to calculate the coefficients Möbius, m_k, from the following expression,

$$m_k = \frac{\varpi(p_k)}{\sum_{j=1}^{t} \varpi(p_j)} \quad (8)$$

and the final capacities, μ_k, are calculated as follows,

$$\mu_k = \frac{\omega(p_k)}{\sum_{j=1}^{t} \varpi(p_j)} \quad (9)$$

where the modified values, $\varpi(p_k)$, will be:

- $\varpi(p_k) = \omega(p_k)$, if $k = i \in G$
- $\varpi(p_k) = \omega(p_k) - \omega(p_i) - \omega(p_j)$, if $p_k = p_{ij}$, for $k \geq n + 1$

Using the SRF software, the values obtained directly from the platform correspond to the values $\omega(p_k)$. With these data it becomes possible to calculate the final capacities, μ_k, as shown in Table 3.

Table 3: *Values to obtain capacities, based on SRF output*

Ranking	$\omega(p_k)$	$\varpi(p_k)$	m_k	μ_k
p5	15	15	0,30612	0,30612
p4	13,92	13,92	0,28408	0,28408
p16	11,77	0,08	0,00163	0,24020
p6	7,46	7,46	0,15224	0,15224
p12	5,31	-1	-0,02041	0,10837
p1	4,23	4,23	0,08633	0,08633
p9	3,15	3,15	0,06429	0,06429
p2	2,08	2,08	0,04245	0,04245
p7	2,08	2,08	0,4245	0,04245
p3	1	1	0,02041	0,02041
p8	1	1	0,02041	0,02041
	z=15		∑ 1	

Note that the following expressions need to be verified:

- $m_1 + m_2 + m_3 + m_4 + m_5 + m_6 + m_7 + m_8 + m_9 + m_{16} + m_{12} = 1$;
- $\mu_1 + \mu_2 + \mu_3 + \mu_4 + \mu_5 + \mu_6 + \mu_7 + \mu_8 + \mu_9 + (\mu_{16} - \mu_1 - \mu_6) + (\mu_{12} - \mu_1 - \mu_2) = 1$

Non-conformities should not exist, and therefore, the conditions described in (i') and (ii') must be satisfied, and the values of m_k must be consistent with the signals of the interactions (mutual-strengthening positive; mutual-weakening negative sign).

4.2.4. Building interval scales

The construction of interval scales for each of the criteria is performed based on the following steps, proposed by Bottero et al. [19]:

1. A discrete scale of a criterion g, with $E_g = \{N_1, N_2, \ldots, N_k, \ldots, N_t\}$ where the levels are ordered by preference, $N_1 \prec N_2 \prec \cdots \prec N_{t-1} \prec N_t$.
2. Define two reference levels, N_p and N_q, and assign these utility values, usually $u(N_p) = 0$ and $u(N_q) = 1$, at most. If more than 2 reference levels are defined, the procedure described for each consecutive two is replicated;
3. Placing white cards, e_k, between two consecutive levels of the already ordered scale;
4. Calculate values representing the number of units between levels N_p and N_q:

$$\alpha = \frac{u(N_q) - u(N_p)}{h} \quad \text{and} \quad h = \sum_{k=p}^{q-1} (e_k + 1) \quad (10)\ (11)$$

5. Calculate utility value, $u(l_k)$, for all intermediate levels of the scale, such as:

$$u(N_k) = u(N_1) + \alpha \left(\sum_{j=1}^{k-1} (e_j + 1) \right), \quad for \ \ k = 2, \ldots, t \quad (12)$$

where N_1 represents the reference level immediately before the level to be considered.

For all discrete scales constructed (except g_4), it is possible to obtain utility values for the different levels, as shown in Table 4.

Table 4: *Utility values for the different levels and blank cards between each one*

	g1	g2	g3	g5	g6	g7	g8	g9
N_1	1	1	1	1	1	1	1	1
e_1	2	0	0	2	1	2	0	2
N_2	0,7	0,875	0,875	0,75	0,8	0,625	0,875	0,625
e_2	1	0	0	1	1	1	0	1
N_3	0,5	0,75	0,75	0,583	0,6	0,375	0,75	0,375
e_3	0	0	0	0	1	2	0	2
N_4	0,25	0,625	0,625	0,5	0,4	0	0,625	0
e_4	0	0	0	0	1		0	
N_5	0	0,5	0,5	0,375	0,2		0,5	
e_5		0	0	0	1		0	
N_6		0,375	0,375	0,25	0		0,375	
e_6		0	0	1			0	
N_7		0,25	0,25	0			0,25	
e_7		0	0				0	
N_8		0,125	0,125				0,125	
e_8		0	0				0	
N_9		0	0				0	

For continuous scale (criterion costs, g_4), the utility values were defined by linear interpolation.

The magnitude of the values associated with the maximum extremes of the interval depends on the type of equipment being analyzed. Thus, since they are magnetic resonance (MR) equipment, the maximum value, referring to the unit utility, corresponds to a cost of € 1 000 000. Similarly, for the minimum utility value (zero), the corresponding cost is € 2 500 000.

5. RESULTS AND DISCUSSION

The results for the application of the previous methodology are presented. This section begins with the assignment of numerical values to the alternatives in order to obtain a final result. The overall score assigned to each alternative are calculated based on the procedure already described, in which the values were compared and ordered. In Table 5 are presented the performance levels assigned and, consequently, utility values for each alternative.

Based on the Table 5, it is possible to proceed to the application of the non-additive model, which results in an overall value calculated for each alternative, and translates the global performance of each one (Table 6). A better performance is reflected by a higher overall value.

Table 5: Performances and utilities of alternatives for each criterion

Performance (and utilities) of alternatives				
		a1	a2	a3
g_1	**Practice health professionals**	Moderate (0,5)	Very strong (1)	Moderate (0,5)
g_2	**Supplier profile**	Strong (1)	Strong (1)	Strong (1)
g_3	**Environmental expertise**	Very strong (0,875)	Excellent (1)	Strong (0,75)
g_4	**Costs**	€ 1 400 000 (0,733)	€ 1 399 000 (0,734)	€ 1 953 500 (0,364)
g_5	**Technological capability**	Excellent (1)	Excellent (1)	Very weak (0,25)
g_6	**Services & Delivery**	Strong (0,6)	Very strong (0,8)	Strong (0,6)
g_7	**Control**	Ideal (1)	Ideal (1)	Good (0,625)
g_8	**Transparency of information**	Very strong (0,875)	Strong (0,75)	Strong (0,75)
g_9	**Supplier reliability**	Moderate (0,625)	Moderate (0,625)	Low (0,375)

Table 6: Ranking of alternatives

Position	Suppliers	Overall score
1st	Alternative 2 (a2)	0,8644
2nd	Alternative 1 (a1)	0,8004
3rd	Alternative 3 (a3)	0,4289

5.1. Sensitivity analysis

The aim of the sensitivity analysis is to verify if there are changes in the overall assessment of the alternatives, in case of some changes in the capacities. For such purpose, the analysis is performed individually for each criterion, where variations are introduced in the values of the capacities of each one to measure the impact on the performance of the alternatives. It was tested a variation of $\pm 7{,}5\%$ in the capacity for a given criteria, where a variation in the capacity assumes that the same proportions remain between the other criteria.

The variation of the capacity for the plausible interval considered is represented by a continuous line. For points outside this range, only a linear extension of the endpoints (dashed lines) was considered in order to give a general idea of their behavior, although the values of the capacities should not be interpreted outside the limits established by the assumptions made during the construction and evaluation of the model.

For criterion 5, the most appreciated one, and for the region of variation considered, it is verified that there is no change in the ordering of the alternatives, and it can be said that the final result (ranking order) is maintained. The same is proved for any other criterion.

The second alternative is the one that have a better performance, for every capacity value considered for these criteria. The ordering of the alternatives is thus unchanged, which is graphically observed because the lines of the alternatives do not intersect throughout the region. In some cases, such as criteria 1,2, 6 and 8, for a given capacity value, alternative 1 will perform better than alternative 2. This value corresponds intuitively to the point where the alternatives intersect, and where alternative 1 becomes prevalent. Even so, this intersection happens to values of

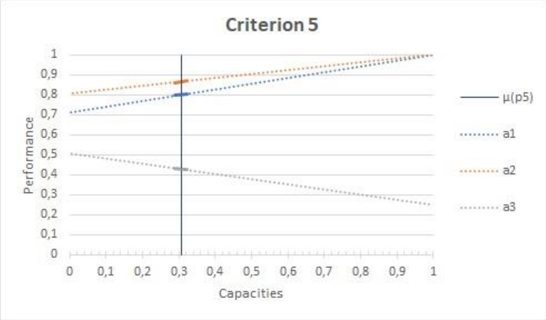

Figure 2: Sensitivity analysis for criterion 5

weighting (capacities) very far from the values of the variation of 7.5% considered plausible. Thus, the order alteration of the alternatives happens in a region whose values do not make sense to consider, given the various assumptions of the model.

Concerning the interactions of the criteria, it is mentioned that in certain situations these may be important and should therefore be considered. By constructing graphs for interactions similar to the one shown above, it turns out that the interactions can have a significant impact on the result obtained. This is due to the fact that, for a small variation in the capacity value, there is a large variation in the performance value of the alternatives. Nevertheless, for the interval of values studied for the capacities, the final ranking does not change.

5.2. Influence of the z-ratio

From Figure 3 it is possible to verify the various variations that were made for the z-ratio and what that influences the value of the capacities ($z = 5; 10; 15; 20; 25$).

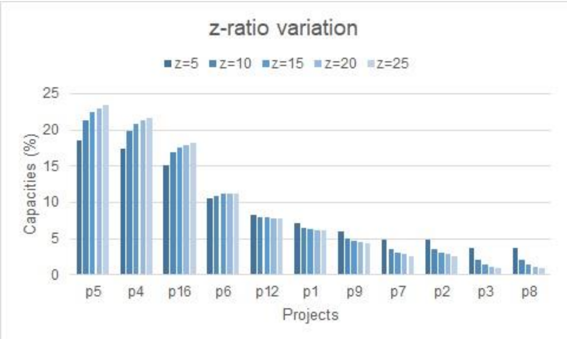

Figure 3: Values of capacities for the projects with z-ratio variations

Table 7: Overall score with variation in the z-ratio

Suppliers	Overall score					Position
	z=5	z=10	z=15	z=20	z=25	
a1	0,823	0,807	0,800	0,797	0,795	2nd
a2	0,866	0,865	0,864	0,864	0,864	1st
a3	0,474	0,441	0,429	0,422	0,418	3rd

For the variation of z studied, there is no significant impact on the final result from the model, since the ordering of the various alternatives is maintained and consequently the selection of the supplier with the highest performance would not be altered (Table 7).

Intuitively, it can also be observed that the higher the value of this parameter, the greater the difference between the overall values of the alternatives for each case. When increasing the value of z, the value of the capacity for the most important criteria increases (as shown in Figure 3), and they are the ones that have a greater influence on the overall value of the alternatives. Thus, this increase will reflect a greater difference between the performance values of the alternatives, which does not alter their ordering.

The study of the influence of the studied z-ratio shows that a variation of this value, considered significant (± 66.7%), does not have a great influence on the obtained ranking of alternatives. In this way, all these aspects allow to assert that the model is sufficiently robust.

5.3. Other possible scenarios

The Public Procurement Code (PPC)), approved by Decree-Law no. 111-B/2017 nº168/2017, August 31, 2017, refers to aspects relating to the evaluation of competitors according to award criteria. The article 75º states that only the content of the suppliers' proposal should be evaluated and that the factors and subfactors should not directly or indirectly include characteristics, situations or other elements relating to the supplier.

One of the criteria evaluated in the constructed model was the "Suppliers profile" (g_2) and, in this sense, a scenario will be developed that considers this attenuating. Thus, the new scenario does not include the criterion g_2 as well as the resulting interactions (interaction p_{12}, between g_1 (practice of health professionals) and g_2 (suppliers profile)). The Table 8 reflects the values taken from this study.

Table 8:*Overall scores for alternatives with and without criterion 2*

Suppliers	Overall score with g_2	Overall score without g_2	Position
a1	0,864	0,786	2^{nd}
a2	0,800	0,862	1^{st}
a3	0,429	0,404	3^{rd}

In the case of this specific public tender, the ranking of the alternatives would be the same. Nevertheless, it can make a difference to other cases, that is, other contests or alternatives under analysis.

The built model aims to be comprehensive enough to be applied in several contexts. Nonetheless, it is always essential to take into account the context of application of the model for each case, and to make the necessary adaptations, as this example.

5.4. Discussion

The support of the various experts and decision-makers was essential for the various phases of this model. The results of a methodology with these characteristics are subjective and can vary significantly by changing the decision maker or other external envelopes concerned such as the experts. The various phases are all dependent on the interaction with these individuals, so the method turns out to be very dependent on their opinions and decisions taken. As for their involvement during the whole process, it can be said that their reaction was, in general, very positive, for all the steps necessary to implement the Choquet integral. In a formulation phase of the model, the explanation of the introduction of interactions between criteria in the model and its influence on the results was well understood by the decision makers, who found it very useful to take this into account.

5.4.1. Application of methodology

Regarding the construction of the model, the deck of cards method was also presented to the decision makers, to build the scale of ratios to obtain the capacities as well as help to construct the interval scales for each criterion. The group of decision makers found that the application of this method was intuitive and easy to understand. After detailed explanation of how the method would work and all the processes necessary for its correct use, those involved used the cards without difficulty. Although the insertion of white letters may lead to some confusion and disagreement when it comes to a set of decision makers and not just an individual, in this case this process facilitated and promoted the discussion among them that helped them to reach consensus on the various assumptions and decisions taken.

Through the information obtained from DM and publicly available information, it has been found that for this model the alternative with a larger overall value corresponds to the successful tenderer of the public tender concerned. Nevertheless, it can be affirmed that the difference between the preferred alternative and the one in second position is smaller for the model under study (8% for the model versus 15% of the hospital evaluation). This may lead one to believe that, in the model constructed within the scope of this dissertation, factors that were not previously considered are being considered, and that they are valuing some aspects that may have an impact on the choice of a given equipment.

5.4.2. Limitations

One of the great limitations of this methodology is that interaction with decision-makers is sometimes difficult to achieve. Being a group of decision-makers, it was difficult to coordinate schedules among all involved, which made it difficult to mark decision conferences.

The duration of the final decision conference was also limited, which made it difficult to gather all the perspectives of the various actors involved in the steps of constructing the model. A small weakness pointed out by DM was the fact that decision-making process was a very extensive, since it included many evaluations and decisions to take, from the ordering of the criteria, to the evaluation of each of the alternatives against all the criteria. In addition, it is more than a decision-maker, which makes it necessary to promote discussion among them in order to reach a consensus. This also causes a longer period of time.

6. CONCLUSION AND FUTURE WORK

Despite the specific context in which the model was applied, it is comprehensive enough to be used in other application contexts in the selection of suppliers of this type of equipment. For example, it could be used outside the scope of public tender, such as direct adjustments in the private sector. It is also possible to use it in particular situations that present slightly different legal frameworks, like the example and adaptation carried out for the Portuguese context, governed by the public procurement code. For these cases and other possible scenarios, some adaptations to the associated criteria or scales are necessary but based on this construction.

In multicriteria decision problems it is important to find a good balance between the number of criteria and the complexity of the model. It should not be too simple, in relation to the number of criteria, since it may not assess all the important characteristics which may have an influence in the context of the decision. Similarly, it should not be overly complex, since it is difficult to convey to the decision maker all the information in a clear way, which can cause problems in all the interpretation and evaluation of the model by the decision maker (as a natural person or group). Undoubtedly, it can also create redundancies and ambiguities between the various criteria, so avoid this latter case.

As future work it is suggested that this methodology be applied to the same case, under the same circumstances, but evaluated by different decision-makers, in order to study their influence on the performance of the alternatives and consequently on the final result obtained. In addition, it is also suggested that the model be applied to other public tenders in the same context of application for which it was constructed, and to compare it with the adjudication decisions taken in each case. For this, the difference in the overall result in the evaluation of suppliers must be studied.

In view of all the data presented, it can be verified that the general objectives proposed for the accomplishment of this dissertation were fulfilled, once a decision support tool for the selection of suppliers in the health units in Portugal to be applied to any category covered by the definition of heavy medical equipment.

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