Multicriteria model to support the replacement of hospital medical equipment

Lígia Margarida Jorge de Figueiredo
Mestrado Integrado em Engenharia Biomédica
Instituto Superior Técnico, Portugal
lmjfigueiredo@gmail.com

Abstract

Hospitals need to implement tools for medical technology management in order to achieve institutional goals and promote clinical safety, quality and efficacy. Tools that manage the replacement of medical equipment are included in this category.

In the Santa Maria Hospital, equipment replacement does not occur in a planned way and does not take into account pre-defined replacement criteria. To solve this problem, this work presents an alternative to the current replacement tools that can inform the Hospital, in a clear methodological way, about the current replacement needs of any type of its equipments.

The replacement support model was built using the MACBETH multicriteria approach. This is a socio-technical methodology, which builds a quantitative evaluation tool based on decision-makers preferences.

The methodology steps followed in the model construction were: construction of a cognitive map to identify replacement criteria and descriptors of impact (from structured questionnaires) and determination of value functions and weights of the criteria in a decision conference. Categories of replacement value were also built in a decision conference, to more easily distinguish between different replacement needs.

In the end, the replacement model was applied to a wide array of medical equipment, identifying a Magnetic Resonance and a Computer Tomography machines as the highest replacement priorities. The results were consistent with those expected and the analysis carried on the results proved the potentiality of the tool built for the Hospital

Keywords: decision analysis**,** multicriteria model, MACBETH, hospital, replacement policy, hospital medical equipment.

I. INTRODUCTION

The practice of modern medicine is dominated by the technology and in general all medical specialities depend, in some way, on medical technology to reach their goals. This is true not only in the prevention field but also in the diagnostic and therapeutic fields. More specifically, the medical technology corresponds to the use of tools that fulfil any medical purpose; these tools have been introduced at an increasing rate during the past hundred years, and include the medical hospital equipment (Jahnke and David, 2005) (David and Jahnke, 2004).

Medical hospital equipments are systems employed in healthcare delivery to general population, and are typically operated by physicians, nurses or technicians. These equipments usually carry mechanical, electronic, hydraulic and pneumatic mechanisms, and incorporate software (Carmo et al., 2007). They can be used in prevention, diagnosis, treatment or in the creation of the necessary comfort for the patient and medical personnel when performing diagnostic, therapeutic and prophylactic measures (Kabatov, 1970).

To manage their investments effectively, to identify priorities, to attain goals (according to a financial plan) and to maximize financial returns, hospitals need to develop medical technology management programs. These programs can integrate relevant information and a planning methodology for the purchase of new equipment, and for optimizing equipment inventories: upgrades, replacements, annual expenditures related with equipment repairs, among others. This efficient management of medical technology will enable the specialization, differentiation and innovation of medical organizations. In turn, this will improve the delivery of healthcare and allow the recruitment and retention of high quality professionals, along with increasing research and revenues (Orlikowski, 2000) (Brach et al., 2008) (Teplensky et al., 1995).

So, due to the increasing dependence of such equipments, it is fundamental to create and implement assessment and management methodologies of technologies, including medical hospital equipment (Jahnke and David, 2005).

To do so, is necessary to understand the relationship between these methodologies and the information that guides the management of medical technology that is being deployed in the complex environment of a healthcare delivery system. It is also necessary to link the technical capabilities of current technology to the clinical requirements.
That need led to the creation of a decision-making support system that helps to assess the hospital´s medical equipment and to inform about the replacement value of such equipments in the Hospital. The assessment took into account the capabilities of current technology and a socio-technical component which integrates the requirements of the decision makers (in this study, the physicians and other institutional managers of the Hospital Santa Maria, HSM, in Lisbon). Furthermore, the assessment was based on the multicriteria methodologies for structuring problems, provided by the field of decision analysis.

II. STRUTURING OF THE PROBLEM

Nowadays, the identification of replacement needs of hospital medical equipment, at the HSM, occurs mostly when a technical problem arises (the equipment has been suffering many technical problems and has been subject to various interventions) or when the equipment suffers a major breakdown. In the latter situation, it is necessary to study whether or not it would compensate to repair it, given its situation. The reasons related with equipment obsolescence, such as functionalities and characteristics that are missing of the hospital service (and often necessary to respond to its needs) assume a secondary role in the replacement decision.
In this process, the hospital department commonly makes request for replacing equipment to the Serviço de Instalações e Equipamentos (SIE); if this service accepts the request, it will be directed to the Administration Board. For those reasons, the equipment replacement policies followed at the HSM is not pro-active and is not planned or apply similar replacement policies for equipments located in different hospital departments.

It was thus necessary to create a model that would help to support the decision of equipment replacement at the HSM, and therefore, propose an alternative to its equipment replacement policy.
The model was built to determine factors and to establish criteria related with equipment replacement. The goal is to identify and inform the Hospital about the equipments that must need to be replaced in a first place, in a systematic and methodological way (and this is not what happens nowadays in the Hospital). The model thus aims to provide a general indicator for replacement need, for any type of medical equipment.
Furthermore, the solutions already present in the literature (Rajasekaran, 2005), (Dondelinger, 2004), (Fennigkoh, 1992) regarding this type of problem are deemed as unsatisfactory; these solutions employ typical mistakes made by decision makers when performing a quantitative assessment of the importance of criteria (Fischer, 1995) and do not take into consideration all replacement criteria. For this reason, it was important to adopt an alternative methodology that model that could overcome those typical mistakes.
The changes proposed for the replacement policy of the Hospital are represented in the Figure 1. The theory associated with the development of the replacement model is discussed in the following section.

III. THEORY

The replacement model was built considering that it was a multicriteria problem, i.e. it was a problem characterised by rank the best options between a number of previously identified options that are characterized by multiple objectives which in turn are characterized by multiple criteria. This is then a problem with multiple and complex objectives, where the choice is subject to uncertainties, risks and different subjective perspectives (Goodwin and Wright, 2004), and was this complexity that justified the use of decision analysis methods.

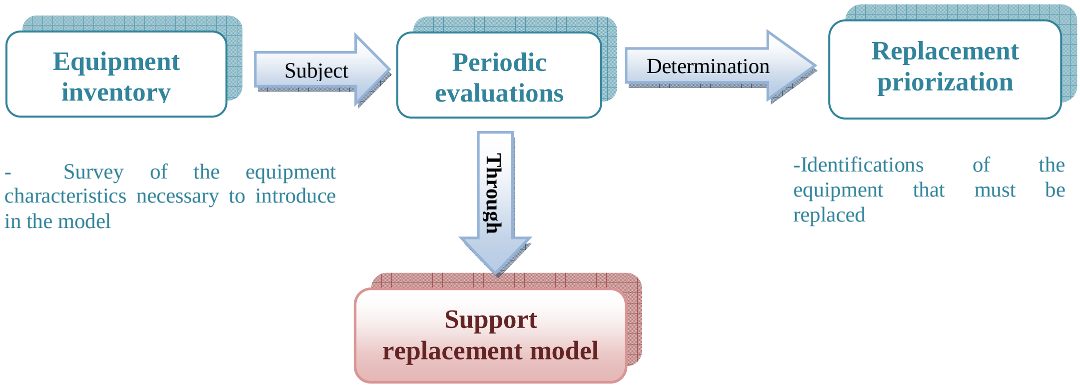

Figure 1. Scheme for the proposed equipment replacement policy at HSM.

In the multicriteria approach developed in this work, a compensatory additive aggregation method was selected. This procedure was chosen because of its simplicity; this way, it helps the decision-maker to achieve a better understanding of the problem, decomposing the problem into smaller pieces, to be analysed separately. In addition, the model also shows be the best solution when multiples decision-makers are involved.
The multicriteria methodology used in the development of the model was the MACBETH methodology (*Measuring Attractiveness by a Categorical based Evaluation Technique*), which is supported by the M-MACBETH software in the construction of the multicriteria computational model. This methodology is widely used to solve problems in many social and economic areas (Bana e Costa and Oliveira, 2002) (Bana e Costa et al., 2008). It uses an interactive and humanistic approach to the problem, and builds a quantitative model based on qualitative (verbal) difference judgments, that facilitates the path from ordinal to cardinal preference (Bana e Costa, et al, 2004).
The advantage associated with this methodology is that qualitative judgments, instead of quantitative judgments, simplify the decision-makers task without losing scientific consistency (Lourenço, 2002). Thus, this approach eases the construction and compreension of the model, as well as the interpretation of consequences associated with the choices made and the final output, when there are multiple decision-makers involved in the decision.
The MACBETH methodology requires interaction and iteration between the group, which means that information entered in the model needs to be discussed and clarified among the participants. The participants need to understand every development stage of the model, and when new ideas and perceptions emerge, modification and revision of the model is required.
This social component that this methodology requires is encouraged through a process of decision conferencing.
These are meetings where the decision-makers (with the help of an imparcial consultant facilitator) are encouraged to discuss and think strategically and to share their perspectives and knowledge about the issues. In the end, the aim is to get a common understanding on the issues and, wherever possible, to get a unanimous and credible decision (Phillips, 2007) (Phillips and Bana e Costa, 2007)
Through this team meetings, and after much discussion and exchange of views, relevant data and judgments are obtained to serve as input to the computer model that will be build by M-MACBETH sofware.
In general, the major steps undertaken in the construction of the model (through the MACBETH methodology and supported by the M-MACBETH software) are represented in Figure 2. The explanations of these steps are presented in the following section.

IV. MODEL CONSTRUCTION

To develop the equipment replacement model, the following phases were required: (1) problem definition, (2) model structuring and impact assessment, (3) analysis of the results (Bana e Costa & Beinat, 2005).

1. Problem Definition

To develop a general replacement model able to assess any type of hospital medical equipment, it was necessary to select a cluster of equipment, representative of the various hospital areas, and a group of users (the decision makers) of such equipments. The aim was to gather information needed to build such model.

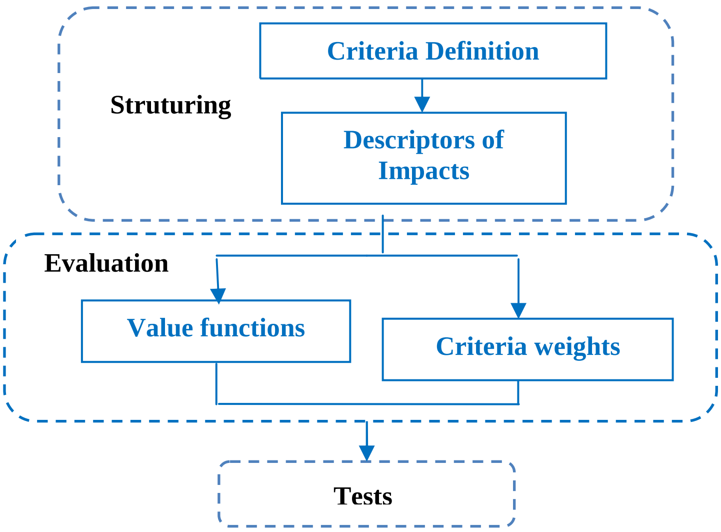

Figure 2. Major major steps undertaken in the construction of the model (Bana e Costa et al., 2008).

The set of hospital medical equipment chosen were: Magnetic Resonance, Computer Tomography, Mono and Biplanar Angiography, Transportable RX, Conventional RX, Linear Accelerator, Gamma Camera (large equipments), Echocardiographer, Electrocardiographer and Perfusion Bomb (small equipments).

Despite the diversity of hospital medical equipment at HSM, the study focused on those because they represent the various hospital departments and, in the case of the larger ones, because of their associated costs and expenditures (be it acquisitions, repairs or replacements). Nevertheless, that set makes it possible to effectively diagnose or treat nowadays the most relevant diseases (like cancer). Small equipments should also be included because are purchased in larger quantities and are also important on the diagnosis, monitoring and treatment of the patients, in all hospital departments.

The decision-makers selected for this study - physicians, medical services directors and technicians - were chosen based on their knowledge about the chosen equipments (such as users), as well as on their availability to participate in an initial questionnaire about the equipment chosen and in the decision conferencing. Some engineers from the SIE were also considered as key actors participating in the replacement decision.

The next step was to survey the equipment background, in particular to collect important data about the repairs, maintenance costs, costs with equipments components, etc. This survey was conducted with the engineers' collaboration.

Finally, and to recognize the firsts impressions about the equipment chosen, meetings with the equipment users were conducted individually, with each user. In these meetings, a few questions were asked in order to assess the general situation of the equipments and to identify the state of current technology.

2. Model Structuring

Based on the users answers to the initial questionnaire, a cognitive map was built.

A cognitive map is a formal system designed to represent the way in which a person defines an issue. It is built to map a person's thinking (in this case, the decision-makers thinking) so as to better relay the nature of a given problem. The construction of this kind of system is advantageous because it helps the consultant facilitators to deal more easily with some important aspects of their work (Rosenhead and Mingers, 2001)

A cognitive map is a network of ideas linked by arrows, and this network is coded from what a person says. The arrows indicate the way in which one idea may lead to (or have implications for) another, which means that "concept A leading to concept B and be explained by C is different has a different meaning from "concept A leading concept D and be explained by E" (Rosenhead and Mingers, 2009). In this context there is a hierarchy in the cognitive maps, related with ideas (or goals) being positioned higher than (i.e. resulting from) a subordinate concept which corresponds to the tail of the arrow.

In this study, a cognitive map was built to represent, intuitively and clearly, the impression of the decision-makers on the factors and criteria pertaining to the hospital medical equipment replacement.

From the network of ideas presented in the cognitive map, replacement criteria and the associated descriptor of impacts were constructed.

The criteria are the fundamental points of view, and they represent, or solve, the issues presented on the cognitive map. The set of criteria can be organized into concern areas and can be also divided into sub-criteria. Criteria should be consensual, exhaustive, non-redundant and as concise as possible (Bana e Costa and Beinat, 2005). Those characteritics are necessary to ensure that it is possible to associate a criterion with a descriptor of impacts.

To the development of the replacement model, fifteen replacement criteria were identified. These took into account the existing alternatives to the improving of the equipment value on a given criterion , thus allowing for establishment of different importance levels for the equipment replacement at HSM. These alternatives could be the replacement of the current equipment as the final solution, or the possibility to integrate upgrades or to improve the manufacturer contract.

On the other hand, a descriptor of impacts is an ordered set of plausible impact levels associated with a particular criterion. These measure (quantitiatively or qualitatively) the degree to which each criterion is satisfied and objectively describe the impact of the each option in a criterion. The aim is to obtain a better understanding of the decision context by constructing different levels of impact which as objectively as possible, so as to the evaluation model be better accepeted (Bana e Costa and Beinat, 2005) (Bana e Costa et al, 2008)

In the evaluation model, the descriptors of impacts associated with a particular criterion are restricted to a range of plausible impacts, from a most attractive level to a least attractive level. In fact, the conditioning impact levels of a descriptor to be ranked in terms of their relative attractiveness, gives the descriptor an ordinal structure of preferences (Bana e Costa and Beinat, 2005).

As required in an additive model, two reference levels were selected in each descriptor of impacts: the good and the neutral reference levels. The choice of reference levels was important for the following stages (development of the model through the MACBETH methodology): it helps to fix scores (for example 100 for the good level and 0 for the neutral level) which allows not only understanding the meaning of each criteria for its weighting procedure

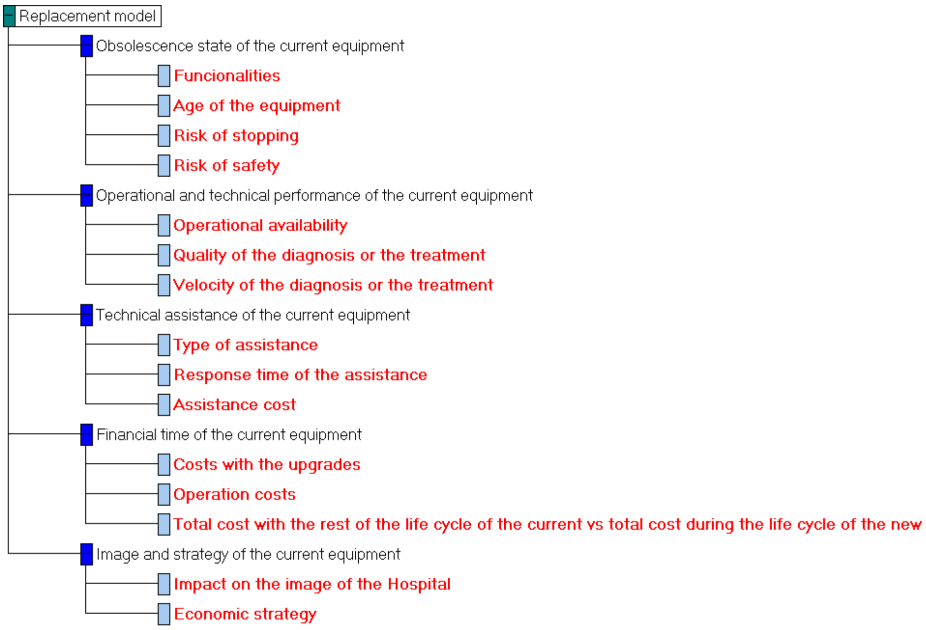

Figure 3. Value tree with the replacement criteria (removed from the M-MACBETH software).

but also provide a sound basis in criteria assessment, namely in differentiating between the criteria preference.

The comparision of the impact profiles of an option with some references of intrinsic value (the good level is an impact level undoubtedly satisfyng and the neutral nevel is an impact level that is neither attractive nor unattractive) contributes significantly to the intelligibility of the criteria and helps to avoid pittfals of classic weighting procedures (Bana e Costa, et al, 2004).

In the development of the replacement model, the range of the impacts of each criterion was related with all the possibilities that could happen, and those possibilities were established according to the severity of the profile of the equipment in each criterion. So, the establishment of the different need levels for equipment replacement (in every criterion) is related with the different types of profiles of the equipments in each criterion and with the existing alternatives to improve these profiles on each criterion.

Each set of descriptors of impacts was then assigned two references levels. In this case, the good level was a level in which gains with some replacement equipment start being unquestionable to the Hospital, and the neutral level was a level in which gains were neither attractive nor unattractive.

The replacement criteria constructed are shown in Figure 3. All the descriptors of impact are not presented in this paper because of space constrains. However, an example (for the descriptor of the criterion "*Age of the equipment*") is presented on Table 1.

Table 1. Descriptor of impacts of the criterion "Age of the equipment".

Level	Description
N1	The useful life time of the current equipment is over
N2=Good	The current equipment is still in use but it has parameters that characterize the end of its useful life time (mean time between failures is short, high costs of maintenance, end of its amortization)
N3=Neutral	The current equipment is still in the middle of its expectable useful life time
N4	The current equipment is in beginning on its useful life time (is a new equipment)

Due to time and availability constrains presented by the decision-makers of this study, the cognitive map, the criteria and the descriptor of impacts were not constructed in a decision conference. Instead, the facilitator has built those steps with the collaboration of the main actor of the SIE (the head of the department), and using information collected in the structured questionnaires.

The decision conference was only performed to validate the selected criteria and descriptors of impact, for the determination of the value functions and the criteria weights. In this decision conference, four different equipment users were present (representing three different hospital areas), as three decision-makers from the SIE.

The decision conference started with the presentation of the different criterion and descriptor of impacts. The participants consensually decided to eliminate one impact level on the criterion *Velocity of the diagnosis or the treatment* and to completely eliminate the criterion *Total cost with the rest of the* *lifecycle of the current vs total cost during the lifecycle of the new*. This was decided because both cases were deemed as not relevant for the replacement model.

The evaluation of the levels of impact ended in the determination of the value functions of the model. This evaluation was made in the M-MACBETH software and was based on answers to questions that require judgments about the difference in attractiveness between pairs of levels. The group was then invited to judge, qualitatively, how large the difference was, this being expressed in terms of semantic categories. These categories are: *Extreme, Very Strong, Strong, Moderate, Weak, Very Weak* (Bana e Costa et al, 2008). As each judgment was entered in the software (on a MACBETH matrix of judgments), its consistency with the other judgments already inserted was checked, and every time an inconsistency was detected, suggestions were made by the software to move on.

In the end, the software provided a quantitative scale which indicated the scores (value scales) for each level in every descriptor of impacts which were then discussed and adjusted. An example of a value function (and the thermometric scale associated) which results on the evaluation of the criterion *Age of the equipment* is present on Figure 4.

	N1	N2	N3	N4	Current scale
N1	no	strong	v. strong	extreme	200
N2		no	strong	strong	100
N3			no	weak	0
N4				no	-50

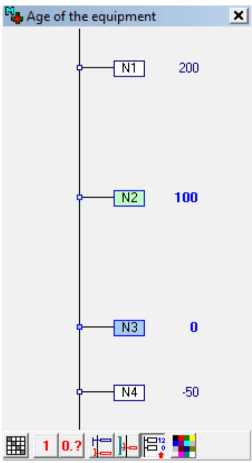

Figure 4. Judgments, value function and thermometric scale of the criterion *Age of the equipment*.

After the identification of the value functions, the next step was the determination of the scale constants that represent the criteria weights, and these reflect the "importance" of the criteria. In order to do this, decision-makers needed to order the criteria considering the performance range of the descriptors of impact scales and the importance of those ranges were established by ranking the good-neutral swing according to their overall attractiveness. After that, decision-makers were asked to judge qualitatively the overall attractiveness of each swing (the most important swing was compared qualitatively with the second most important, and so on). To achieve this, the previously used semantic categories were applied (Bana e Costa et al, 2008).

The weights resulting from this process are present in the Figure 5.

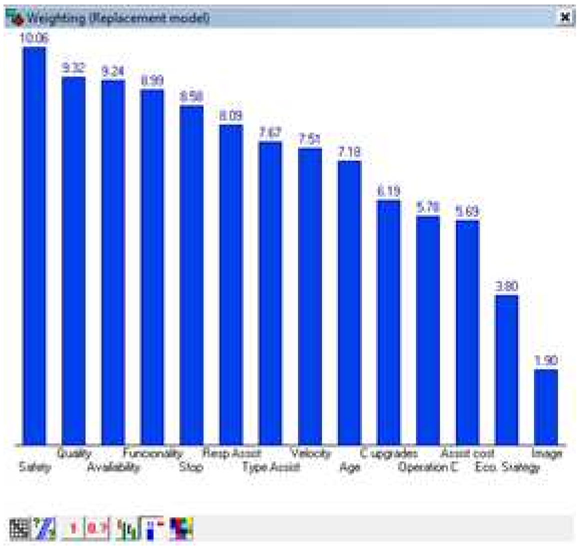

Figure 5.Weights of the criteria.

The last step on the development of the replacement model for the hospital medical equipment was the construction of value categories of replacement. The construction of these categories was intended to allow for an easier recommendation of the equipment to be replaced first, based on the gains that certain equipment replacements represent to the Hospital, at the time of the evaluation.

To do so, three different value categories were constructed (the category of high value, the category of median value and the category of low value) through the top-down procedure (Bana e Costa and Oliveira, 2002). In this procedure, different good-neutral swings were performed to determine the different profiles of the equipment which identified the thresholds (the separation moments) of the value categories. After the reference profiles had been identified, they were subjected to the evaluation model to obtain the indexes that correspond to the separation thresholds.

The top-down procedure started with a fictitious equipment characterised by a 'good' level profile in all the criteria, and thus belonging to the high value category. Then, in each stage of the evaluation, a new 'good' impact level lower to its 'neutral' level (this methodology followed a predefined order of the criteria), until the decision-makers hesitated about the category that should be assigned the resulting equipment profile. On this phase, the profile that defines the category of median value was identified. The process carried on until profile that corresponded to the category of low value was identified.

3. Analysis of the results

The equipment replacement model constructed was applied to the group of equipments selected for this study. The next additive value function was then applied to the equipment evaluation (Bana e Costa et al, 2008):

$$V(a) = \sum_{j=1}^{n} p_j \, . \, v_j(a) \text{ with } \sum_{j=1}^{n} p_j = 1 \text{ e } p_j > 0$$

$$\text{and } \begin{cases} v_j(good_j) = 100 \\ v_j(neutral_j) = 0 \end{cases} \text{ for } j = 1, \ldots, n \qquad (1)$$

In the latter formula, the $V(a)$ represents the overall score of the equipment (resulting from the evaluation by the equipment replacement model created), the p_j represent the weights of the criteria and the $v_j(a)$ represent the partial values of each equipment, in every criterion.
The replacement scores that result from the evaluation of the study equipments are present in Figure 6.

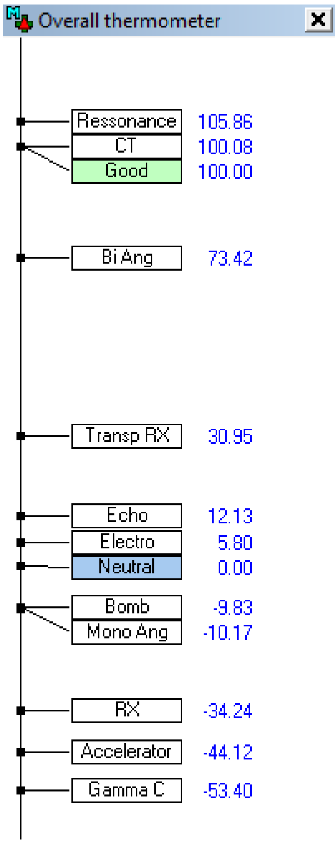

Figure 6. Global results of the model, shown in a thermometric scale.

To obtain the replacement scores (shown in the last figure) in the M-MACBETH software, it was necessary to apply the replacement criteria and the descriptors of impact to all the studied equipments. To do so, the facilitator met with all the equipment users, individually, in a first stage, and with three actors from the SIE in a final stage.
The results obtained revealed that the Magnetic Resonance and the Computer Tomography are the equipments more attractive to replace (scored above 100), the Biplanar Angiography, the Transportable RX, the Echocardiographer and the Electrocardiographer are the equipments attractive to replace (scored above 0) and the Perfusion Bomb, Monoplanar Angiography, Conventional RX, the Linear Accelerator and the Gamma Camera are the equipments less attractive to replace (scored below 0).
The different replacement needs of equipments, according to the preferences of the decisions-makers, were then identified when they were assigned to the replacement value categories. This is shown in Figure 7.
The thresholds of the categories represented in the Figure 7 were obtained through the top-down procedure.

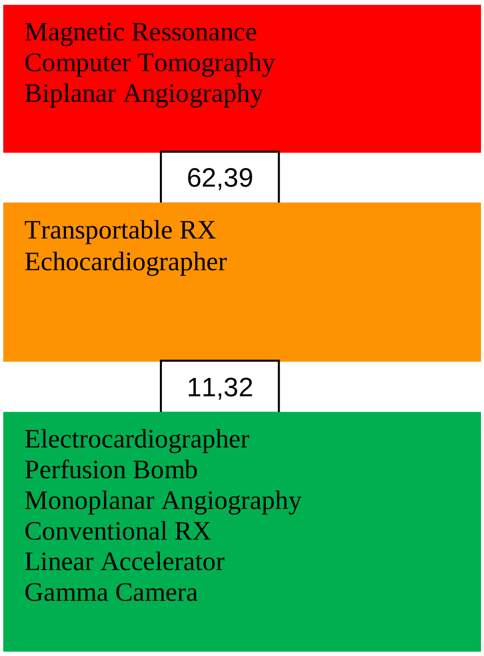

Figure 7. Distribution of equipments in the replacement value categories.

In the last figure, the red color corresponds to the category of high value, the orange color to the category of median value and the green color to category of low value.
A series of analysis were then performed on the results obtained, using the capabilities of the M-MACBETH software.

In order to understand the model´s results, it is possible to analyze how equipment score in some criteria contributes to its overall score, using the software. This analysis can be done in two ways: by comparing the equipment scores to the good and neutral references or by determining the individual contributions made by the equipment's scores to the equipment's overall score.

These situations are shown, respectively, is Figure 8 and Figure 9, for the Magnetic Resonance.

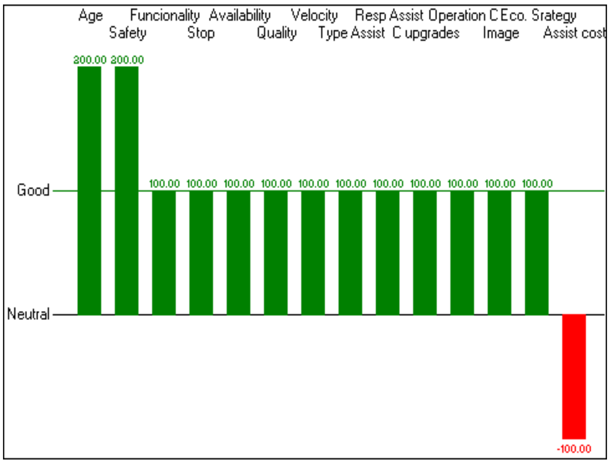

Figure 8. Profile of the Magnetic Resonance (criteria scores).

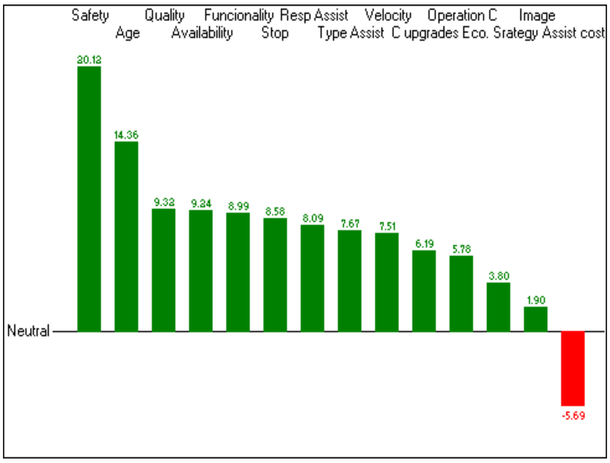

Figure 9. Profile of the Magnetic Resonance (weights scores).

In the latter figures, the green bars indicate positive contributions in the overall result and the red bars the opposite.

For the Magnetic Resonance, the analysis realized showed that in all criteria the contribution to its replacement score is positive, with the exception of the criterion *Assistance costs.*

Sensibility and robustness analysis were also performed on the results. The sensibility analysis was conducted changing the weights of the criteria and the scores of the impact levels, and the robustness analysis was conducted when some levels of imprecision or uncertainty were introduced in the model.

The results of the analysis revealed that Magnetic Resonance is the equipment with a more attractive need for replacement at HSM. Furthermore the model proved itself to be sensible to changes in the preferential replacement order of the Perfusion Bomb and the Monoplanar Angiography.

A final analysis was performed to assess the cost-benefit of the options. This analysis is present in Figure 9.

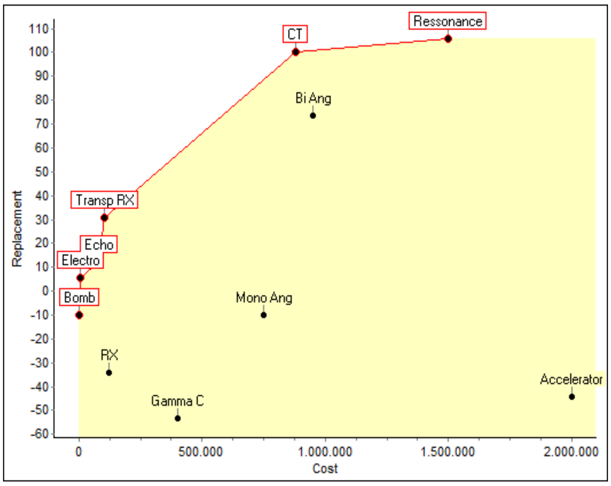

Figure 9.Cost-Benefit analysis.

The cost-benefit graph showed in Figure 9 contrasts each equipment's overall score (the benefit of replacement) with its respective investment costs. Furthermore, the red line indicates the efficient frontier, where are the non-dominated equipments.

The information contained in the graph reveals the best replacement options taking into consideration the investments costs.

For example, the graph reveals that if the Hospital spends around 1.000.000€ in equipment purchase, the best option is the Computer Tomography instead the Biplanar Angiography. This happens because the Computer Tomography is on the efficient frontier.

V. DISCUSSION

The MACBETH methodology, used in the model development, was understood and supported by the decision-makers involved in the study. The decision-makers found out that the decision conference helped in the knowledge and perspectives exchange when a unanimous decision was required. It was accepted that the application of qualitative judgments, in the assessment of replacement criteria and the descriptors of impact, helps in the process, maintaining the accuracy.

The pointed weaknesses in the MACBETH methodology were the duration of the decision conference and some difficulties to concentrate in the criteria assessment, on a MACBETH matrix of judgments.

As the model application results indicate, the expected replacement needs were observed (larger for the Magnetic Resonance and Computer Tomography and lower for the Gamma Camera and Linear Accelerator), being possible to conclude that the model was effectively applied to all the equipments and it is general enough to assess large or small equipments, either are they used for diagnose or in therapeutics. This means that one of the principal goals of the work was reached.

Those results were expected because (for example) the Magnetic Resonance is the equipment with the longest service years and presents a limited technology according to user, patient and the hospital needs. On the other hand, the Gamma Camera is a recent equipment, acquired in the current year by the Nuclear Service of the HSM.

The only result that wasn´t expected by the decision-makers was the value of the replacement index of Monoplanar Angiography. This reveals that either the decision-makers are wrong about the need for replacement of that equipment or the physician who attributes the impact levels to this equipment has different opinion.

This non consistent result reveals that a decision conference was necessary to correctly attribute the impact levels to the equipment.

Analyzing the results from sensibility and robustness analysis, it is possible to conclude that the Magnetic Resonance is more attractive to replace, and its replacement needs dominate the other equipment replacement needs.

According to the distribution of the equipment through the replacement value categories, it was observed that most of the equipment ended up either in the highest and the lowest category. An explanation for this might be the type of equipment chosen to model construction and evaluation. In fact, the selected equipments to this study were either old equipment, with several maintenance records or new equipment. With this selection it was possible to determine the Hospital needs and analyze the reasons why new equipment is purchased in the Hospital, to then determine and build the replacement criteria and the descriptors of impact.

The model limitations are related to difficulties encountered during the development of the model. The development of precise and rigorous descriptors of impact was one of them. As a result, it was not possible to use quantitative impact descriptors, because the development of a generalized equipment replacement model could not specify, for example, replacement costs or operational available percentages in the descriptions of the impact levels. However, these limitations did not created problems to understanding of the model by the decision-makers, especially in the establishment of the value functions and in the level attribution of each descriptor to all equipments assessed.

Another limitation of this work was the extreme difficulty to get all the equipment users together in a decision conferencing. As a result, the criteria and descriptors of impact were established by the facilitator (with the support of the main actor from the SIE), rather than in a decision conference, as would be ideally applied. It was then in the decision conference used to assess the descriptors of impact and the replacement criteria that was possible to discuss the criteria content and the descriptors, and modify them if it was suggested by the actors.

Another limitation was the incapability to develop the *bottom-up* procedure for the establishment of three different value categories of replacement. This has lead to the inability to rigorously validate the obtained thresholds, which separate the value categories.

To implement this model, the hospital would have to ensure certain conditions. For instance, it would be necessary to implement an active and periodic management of the equipment inventory to obtain the information needed to assess the equipment characteristics, required to introduce in the replacement support model, for example, by inserting in a database the levels of the different descriptors of impacts.

A long term implementation of the model requires periodic updates, obtained through new decision conferencing sessions. For this to be possible, participation of representatives from all hospital services, including the administration board, is required.

VI. CONCLUSION

Nowadays, the medical equipment replacement method in use, at the HSM, is substantially based in the history of its repairs and maintenance, rather than on an active policy which evaluates the equipments in need of substitution according to several parameters and replacement criteria. Based on this, it was imperative to develop a supportive tool to, clearly and methodologically, inform the HSM on the actual need for replacing the medical equipments, which considered the current state of the equipment, the existing technology and the decision-makers objectives.

This thesis intended to develop and test a multicriteria decision making model that could improve the process of equipment replacement in the HSM, which could be applied to any type of medical equipment. Furthermore, it was important to build an alternative model to the existing methods for replacing the equipment, already implemented in international hospitals and which have several weaknesses, such as the way the equipment performance is evaluated.

The multicriteria model constructed was based on the MACBETH methodology. This is a socio-technical methodology, which builds a quantitative evaluation tool based on decision-makers preferences.
This model was applied to a set of equipments, so it was possible to evaluate its potentiality. The results showed the expected need for replacement, based not only in the ranking level, but also on the analysis made, such as the robustness analysis and the cost-benefit ratio analysis.
Based on the results, it is possible to say that the proposed goals were achieved: it was developed a support tool for the replacement of any kind of medical equipment at HSM.
For future work, we propose the following suggestions:
- the support tools for medical technology management in Hospitals should not be restricted to replacement evaluation tools. In HSM, the first step was taken in the development of this replacement support model, but other tools should be encouraged to be created, namely for managing the use of equipments during their life cycle and the management of investment in medical technologies;
- for the correct application of the model, it is necessary that those who decide know the status of current technology and the potentialities of the new equipments;
- the supporting tools for equipment replacement do not need to be built in a general way, for all kinds of equipments. To build and apply a replacement tool to a certain type of equipments can be an advantage, as it allows building the substitution criteria and the impact descriptors more precisely;
- it is desirable that in similar projects, when the MACBETH methodology is to be applied, the decision conferences may be used in the development of all methodological steps, since it is from the involvement of key actors and sharing of knowledge that good supporting tools for management can be built.

VII. REFERENCES

-Bana e Costa, C. A., and Beinat, E. (2005). *Model-structuring in public decision-aiding.* London School of Economics and Political Science: Department of Operational Research.
-Bana e Costa, C. A., and Oliveira, R. C. (2002). Assigning priorities for maintenance, repair and refurbishment in managing a municipal housing stock. *European Journal of Operational Research*, Vol. 138, pp. 380-391.
-Bana e Costa, C. A., Lourenço, J. C., Chagas, M. P., and Bana e Costa, J. C. (2008). Development of Reusable Bid Evaluation Models for the Portuguese Electric Transmission Company. *Decision Analysis*, Vol 5(1), pp. 22-42.
-Bana e Costa, C., De Corte, J., and De Varnick, J. (2004). *MACBETH.* London School of Economics: Working Paper LSE OR 03.56.
-Brach, C., et al (2008). *Will It Work Here: A Decisionmaker's Guide to Adopting Innovations.* Agency for Healthcare Research and Quality. Obtido em Junho de 2009 de http://www.innovations.ahrq.gov/resources/InnovationAdoptionGuide.pdf
-Carmo, P., Ogliari, A., and Nascimento, D. (2007). Process of diagnosis and analysis of attrubites of maintainability in medical and hospital devices. *19th International Congress of Mechanical Engineering.* Brasil.
-David, Y., and Jahnke, E. G. (2004). Planning Hospital Medical Technology Management. *Engineering in Medicine and Biology*, Vol. 23(3), pp. 73-79.
-Dondelinger, R. M. (2004). A complex method of equipment replacement planning. *Biomedical Instrumentation & Technology*, Vol 38(1), pp 26-31.
-Fennigkoh, L. (1992). A medical equipment replacement model. *Journal of clinical engineering*, Vol. 17(1), pp 43-47.
-Fischer, G. W. (1995). Range sensitivity of attribute weights in multiattribute value models. *Organizational Behaviour and Human Decision Process*, Vol 62(3), pp. 252-266.
-Goodwin, P., and Wright, G. (2004). Decision Analysis for Management Judgment. Jon Wiley & Sons, Ltd.
-Jahnke, E., and David, Y. (2005). Medical Technology Management: From Planning to Application. *Engineering in Medicine and Biology 27th Annual Conference.* Shangai, China.
-Kabatov, Y. K. (1970). Definition of the main concepts of medical equipment. *Biomedical Engineering*, Vol. 4(5), pp. 274-276.
-Lourenço, J. C. (2002). *Modelo aditivo hierárquico: exemplos de métodos de ponderação e problemas associados.* Centro de Estudos de Gestão - Instituto Superior Técnico.
-Orlikowski, W. J. (2000). Using Technology and Constituting Structures: A Practice Lens for Studying Technology in Organizations. *Organization Science, Vol 11, Nº4* , 404-428.
-Phillips. (2007). *Chapter 19: Decision Conferencing.* London School of Economics and Political Science: Department of Operational Research.
-Phillips, L. D., and Bana e Costa, C. A. (2007). Transparent prioritisation, budgeting and resource allocation with multi-criteria decision analysis and decision conferencing. *Ann Opera Res*, Vol. 154(1), pp. 51-68.
-Rajasekaran, D. (2005). Development of an automated medical equipment replacement planning system in hospitals. *31st Annual Northeast Bioengineering Conference*, pp. 52-53
-Rosenhead, J., and Mingers, J. (2001). *Rational Analysis for a Problematic World Revisited.* Inglaterra: John Wiley & Sons.
-Teplensky, J. D., et al (1995). Hospital adoption of medical technology: an empirical test of alternative models. *Health Services Research*. Vol 30(3), pp. 437-465.