Multicriteria Model for Choosing Maintenance Strategies in Water Softening and Water Production Systems for Domestic Use

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Abstract

Hospitals consume more water than other organisations since, in addition to human consumption, healthcare environments require a high level of hygiene and cleanliness. In some cases, moreover, the water must be pure, or have special characteristics, in order for healthcare services such as haemodialysis and therapeutic pools. In addition, high water consumption implies significant energy consumption and a significant amount of hazardous waste produced. Healthcare centres must reduce water consumption, as required by Goal 6 of the Sustainable Development Goals (SDG) of the 2030 Agenda. One of the aspects that can contribute is to provide optimal maintenance of the facilities. However, there is a significant lack of objective mathematical models allowing the selection of the most appropriate maintenance strategies to be applied in systems involved in the softening and production of domestic water. Therefore, this contribution sets out a model agreed upon by a number of hospital service managers, developed using the Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH), to select the optimal combination of maintenance strategies to be applied in a public university hospital. The results of the model have allowed us to objectively determine the validity or need for updating of the maintenance strategies applied, analysing the effects that the proposed changes would have on the quality of care.

Keywords: maintenance strategies, multi-criteria techniques, health-care organisation, MACBETH

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Introduction

The water that arrives at a hospital, although suitable for human consumption, contains dissolved salts (chlorides, sulphates, calcium, etc.), which must be removed before it can be used in healthcare processes such as haemodialysis, therapeutic pools, laboratory analysis, etc., but also for routine processes such as cooking, laundry, or air conditioning. For example, the presence of contaminants in dialysis fluid can expose the patient to the risk of accumulating toxic substances that can interact with cells or proteins, triggering bioincompatibility and toxicity. Hot water is essential in hospitals, as its interruption can lead to the suspension of healthcare activities. However, it also entails significant energy consumption, accounting for 10 to 20% of a hospital's energy expenditure. Furthermore, maintaining the appropriate temperature is essential, as too low a temperature may not eliminate bacteria, and too high a temperature can pose a risk of burns. Although the water supplied to a hospital from the supply network is disinfected, the accumulation of water in tanks causes the gradual evaporation of chlorine, especially when temperatures rise. Therefore, facilities dedicated to producing domestic hot water require proper maintenance, including chlorination, to eliminate the bacteria that cause legionellosis. Thus, maintenance programs for domestic hot water facilities should include at least the following points (COIIM-AIIM, 2021):

- Prepare a marked and updated plan of each facility, showing its components. Critical points where water sampling will be performed must be indicated.
- Inspect all parts of the facility to ensure proper working, establishing critical points, parameters to be measured, procedures to be applied, and their frequency.
- Schedule water treatment to ensure quality, including products, dosages, and procedures, physical, chemical, and biological control parameters, measurement methods, and frequency of analysis.
- Schedule the cleaning and disinfection of the facility to ensure it operates safely, establishing the procedures, products to be used and dosages, precautions to be taken, and the frequency of each activity.
- Keep a facility maintenance log that includes incidents, activities performed, results obtained, and dates of technical shutdowns and restarts of the facility, including the reasons for them.

Therefore, carrying out quality maintenance in a hospital will influence the availability and quality of domestic water required in Hospitals which can affect care and non-care staff, patients, and their companions. Therefore, the application of a certain combination of maintenance strategies in a hospital, influence its quality of care.

The choice of maintenance strategies is a complex decision as it involves strategic, economic, environmental, technical, and safety issues. Therefore, the use of Multi-Criteria Decision Analysis (MCDA) techniques is considered highly appropriate. Furthermore, they allow for obtaining results based on an objective mathematical model, in which a number of stakeholders or decision makers can participate, issuing judgements to ensure optimal decisions when public expenditure is involved.

The existing literature on the selection of maintenance strategies using MCDA techniques in the healthcare field is very limited, although the contribution of Taghipour et al. (2011) stands out. They use the Analytic Hierarchy Process (AHP) to prioritise medical devices according to their criticality, and select the ideal maintenance strategy for different device classes. Houria et al. (2017) prioritise medical equipment according to their criticality using fuzzy AHP to weight the decision-making criteria and the fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to select the most suitable maintenance strategy. In the research of Jamshidi et al. (2015), an additive weighting model integrated with fuzzy Failure Mode and Effect Analysis (FMEA) has been used to obtain a prioritisation of medical devices; AHP allows the weights of the criteria and a maintenance-planning diagram to be obtained, in order to assign a maintenance strategy to each medical device. Mahfoud et al. (2016) integrated the Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHEE) and AHP to carry out a decision support system for medical device ranking using a decision-making group of medical experts. Carnero and Gómez (2016) utilize the Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH) approach to construct a methodology for the selection of integrated maintenance strategies and back-up devices in dialysis devices related with acute or chronic patients and, those infected with hepatitis B or C. Houria et al. (2017) combined the most applied MCDA techniques in literature, that is, AHP and TOPSIS to rank maintenance policies and mixed integer techniques to choose the most suitable strategies for each medical device. Ighravwe and Oke (2019) applied Stepwise Weight Assessment Ratio Analysis (SWARA), Weighted Additive Sum Product Assessment (WASPAS), Fuzzy Axiomatic Design (FAD), and Additive Ratio Assessment (ARAS) to select the best maintenance strategy in public buildings, such as hospitals (Carnero & Gómez, 2021).

Most previous research selects a single maintenance policy, but fails to consider that an organisation typically uses several maintenance strategies, combined in different percentages. It is therefore necessary to decide the best integration of strategies to carry out. Furthermore, they are never applied to a hospital's domestic water production and storage facilities.

This contribution presents a multicriteria model that integrates continuous-time Markov Chains with the multicriteria Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH) to undertake the choice of the ideal combination of maintenance strategies in two domestic water production and storage systems of a health care organization.

The layout of this contribution is as follows: first, the main features of the MACBETH approach are described; the following section exposes the decision support model for choosing maintenance strategies, including the structuring process, weighting, definition of alternatives, and the results of applying the model to a domestic water production system and another hot water production and storage model. The conclusions and finally the bibliography section are presented below.

Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH) Approach

MACBETH was developed by Bana e Costa and Vansnick (1997) and has been applied to numerous decision-making problems (see, for example, Gokasar et al., 2023; Mishra & Syed, 2025; Singh, 2024).

MACBETH has numerous advantages over other MCDA techniques, including (Bana e Costa et al., 2003; Carnero & Gómez, 2018):

- It is easy to implement.
- It can be applied using the M-MACBETH software, which also allows for the analysis of the model's robustness and sensitivity.

- It can verify the consistency of the judgements made by decision makers and resolve any inconsistencies detected.
- Its application simply needs to compare pair of criteria or pairs of scale levels for each descriptor qualitative judgements related to the change in performance between each one.
- In making each judgement, a range of semantic categories instead of just one can be associated with the difference in performance, which allows for the inclusion of uncertainty in the decision.
- The use of two reference levels for each descriptor allows for more accurately generated value functions.
- It avoids the difficulties inherent in ordinal aggregation (Arrow's theorem, Condorcet's paradox).

Furthermore, MACBETH can handle models that include a large number of criteria, which can be both quantitative and qualitative.

MACBETH evaluates alternatives using an additive aggregation model as shown in Equation (1).

$$v(A) = \sum_{i=1}^{n} w_i v_i(A_i) \qquad \sum_{i=1}^{n} w_i = 1 \quad w_i > 0 \tag{1}$$

with v_i (most attractive impact level on criterion i) = 100 and v_i (least attractive impact level on criterion i) = 0, where A is the alternative evaluated, n is the number of criteria, w_i the weight of criterion i, A_i the value of the alternative in criterion i, $v_i(A_i)$ is the impact of alternative A on criterion i and $v(A)$ is the global value of alternative A.

The implementation of the MACBETH approach requires asking the experts to get the scales of performance v_i and weights w_i.

Multicriteria Model for Choosing Maintenance Strategies

The systems analysed were analysed applying continuous time Markov chains, returning the system of equations that allows computing the mean availability through the life cycle of each domestic water treatment system of the Healthcare Organisation.

Two systems were analysed. System 1 stores decalcified water generated by other systems and maintains in a range of 2-3x10^{-6} kg per litre of water, the value of free residual chlorine. System 2 produces and stores hot water at 60 Celsius degrees and, in pasteurisation process at 70 Celsius degrees, to remove legionella (Carnero & Gómez, 2018).

λ_1 and μ_1 are defined as the equivalent failure and repair rates respectively of System 1. Corresponding to the another System, λ_2 is associated to the failure rate and μ_2 to the repair rate related to the water production circuit, meanwhile λ_3 and μ_3 are associated to the failure and repair rates of the accumulation circuits. The results obtained for both systems in each possible maintenance strategy to be applied are shown in Table 1.

Table 1
Equivalent Failure and Repair Rates and Average Availability of Each System

System 1					
Alternatives	λ_1		μ_1		Mean availability
CM-MPM	0.001454		0.00995		0.9882
CM-DPM	0.001454		0.077		1
CM-CPM	0.001454		0.267		1
System 2					
Alternatives	λ_2	μ_2	λ_3	μ_3	Mean availability
CM-MPM	0.000577	0.016	0.000463	0.014	0.9980
CM-DPM	0.000577	0.021	0.000463	0.077	0.9999
CM-CPM	0.000577	0.041	0.000463	0.267	1

Structuring Process

The decision criteria chosen to build the model, and the scale levels of each descriptor associated with each criterion, including the reference levels good and neutral, are (Carnero & Gómez, 2018):

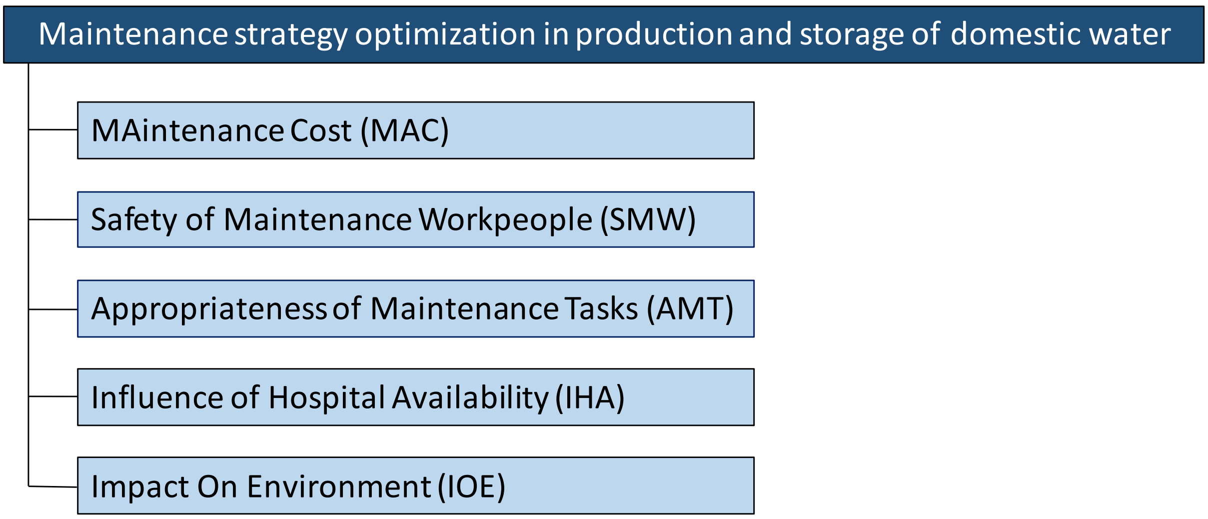
- MAintenance Cost (MAC): Evaluate annual maintenance costs, including those related to labor, materials, spare parts, and subcontracting activities (Gómez & Carnero, 2016).
    1. The best value of performance (good level): € 5,000.
    2. € 10,000.
    3. Neutral level of performance: € 20,000.
    4. € 30,000.
    5. The worst value of performance: € 40,000.
- Safety of Maintenance Workpeople (SMW): assesses the risk to which the technicians, and, in general, those who operate the subsystem directly, are exposed (Gómez & Carnero, 2016).
    1. The best value of performance (good level): There are no risks to the operator at any time.
    2. There is some potential risk, so the operator should take certain basic precautions during operation of the system.
    3. Neutral level of performance: There is a specific risk, so the operator must take certain basic precautions during the operation of the system.
    4. There is a specific risk, so the operator must take certain basic and specific precautions during the operation of the system.
    5. The worst value of performance: There is a specific risk, so the operator must take certain basic, specific and emergency precautions during the operation of the system.
- Appropriateness of Maintenance Tasks (AMT): considers the level of satisfaction of the maintenance workers (Gómez & Carnero, 2016).
    1. The best value of performance (good level): The maintenance worker is certain of the diagnoses of the anomalies and breakdowns analysed. Corrective activities should be programmed.
    2. The maintenance worker is certain of the diagnoses of the anomalies and breakdowns analysed, and corrective activities should be programmed.
    3. Neutral level of performance: The maintenance worker is certain of the diagnoses of the anomalies and breakdowns analysed, and corrective activities must be undertaken immediately.

4. The maintenance worker is not certain on specific occasions of the diagnoses of the anomalies and breakdowns analysed, asking his superiors to authorise immediate corrective activities.
5. The worst value of performance: The maintenance worker is not certain of the diagnoses of the anomalies and breakdowns analysed, and the corrective activities must be undertaken immediately.

- Influence on Hospital Availability (IHA): This criterion evaluates the influence that the loss of functionality of the analyzed systems has on the remaining systems of the hospital.
  1. The best value of performance (good level): 0.
  2. Neutral level of performance:(0, 50].
  3. (50, 100].
  4. (100, 200].
  5. The worst value of performance (200, 377.60].
- Influence On Environment (IOE):
  1. The best value of performance (good level): Does not inflict any kind of damage to the environment.
  2. May inflict slight damage to the environment although environmental standards are still being met.
  3. Neutral level of performance: May inflict damage on the environment, requiring corrective activities to minimize it.
  4. The worst value of performance: May inflict irreversible damage on the environment inside and outside the Healthcare Organization therefore, it is necessary to make the situation known to the authorities.

The hierarchy of the MCDA model proposed can be seen in Figure 1.

Figure 1
Hierarchy of the Model



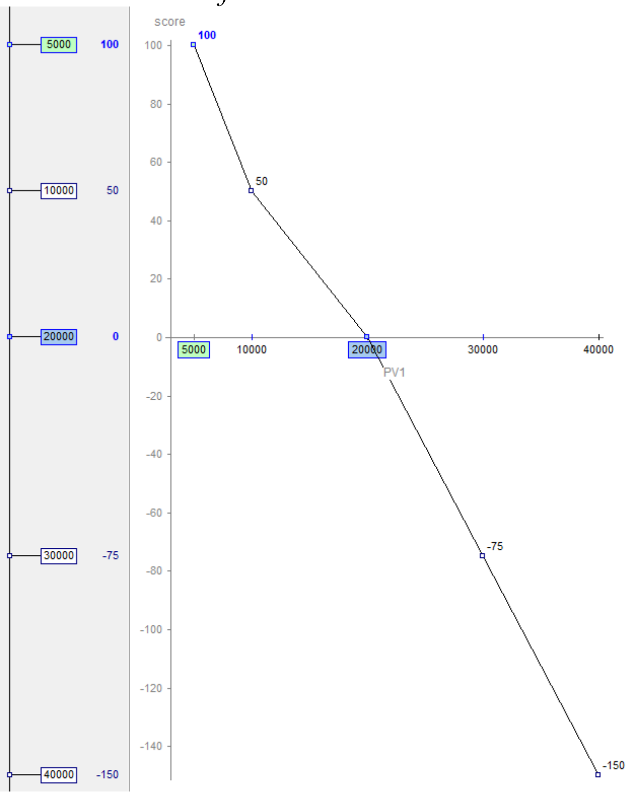
Weighting Process

The MACBETH judgements matrix given by the decision group, by consensus, when comparing the different scale levels of the descriptor of criterion Maintenance Cost considering the semantic categories: No (N), Very Weak (VW), Weak (W), Moderate (M), Strong (S), Very Strong (VS) or Extreme (E) is shown in Table 2 and, the value function obtained by linear programming using M-MACBETH for the same criterion in Figure 2, as an example.

Table 2
MACBETH Judgement Matrix Between the Scale Levels of the Criterion MAC

	1	2	3	4	5
1	N	W-M	M	M-S	S
2		N	W	M	S
3			N	M	M-S
4				N	M
5					N

Figure 2
Value Function of Criterion MAC



Bana e Costa and Chagas (2004) describe the procedure required to compute the weights of the criteria. By applying this procedure, the MACBETH judgement matrix was obtained between the decision criteria, as shown in Table 3. Finally, the weights w_i, w_{IAH} = 0.3636, w_{IOE} = 0.2727, w_{MAC} = 0.1818, w_{SMW} = 0.1364 and w_{SMA} = 0.0455 were obtained.

Table 3
MACBETH Judgement Matrix Between the Criteria

	IHA	IOE	MAC	SMW	SMA
IHA	N	W	W-M	M	M-S
IOE		N	W	W-M	M-S
MAC			N	VW-W	W-M
SMW				N	W
SMA					N

Alternatives

The viable alternatives to be applied in the systems analysed in the Healthcare Organisation are:

- Corrective Maintenance and Monthly Preventive Maintenance (CM-MPM).
- Corrective Maintenance and Daily Preventive Maintenance (CM-DPM).
- Corrective Maintenance and Continuous Preventive Maintenance (CM-CPM).

Results

The assessment of the alternatives in each of the criteria using the scale levels of each descriptor, and the overall scores obtained by the maintenance strategies in each System analysed, are shown in Table 4.

Table 4
Assessment of the Alternatives on the Criteria and Final Global Value

Alternatives	MAC	SMW	SMA	IOE	IHA	Global Score
System 1						
CM-MPM	2,880	3	3	2	8.82 (1)	43.34
CM-DPM	21,900	1	2	1	0 (0)	56.95
CM-CPM	35,000	1	0	0	0 (0)	54.55
System 2						
CM-MPM	2,880	2	2	2	0.4 (1)	74.47
CM-DPM	21,900	1	2	0	0.02 (1)	67.84
CM-CPM	35,000	1	0	0	0 (0)	54.55

Conclusion

The results obtained with the model suggest that the most appropriate option is to use CM-DPM in the System 1, and CM-MPM in the System 2. The advantages of the methodology proposed are (Carnero & Gómez, 2018):

- Ease of application, and therefore other health care organisations could use this methodology, after some adaptation.
- In the case of public organizations or companies, the use of a mathematical model in decision-making ensures that the expenditure of public funds is better justified in the eyes of the public.
- A decision-making group made up of various managers from different hospital areas provided the necessary judgments for the application of the model, with all decisions being reached by consensus.
- The MACBETH multicriteria technique facilitates including in the models the uncertainties, doubts or ambiguities of real decisions without having to use fuzzy MCDA techniques, which would be more complex to apply, and more difficult for the decision makers to understand.

References

Bana e Costa, C. A., & Vansnick, J. C. (1997). Applications of the MACBETH approach in the framework of an additive aggregation model. *Journal of Multi-Criteria Decision Analysis*, 6, 107–114.

Bana e Costa, C. A., de Corte, J. M., & Vansnick, J.C. (2003). Overview of MACBETH multicriteria decision analysis approach. *International Journal of Information Technology & Decision Making*, 11(2), 359–387.

Bana e Costa, C. A., & Chagas, M. P. (2004). A career choice problem: an example of how to use MACBETH to build a quantitative value model based on qualitative value judgments. *European Journal of Operational Research*, 153(2), 323–331.

Carnero, M. C., & Gómez, A. (2016). A multicriteria decision making approach applied to improving maintenance policies in healthcare organizations, *BMC Medical Informatics and Decision Making*, https://doi:10.1186/s12911-016-0282-7.

Carnero, M.C., & Gómez, A. (2018). Optimization of Maintenance in Production and Storage Systems for Domestic Water. *Water Resources Management,* 32, 359–380.

Carnero, M. C., & Gómez, A. (2021). Optimisation of maintenance in delivery systems for cytostatic medicines. *BMC Health Serv Res,* 21, 1188. https://doi.org/10.1186/s12913-021-07093-w

COIIM-AIIM. (2021). *Guía de gestión y mantenimiento de instalaciones hospitalarias*. Madrid: Colegio Oficial y Asociación de Ingenieros Industriales de Madrid.

Gokasar, I., Pamucar, D., Deveci, M., & Ding, W. (2023). A novel rough numbers based extended MACBETH method for the prioritization of the connected autonomous vehicles in real-time traffic management. *Expert Systems with Applications*, 211, 118445. https://doi.org/10.1016/j.eswa.2022.118445

Gómez, A., & Carnero, M.C. (2016). Decision Support System for maintenance policy optimization in medicinal gases subsystems. *IFAC-PapersOnLine*, 49(28), 268–273.

Houria**,** B., Masmoudi**,** Z., Al Hanbali, M., & Masmoudi, A. F. (2017). Quantitative techniques for medical equipment maintenance management. *European Journal of Industrial Engineering*, 10(6), 703–723.

Ighravwe, D. E., & Oke, S. A. (2019). A multi-criteria decision-making framework for selecting a suitable maintenance strategy for public buildings using sustainability criteria. *Journal of Building Engineering*, 24, 100753. https://doi.org/10.1016/j.jobe.2019.100753

Jamshidi, A., Rahimi, S. A., Ait-kadi, D., & Ruiz, A. (2015). A comprehensive fuzzy risk-based maintenance framework for prioritization of medical devices. *Applied Soft Computing*, 32, 322–334.

Mahfoud, H., El Barkany, A., & El Biyaali, A. (2016). A Hybrid Decision-Making Model for Maintenance Prioritization in Health Care Systems. *American Journal of Applied Sciences*, 13(4), 439–450.

Mishra, V., & Syed, Z. Q. (2025). Health technology assessment of nailfold capillaroscopy and digital retina imaging in diabetes screening. *Health Policy and Technology*, 14(1), 100938. https://doi.org/10.1016/j.hlpt.2024.100938

Singh, T. (2024). Entropy weighted WASPAS and MACBETH approaches for optimizing the performance of solar water heating system. *Case Studies in Thermal Engineering*, 53, 103922. https://doi.org/10.1016/j.csite.2023.103922

Taghipour, S., Banjevic D., & Jardine A.K.S. (2011). Prioritization of medical equipment for maintenance decisions. *Journal of the Operational Research Society*, 62, 1666–1687.

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