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Decision-making through Sustainability

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ABSTRACT

From immemorial time, dams have contributed significantly for the progress of civilizations. For this reason, nowadays, there is a vast engineering heritage. Over the years, these infrastructures can present some ordinary maintenance issues associated with their normal operation or with ageing processes.

Normally, these problems do not represent an important risk for the structure, but they have to be attended. To do it, owners of dams have to finance many ordinary interventions. As it is impossible to carry out all of them at the same time, managers have to make a decision and select the most "important" ones. However, it is not easy because interventions usually have very different natures (for example: repair a bottom outlet, change gates, seal a crack...) and they cannot use a classical risk analysis for these type of interventions.

The authors, who are aware this problem, present, in this paper, a multi-criteria decision-making system to prioritize these interventions with the aim of providing engineers a useful tool, with which they can prioritize the interventions from the most important to the least. To do it, the authors have used MIVES. This tool defines the Prioritization Index for the Management of Hydraulic Structures (PIMHS), which assesses, in two phases, the contribution to sustainability of each intervention. The first phase measures the damage of the dam, and the second measures the social, environmental and economic impacts. At the end of the paper, a case of study is presented where some interventions are evaluated with PIMHS.

Keywords: *Sustainability, decision-making, MIVES, MCDM, Dams, Prioritization.*

1. INTRODUCTION

Dams are considered fundamental structures for the development of nations in providing numerous socio-economic and environmental advantages (ICOLD, 2007). Their main functions are water supply, irrigation, flood control throughout the whole year, power generation, navigation, fishing, and even leisure. At the same time, these structures generate obvious environmental and social impacts caused by their construction (ICOLD, 1997). Given the evidence that society cannot live without the benefits which dams provide, it is necessary to maximize the utility of the dams that are already in operation.

Over the years, these infrastructures can present some ordinary maintenance problems associated with their normal operation or with ageing processes. Due to these problems, dams can lose resistance capacity, while, as a general rule, the solicitations, at least, are equal or even bigger than when they started to work. For this reason, direct managers of each structure suggest to their superiors some maintenance interventions to re-establish or to improve functional, mechanical and/or safety aspects of each dam. As it is impossible to carry out all of these interventions (budgets are usually very important) at the same time, general managers have to make a decision and select the most "important" ones. However, it is not easy because interventions usually are very different (for example: repair a bottom outlet, change a gate, seal a crack...) and they cannot use a classical risk analysis for these type of interventions because they are used to studying events or loads that can provoke the failure of the dam. Moreover, these kinds of studies need sophisticate calculations that required month of work. Thus, it is important to develop a decision support system that ranks, prioritizes, and selects the required maintenance interventions.

Given this need, this communication aims to present the Prioritization Index for the Management of Hydraulic Structures (PIMHS) a multi-criteria decision-making system, based on Integrated Model for Sustainable Value Assessments (MIVES for its name in Spanish) and on Analytic Hierarchy Process (AHP), which orders and prioritizes non-similar maintenance investments in hydraulic structures. The final and most important objective is that *n* maintenance and conservation actions, which have no common characteristics, may be compared, in order to select the ones with best global result to deliver the most benefit to all citizens (Pardo-Bosch 2014, Pardo-Bosch & Aguado 2015).

2. BACKGROUND

2.1. Management classic systems on the hydraulic field

According to ICOLD (1987), a structure is safe when it is free of any condition that may lead to deterioration or destruction. To measure the distance between the real condition of the structure and a state regarded as not safe, the technical community has developed two types of methodologies: Condition Index and Risk Analysis.

Infrastructures management methodologies, which use a condition index, are based on the Pavement Condition Index (Sahin et al. 1977), was developed to study the condition of pavements on airfields. This index assesses the type, the amount, and the severity of damage to obtain a value from 0 to 100, where 100 is assigned to a perfect pavement. Despite the technological advances developed since the 80s, this method remains as the reference system for the air industry (Broten and De Sombre 2001). Using PCI as a reference, the US Army Corps of Engineers developed a Condition Index (CI) to assess the state of the concrete of dams, including spillways (Bullock and Folz 1995), and another one to assess the state of the gates (Greimann *et al.* 1995), because they understood that it was impossible to develop a single system to evaluate all cases. These methods and those that have followed them only focus on the study of the structure, so it is impossible, by their nature, to assess the consequences that the detected damage can cause in other elements, such as the dam or the environment.

Risk analysis, which can also be used to manage hydraulic structures, can be divided in two different groups: stochastic and deterministic. The stochastic group is used to study events or loads that can provoke the failure of the dam, so it is not adapted to the current needs of daily management of dams (ICOLD, 2005). Due to this fact, the Bureau of Reclamation and Army Corps of Engineers (2010) have converted the stochastic approach into a deterministic one, using qualitative or semi-quantitative methods. In this case, risk severity is calculated through Eq. (1), where P(failure) may be low, moderate, high or very high; and the Consequences can be Level 1 (minimum), Level 2, Level 3 and Level 4 (maximum). As the methodology is so general, the problem is that many damages can be located in the same group of preferences. So, it is fantastic to define a first approximation, it is not possible to classify a large number of very similar interventions in order to select only the most important ones.

$$Risk=P(failure) * Consequences \qquad (1)$$

2.2. Integrated Model for Sustainable Value Assessments (MIVES)

In civil engineering, as in other fields, multi-criteria decision-making (MCDM) methodologies have been incorporated on the decision making process in order to assist those who have to make decisions. These systems usually assess a set of variables to compare the benefits and damages of different alternatives. Among them, there is the Integrated Model for Sustainable Value Assessments (MIVES) a methodology developed in Spain within the field of industrial construction (San-José and Cuadrado 2010, Aguado *et al.* 2012, Pons and Aguado 2012).

MIVES has the particularity that combines multi-criteria decision-making and multi-attribute utility theory (MCDM, MAUT) with the concept of value function (Alarcon, 2010) in order to standardize the indicators with different units (very typical for a global comparison); this process is more qualitative than quantitative in nature,. Its first applications were within the field of industrial construction, but over the years it has been adapted to any construction typology, in aspects such as localization, materials, energy and water consumption, construction solutions, etc.

The MIVES method has special features that are lacking in other sustainability assessment methods. It not only focuses on costs or product data, because it offers the possibility of incorporating other types of requirements, for example, social or environmental impacts, and doing so at any stage of the life cycle of a construction. MIVES encompasses the upward process of assessing indicators and weighing sub-levels, effectively integrating the set of indicators, criteria, requirements and fields of assessment proposed, and thus emerging as a dynamic and convenient method. To reflect the relative importance and prioritization of each requirement, criterion, and indicator level weights are assigned by decision-makers using the Analytic Hierarchy Process (AHP), developed by Saaty (1980).

Until this project, MIVES had been used to comparing homogeneous alternatives (for example, to decide the location of a factory between two different cities), but now the problem is much more complex because the alternatives are not homogenous, and as a result, it will be necessary to introduce a modification in the regular structure of MIVES.

3. SUSTAINABILITY AS A GUIDE TO DECIDE

As seen on section 2, MCDM have been and are a reference as methodologies to assist the decisions makers. The only problem, which is not so trivial, is to find, among stakeholders, consensus on the definition of the concepts to be measured, either by variables or attributes.

Sustainability has been introduced firmly, despite being a recent discipline (United Nations World Commission on Environment and Development used this concept for the first time in the Brundtland Report in 1987), as a valid argument when it is necessary to create consensus to define the variables that have to be measured in some areas of the civil engineering sector. Sustainability, according the World Commission on Environment and Development (1987), is the capacity to meet the needs of the present without compromising the ability of future generations to meet their own needs. The concept of sustainable development does imply limits - not absolute limits but limitations imposed by the present state of technology and social organization on environmental resources." Any sustainable development is based on a long-term approach, taking into account the inseparable nature of environmental, social and economic impacts of human actions, as shown in Figure 1 (United Nations 2013).

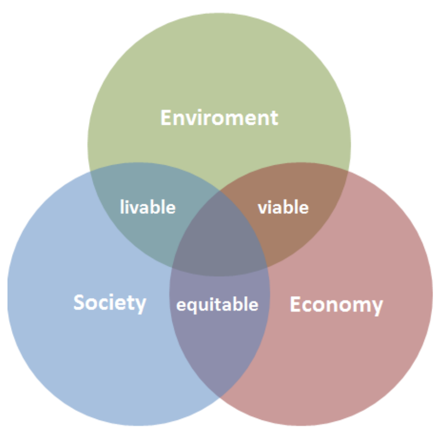

Figure 1. Axioms of sustainability

The *Economic* area assesses the use given to the limited economic resources of the decision-makers, either to perform a new project or to maintain it in operation. Executing a project ‘A’ can mean not executing project ‘B’, so companies (public or private) should strive to achieve maximum yield. The *Environmental* area considers the capacity of the project to preserve the environment (natural and constructed) in which the new project should be located. The goal is to promote those projects that encourage this preservation. Finally, the *Social* area evaluates the consequences (direct or indirect) that a project could generate on people that use or live with it.

Despite its transcendence, in civil engineering, sustainability as a main argument of a multi-criteria analysis has only been used to select, in a specific project, the most convenient alternative among a finite number of homogeneous alternatives, as shown in Shang et al. (2004), Abrishamchi et al. (2005), Comisión Permanente del Hormigón (2008), Koo and Ariaratnam (2008), and Ariaratnam et al. (2013), among others. Due to the existing hole in this field, the decision model will use the axioms of the sustainability as main guidelines.

4. NEW DECISION-MAKING MODEL

In a dam, it is possible to find structural units (*SU*) as different as: the body of the dam (*BD*), the abutments (*Ab*), the foundation (*Fd*), the reservoir (*Rv*) and auxiliary structures (*AS*). Each of them has its functions, all essential for the development of the hydraulic activity. These structures can present very different types of damage, associated with different causes that must be repaired in order to keep operating the dam. Given the evidence that the interventions needed will correct the damages will be also very different, it is necessary, according to Pardo-Bosch and Aguado (2015), to divide the analysis and evaluation process in two phases (see Figure 2).

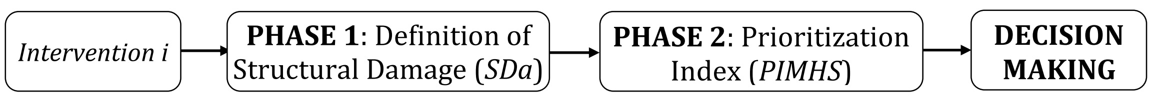

Figure 2. Decision Model

4.1. Structural damage (phase 1)

To understand the benefits of an intervention, it is essential to know the damage that affects the structure, because severe damage means severe consequences, and it is important to remember that the mission of owners and managers is to avoid negative consequences. In order to assess the damage that affects the structure, a new engineering concept called Structural Damage (*SDa*) has been defined, which is a universal system (valid for all structural typologies) to perform a semi-quantitative evaluation of the capacity of the structure to operate without compromising the safety. As equivalent units, *SDa* allows technicians to compare the condition of different structural units, which is basic in order to compare the consequences in the next phase.

SDa, as it shown in Figure 2, is evaluated through 4 independent and complementary variables that ensure the rigor and quality needed with that this type of analysis. These variables are defined to answer strategic questions (see Figure 2). All of them are assigned a score, which ranges from one (very low) to five (very high/ very significant) points as recommended in Williams (2009). As all variables are independent, each score is not conditional upon the values of others. The 4 variables are Degree of Damage (*DeD*), Location of Damage (*LoD*), Extension of Damage (*ExD*) and Evolution of Damage (*EvD*).

- Degree of Damage (*DeD*), which answers the question "*what is the severity of the damage?*" This defines the intrinsic seriousness of the damage. It means that *DeD* assesses the physical condition of the structure after it has been modified by the action of the damage. The decision maker will assign 5 points when the damage compromises the ultimate limit-state of the structure, and 1 point when the problem (damage) be simply aesthetic
- Location of Damage (*LoD*), which answers the question "*where does the damage happen?*" This defines the relative position where damage appears. The importance of damage will vary in accordance with the relevance of its location on the structural unit.
- Extension of Damage (*ExD*), which answers the question "*what is the extent of the damage?*" This defines which part of the structure is affected by the damage. To obtain the punctuation of the variable easily, the measurement is done in percentage.

- Evolution of Damage (*EvD*), which answers the question "*how the damage is evolving?*" This defines the potential capacity of the pathological process to increase the damage in the immediate future.

To obtain the final value of the *SDa*, these 4 variables are related through a summation [see Eq. (2)], where they are weighted according to their relative importance as determined by a group of experts using the Analytic Hierarchy Process (Saaty 1980).

$$StD(A_x)=0.35DeD(A_x)*0.35LoD(A_x)*0.10ExD(A_x)*0.20EvD(A_x) \quad (2)$$

4.2. Prioritization Index for the Management of Hydraulic Structures (phase 2)

Phase 2 of the decision model develops, through MIVES, the Prioritization Index for the Management of Hydraulic Structures (*PIMHS*). *PIMHS* is an index that assesses the degree of sustainability associated with a proposed maintenance intervention. The evaluation is semi-quantitative and uses the value of *SDa* to relate the damage and the consequences. The degree of sustainability depends on the social, environmental and economic consequences, for this reason the decision model is articulated through the 3 axioms of sustainability, as it shown in Table 1, which, in this case, are defined as:

Table 1: Decision framework for the Investment Prioritization Index

	Requirements	*Criteria*	*Indicators*
PIMHS	R1. Social (50%)	C1. Physical people (60%)	I1. Population Exposed to Risk* (70%)
			I2. Collective Perception of Risk (30%)
		C2. Effects (40%)	I3. Essential Services Affected* (50%)
			I4. Material-Economic loses* (50%)
	R2. Environmental (15%)	C3. Environmental impact (100%)	I5. Negative Impact of Damage* (65%)
			I6. Value Added Actions (35%)
	R1. Economic (35%)	C4. Service change (50%)	I7. Annual Unitary Cost* (100%)
		C5. Return on investments (50%)	I8. Maintenance Supervision Savings (30%)
			I9. Estimation Increase in Production (70%)

** Indicators conditioned by SDa*

- The Social requirement assesses the affects that damage can cause on people. The health and welfare of people are prioritized above any other consideration. The requirement is divided into two criteria: Individuals, which evaluates direct damages that a person may suffer; and conditions, which assesses the indirect damage that may alter the normal activity of people or companies.
- The Environmental requirement assesses the negative impacts that damage can generate on the natural surroundings of the dam. Also, it assesses the positive impacts that interventions generate on that environment. Usually, these kinds of impacts are not very important (the most important impact was occasioned by the construction of the dam) so the weight of this requirement should be pretty small.
- The Economic requirement aims to maximize the yield of every dollar invested in eliminating damages, which is not the same as to prioritize those actions that will increase the owner's benefits. This requirement breaks down into two criteria to complete the economic study of the project to be carried out: the first one analyzes the initial investment, and the second one the potential impact of that investment.

The final result of the *PIMHS* for each investment project is calculated according to Eq (30 as the weighted sum of each indicator, $IV_j(A_{i,x})$. As previously mentioned in section 2, the relative weights of each indicator (w_{I_j}), criteria

(w_{C_y}) and requirement (w_{R_t}) were calculated by the Analytic Hierarchy Process (AHP), and the indicator *IVj(Pi,x)* with the function value of each indicator.

$$PIMHS(A_x) = \sum w_{R_t} \cdot w_{c_y} \cdot w_{I_j} \cdot IV_j(A_{i,x}) \tag{3}$$

PIMHS value goes from 0 (low priority) to 1 (high priority). A qualitative assessment may be assigned to each project according to the *PIMHS* five category levels presented in Table 2 (ICE 2010, ASCE 2013). Projects will likely be classified among the B, C and D level due to the high demanding requirements of the multi-criteria analysis. The maximum and minimum contributions to sustainability are represented by levels A and E, respectively. According to Pardo-Bosch and Aguado (2015), investment projects may hardly score over 0.8 due to the highly demanding requirements of a multi-criteria analysis. At the same time, it is unlikely to get projects with an E level score, as those are directly rejected beforehand for its obvious lack of contribution to sustainability.

Table 2. PIMSH levels to classify the projects (ICE, 2010; and ASCE, 2013)

Level A	**Level B**	**Level C**	**Level D**	**Level E**
0.≤ *PIMHS* <0.8	0.8≤ *PIMHS* <0.6	0.6≤ *PIMHS* <0.4	0.4≤ *PIMHS* <0.2	0.2≤ *PIMHS* <0

This paper, because of its length, cannot explain the details of the calculation of the indicators presented in Table 1. The reader can find complete information either on Pardo-Bosch (2014) or Pardo-Bosch and Aguado (2015).

5. CASE OF STUDY

This section aims to present a real case in which the decision-maker could use *PIMHS* to prioritize its maintenance investments. Nine (9) different interventions have been selected to show the usefulness of this tool. All of them were projected by a private hydroelectric company in 6 different dams. The prioritized interventions are described below:

A1.- Treatment and sealing of cracks which affect two thirds of the dam, mainly the left abutment.

A2.- Building a wall to reinforce the rock mass where the dam is supported. The aim is to increase the safety factors, and thus prevent slippage.

A3.- Reparation and reinforcement of a land retaining wall on the road access to hydroelectric power station, where it is registered low displacements.

A4.- Replacing valves of bottom outlets to adapt them to the design criteria. The current ones suffer a widespread deterioration due to aging. Furthermore water leaks are considerable.

A5.- Grout injections to waterproof the dam body, with the aim of halting: the loss of cohesion, increased porosity and surface erosion.

A6.- Injection of cold joints in the dam body where has appeared some water leaks.

A7.- Reconstruction of a side compartment (10m high) collapsed by an avenue. There is no risk for people or environment.

A8.- Stabilizing a rock mass to avoid a landslide, which could generate a wave that would affect the dam crest, as well as the dam body.

A9.- Injection of cold joints in dam body. They have been opened by the combined action of concrete expansion and uplift pressure.

5.1. Prioritization

Due to the limited extent of this communication, it is not possible to present the evaluation of each variable of the decision model (the reader can find more information on Pardo-Bosch 2014). In order to present the results, Figure 3 shows, for each of the 9 interventions, the value (from 0 to 1) of each indicator, before applying their weight. It is easy to see that the value of each indicator varies significantly depending on the intervention, which means that all of them are important to generate discrimination among the interventions.

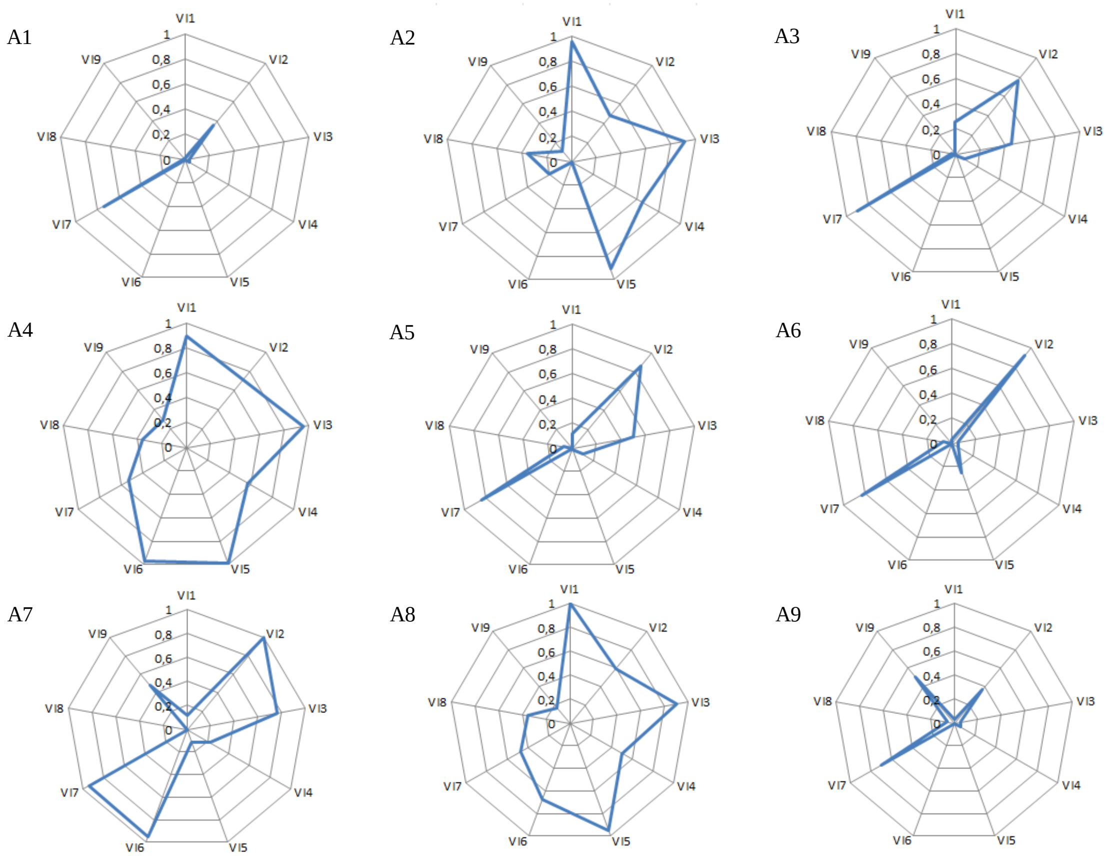

Figure 3. Indicators value (from 0 to 1) for each project

The prioritization is presented in Table 3. As the reader can see, the variability of the PIMSH values for the intervention options (values are ranged between 0.22 and 0.77) is sufficient to help identify the more important options. It's also important to remark regarding three different aspects. First, the order that we obtain with PIMSH is not the same as would be obtained if using only the *SDa* parameter (as an example, intervention A2 is located on the 3rd position using *PIMHS*, while it would have been located on the 5th position only using *SDa*), so we need to use both phases of the decision model. Another relevant aspect is that the cost of the operation does not determine the result of the classification. The first two prioritized interventions are much more expensive than the third, for example. Finally, it's important to say the all of structural units are ordered randomly, so none of them determine the result.

5.2. Sensitivity analysis

Sensitivity analyses are essential in any multi-criteria decision-making tool. These studies involve changing the value of variables to determine the impact that they can have on the final outcome (French 2003). In this case, to do this study, three new alternatives are presented, which were obtained by changing the weight of the requirements in the decision tree (see Table 4). Variation 1 and Variation 2 represent two combinations with weights that are considered consistent (possible).

On Variation 1, the weight of social requirement is reduced by 20%, so it goes from 50% to 40%. The remaining 10% is divided in two equal parts between the other two requirements. On variation 2, the weight of social requirement is increased by 20%, so it goes from 50% to 60%. In that case, the additional 10% was obtained from the economic, as it is not possible to reduce more weight from the environmental requirement. Moreover, in Variation 3, the *SDa* was removed, but the weight remained the same as in the original decision model. The aim of this Variation is to show the significance of the *SDa*.

Table 3. Interventions classification obtained by PIMSH

Classification	Actuation	*PIMSH*	*SDa*	Level	*SU*	Cost ($)
1	A4	0,70	4,25	B	*AS*	4,500,000
2	A8	0,66	4,35	B	*Rv*	5,500,000
3	A2	0,57	3,35	C	*AS*	160,000
4	A7	0,48	4,2	C	*DB*	470,000
5	A3	0,34	2,95	D	*Ab*	7,500,000
6	A5	0,31	3,45	D	*DB*	330,000
7	A6	0,27	2,65	D	*DB*	270,000
8	A9	0,22	2,65	D	*DB*	330,000
9	A1	0,17	2,05	E	*DB*	220,000

Table 4. Weight of the requirements in each alternative

	Social	**Environmental**	**Economic**
Initial Weight (%)	50	15	35
Variation 1 (%)	40	20	40
Variation 2 (%)	60	15	25
Variation 3	Initial Weight, without StD		

In Figure 4a, the reader can see that the results of Variations 1 and 2 do not introduce big changes in the valuation for the interventions, and for this reason the prioritization order is exactly the same that was obtained by the original weight. These results demonstrate the robustness of the model.

The case of the Variation 3 (V3) is quite different. Without the *SDa*, the evaluation of the interventions, in some cases, is different enough to change the order of the prioritization (see Figure 4a and 4b). This result reinforced the indivisible nature of the two phases of the decision model.

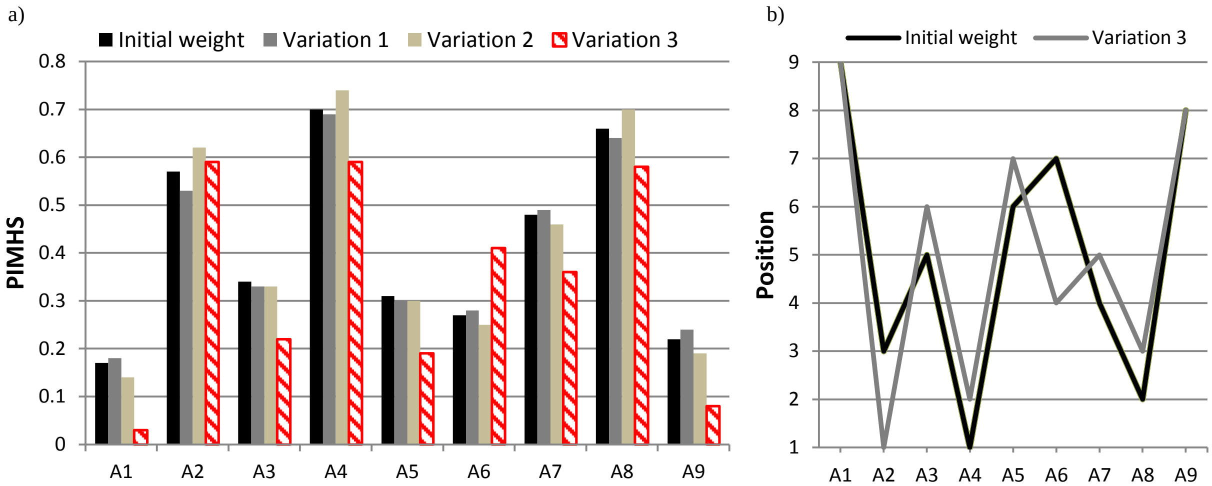

Figure 4. a) Value for each intervention in each variation of weight; b) Classification order Initial Weight vs V3

6. CONCLUSIONS

PIMHS allows prioritizing maintenance interventions in hydraulic structures with technical rigor. The main contribution of PIMSH is that it allows comparing different interventions, which would take place in very different hydraulic structures. The definition of the Structural Damage (*SDa*) is essential in order to allow comparisons between different interventions. Another advantage is that an expert can assess a large number of interventions in a few hours because the analysis is very simple, but at the same time, it is also very accurate.

This multi-criteria decision model based on MIVES will minimize the subjectivity in the entire decision-making process, and it will help companies and public administrations to explain their policies. Sustainable development is, at all times, the main argument that guides the process through the decision three requirements: economic, environmental, and social.

Once the model is defined, each institution can change the weight of any variable to introduce its philosophy or the citizens' demands in the decision-making process.

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