MIVES MULTI-CRITERIA APPROACH FOR THE EVALUATION, PRIORITIZATION, AND SELECTION OF PUBLIC INVESTMENT PROJECTS. A CASE-STUDY IN THE CITY OF BARCELONA

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Abstract

A meaningful contribution to the evaluation of heterogeneous public investments is described in this paper. The proposed methodology provides a step towards sustainable urban planning in which decisions are taken according to clear, consistent and transparent criteria assisted by the MIVES multi-criteria analysis framework. The MIVES methodology combines Multi-criteria Decision Making (MCDM) and Multi-Attribute Utility Theory (MAUT), incorporating the value function (VF) concept and assigning weights through the Analytic Hierarchy Process (AHP). First, a homogenization coefficient is calculated to develop the Prioritization Index for Heterogeneous Urban Investments (*PIHUI*), so that non-homogenous alternatives may be comparable. This coefficient measures the need of society to invest in each public project through the consideration of its contribution to the regional balance, the scope of its investment, the evaluation of the current situation and the values of the city. Then, the MIVES multi-criteria framework is used to evaluate the degree to which each investment would contribute to sustainable development. Different economic, environmental and social aspects were considered through a decision framework, constructed with the 3 aforementioned requirements, 5 criteria and 8 indicators. The case study conducted for the Ecology, Urban Planning and Mobility Area of Barcelona municipal council is presented in this paper, showing how this method performs accurate, consistent, and repeatable evaluations.

KEYWORDS: Decision Making - MIVES - Multi-criteria - Urban Planning – Urban Management – Public Investment

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1- INTRODUCTION

The challenges to achieve sustainable urban development are increasing significantly as the populations of our cities grow and their boundaries expand (Tiwari, 2003; Daigger, 2007; Lee and Chan, 2008 and Wallbaum et al., 2011). A large number of significant non-homogeneous capital investment projects are proposed every year to Public Administrations by a range of different stakeholders and agencies. However, limited resources mean that the selection of all the proposed projects is quite obviously impossible. These investments can have dramatic economic, environmental, and social impacts due to the sheer volume of people who are directly and indirectly affected, so decision-makers need to consider how to maximize their return on the investment of public funds (Yin, Madanat, & Lu, 2009). As the gap between the available funds and investment needs widens, identifying the most sustainable projects becomes a critical activity.

The realities of the urban planning process demonstrate the difficulties of implementing sustainable development as an objective in practice. Various investigations have shown that human decision-makers have difficulties handling large amounts of complex information in a consistent way. City councils and their agencies aim to develop methodologies, in order to assure rational and systematic choices based on economic, social and environmental grounds. In practice the most common form of analysis in government is cost-effectiveness analysis (CEA), where the costs of different homogeneous alternatives are compared. Other Monetary-based decision-support techniques are: financial analysis (FA); and cost-benefit analysis (CBA). It should be recalled that monetary-based techniques consider social and environmental aspects that are identified as relevant impacts and are often (but not always) valued with various limitations on both their methods and their accuracy. However, in some circumstances they might be sufficient to change the resultant order (Dodgson et al, 2009). In these circumstances multi-criteria analysis (MCA) techniques may be useful.

A number of multi-criteria methodologies have been developed over time with the aim of providing a systematic framework that considers the multidimensional nature of the real-world problem. MCM implies that each problem is broken down into its constituent parts in order to understand the evaluation process (Cafiso et al., 2001). A complete review of the MCA methodologies for ranking homogeneous alternatives developed over the last twenty years can be found in Kabirb Sadiq and Tesfamariam (2013).

Although project prioritization is a widely used tool to evaluate and to rank projects, all the existing research on this topic has mainly focused on the evaluation and the ranking of transportation infrastructure planning projects and the selection of other homogeneous alternatives. However, little (or no) attention has been paid to the prioritization of non-homogeneous alternatives.

Thus, the main objective of this paper is to describe the MIVES methodology that has been developed to assist decision-makers in finding strategies for the prioritization and selection of heterogeneous investments projects. MIVES is a Multi-Criteria methodology originally developed for the assessment of sustainability in construction (San Jose and Cuadrado, 2010; Aguado et al. 2012; Pons et al. 2012; de la Fuente et al.,

2015) and the prioritization of homogenous (Viñoles et al., 2009) alternatives. Its main contribution is that it combines Multi-criteria Decision Making (MCDM) and Multi-Attribute Utility Theory (MAUT), incorporating the value function concept (Alarcón et al., 2011) and assigning weights using the Analytic Hierarchy Process (AHP) (Saaty, 1980).

This methodology provides rational sustainability-based reasoning for the decision criteria. A case study of the Area of Urban Ecology of the Barcelona Municipal Council will guide the explanation of the methodology that is developed.

2.- MIVES MULTI-CRITERIA ANALYSIS

All classification and sorting techniques require the consideration of a realistic framework that will consider the multidimensional nature of the real-world problem. Consequently, the methodology in use should include all three sustainability dimensions (ecological, financial, and social (United Nations, 2005)) in the prioritization processes. The MIVES approach allows the consideration of such dimensions.

MIVES structures the problem within a multi-criteria analysis framework in which different investment projects may be prioritized according to pre-established criteria, in order to satisfy a pre-defined sustainable objective. A 3-level MIVES framework is developed here, in order to set the pre-established criteria. The three levels range from the most general to the most specific: requirements, criteria and indicators.

The weights are assigned by decision-makers using the Analytic Hierarchy Process (AHP), to reflect the relative importance of each requirement, criterion and indicator for the purposes of the prioritization. The AHP, originally devised by Saaty (1980), is a linear additive model that converts subjective assessments of relative importance into a set of overall scores or weights that are respectively based on pairwise comparisons between criteria and between options. Thus, for example, in assessing weights, the decision-maker is asked a series of questions, each of which inquires into how important one particular criterion is in relation to another for the decision that is addressed. Further details on the AHP process of creating the comparison matrix, checking the consistency of the assessments and the calculation of the final weights of the variables, may be found in Appendix A.

From the three levels of the framework analysis, indicators are the only concepts that are evaluated during the prioritization process. Such an evaluation can be done using qualitative or quantitative variables, and different units and scales depending on the indicator. The value function (Alarcón et al. 2011) is a single mathematical function that converts the qualitative and quantitative variables of the indicators, with their different units and scales, into a single scale from 0 to 1. These respective values represent the minimum and the maximum degree of satisfaction of the decision maker. In MIVES this value function (eq. 1, for growing functions) depends on 5 parameters, the variations of which generate all types of functions: concave, convex, lineal, or in an S shape, according to the decisions that are taken. A complete description of the definition of the function values may be found in Appendix B.

$$\mathrm{IV_i} = \mathrm{B_i} * \left[1 - \mathrm{e}^{-\mathrm{Ki} * \left(\frac{|\mathrm{X} - \mathrm{X_{min_i}}|}{\mathrm{C_i}} \right)^{\mathrm{P_i}}} \right] \qquad [1]$$

Previous MIVES frameworks were always developed for the evaluation and/or prioritization of homogeneous alternatives. This fact allows the direct application of the MIVES framework to all the studied alternatives, and its latter evaluation and ranking. However, the problem faced in this paper is even more challenging, as it requires the prioritization of a non-homogeneous set of alternative investments. This situation can be solved by adapting the homogenization index concept developed by Pardo-Bosch, and Aguado (2015).

3.- FRAMEWORK FOR THE INVESTMENT PRIORITIZATION INDEX

3.1- System boundaries

The framework presented in this paper was designed for the Barcelona Ecology, Urban Planning and Mobility Area. This section of the Barcelona Municipal Council is responsible for developing strategic projects aimed at reorienting Barcelona to a more sustainable urban model. A large number of non-homogeneous public investment projects are proposed every year in this area by many different stakeholder agencies. The project proposals include infrastructural and service-related solutions: mobility, energy, waste, urban planning, water, biodiversity and social cohesion. Moreover, when proposed, the investment is at a preliminary stage and there are generally no clearly defined details on the investment project.

The definition of a suitable homogenized decision framework is of great importance, to arrive at the correct assessment. To that end, the most significant and discriminatory variables were chosen in accordance with urban planning and investment experts.

3.2- Coefficient for the homogenization of the investment alternatives

The Homogenization Coefficient (*HC*), based on Pardo-Bosch and Aguado (2016), aims to make heterogeneous investment projects comparable between them by assessing them against identified needs in society. The HC considers four different but complementary independent variables ($N_n(P_x)$), which despite their generic character, ensure the accuracy and representativeness needed in the analysis: (1) Contribution to the Regional Balance (N_1 or CRB); (2) Investment Scope (N_2 or InS); (3) Evaluation of the current situation (N_3 or ECS); and, (4) Values of the City (N_4 or VaC). All the aforementioned variables are evaluated by means of attributes. Following the suggestion of considering no more than 5 ranges in a decision, from Williams (2009), a score ranging between 1 to 5 points was assigned to each variable ($N_n(P_x)$) according to the attribute-criteria defined in Table 1. As all $N_n(P_x)$ are independent variables, each score is not conditioned by the others. The 4 variables are described below.

The variable *Contribution to the Regional Balance (CRB)* represents the level of public investment in each district over the past few years with regard to its representativeness in the whole city (it aims to consider a proportional distribution of wealth). A score ranging between 1 to 5 (see Table 1) is assigned to the CRB variable depending on the Investment Deficit (InD), calculated according to equation 2. For its calculation, the rent level (RL), population density (PD), and the investments over the last 8 years (Inv) for a specific district (i) and in relation to the total city (T) are considered.

$$InD = \left(1 - \frac{\frac{Inv_i}{Inv_T}\ x\ 100}{\alpha_1 \cdot \frac{DP_i}{DP_T} + \alpha_2 \cdot \frac{RL_T}{RL_i}}\right) \qquad [2]$$

The variable *Investment Scope (InS)* represents the scale of the investment project that is proposed. It is measured as the weighted sum of two parameters (see eq. 3): the population that can benefit from the new service (Population Served or PoS) and how important, from fundamental to unnecessary, the investment is for that population (service Importance or SeI). Both parameters (PoS and SeI) are at the same time evaluated using the 1 to 5 range of the attribute-criteria defined in Table 1.

$$InS = \beta_1 \cdot PoS + \beta_2 \cdot SeI \qquad [3]$$

The *Evaluation of the current situation (ECS)* is measured as the weighted sum of the Condition of the Current Alternatives (CCA) and Saturation of the Current Alternatives (SCA), see eq. 4. Again, both parameters (CCA and SCA) are evaluated using the 1 to 5 range of the attribute-criteria defined in Table 1. Note that the maximum marks from among the three aspects - the condition state, the level of proximity and the level of technical obsolescence – are assigned for the evaluation of the CCA.

$$\mathrm{ECS} = \gamma_1 \cdot CCA + \gamma_2 \cdot SCA \qquad [4]$$

The variable *Values of the City (VaC)* aims to measure the alignment of each of the investment projects with the intangible values of the City. Its calculation is done as the weighted sum of the progress level of the unfinished investments (PUI) and the alignment of the investments with the Strategic Concerns of the City (ASC), see eq. 5. The ASC considers the principles to ensure a quality public space, a green and biodiverse city, that is productive and resilient, a city committed to active mobility with public involvement and commitment. The ASC is evaluated through a check list in which a ranking of between 1 and 5 is given for each strategic concern. The final ASC value is given as the average rank between the 5 better ranked concerns.

$$\mathrm{VaC} = \delta_1 \cdot PUI + \delta_2 \cdot ASC \qquad [5]$$

Table 1 – Attribute-criteria for the variables defining the HC

Variable	**InD**	**Points**
CRB	0.95 < InD	5
	0.91 < InD ≤ 0.95 %	4
	0.88 < InD ≤ 0.91	3
	0.85 < InD ≤ 0.88	2
	InD ≤ 0.85	1

Variable	**PoS** $\beta_1 = 0,4$	**SeI** $\beta_2 = 0,6$	**Points**
InS	City	Essential	5
	Inter-district	High	4
	District	Normal	3
	Neighborhood	Low	2
	Local	None	1

Variable	**CCA** $\gamma_1 = 0,6$			**SCA** $\gamma_2 = 0,4$	**Points**
	condition state	level of proximity	obsolescence		
ECS	No service	No service	No service	No service	5
	Low	Low	Obsolete	Overused	4
	Acceptable	Acceptable	Acceptable	Highly used	3
	High	High	Updated	Acceptable	2
	Not applicable	Not applicable	Not applicable	Underused	1

Variable	**PUI** $\delta_1 = 0,2$		
VaC	**Attribute**		**Points**
	PUI >75%		**5**
	50% <PUI ≤ 75%		4
	25% < PUI ≤ 50%		3
	PUI ≤25%		2
	New project		1
	ASC $\delta_2 = 0,8$		
	ASC Key-issues	**Attribute**	**Points**
	Healthy and Vital City Regenerative City Green and Biodiverse City Accessible and peaceful City Productive and resilient Sustainable Metropolitan	Very high	5
		High	4
		Medium	3
		Low	2
		Very low	1

Finally, the HC for each investment project is calculated according to equation 6 as the weighted sum of each of the $N_n(P_x)$ variables. The relative weights ($w_{HC,n}$) of the variables CET ABA, ASP and GVA assigned by the decision makers are 0.48; 0.21; 0.10 and 0.21, respectively. The HC coefficient is a value ranging between 1 (not needed) and 5 (highly needed) that affects some of the indicators involved in the economic, environmental, and social requirements (see section 3.3).

$$\mathrm{HC}\ (\mathrm{P}_x) = \sum \mathrm{w}_{HC,n} \cdot \mathrm{N}_n(\mathrm{P}_x) \qquad [6]$$

This coefficient measures the need of the society to invest in each public project. One may think that the HC could be directly used to rank the public investments, however, even if one investment might be highly needed, it may not be sustainable enough and consequently should not be prioritized. In this case, the public project should be modified, in order to become more sustainable, so that the project would not only be sustainable, but also highly needed, and consequently, well prioritized.

3.3- Decision framework

The Prioritization Index for Heterogeneous Urban Investments (*PIHUI*) aims to evaluate the degree to which each investment project, if chosen, would contribute to the sustainable development of the urban territory. According to the definition from the Sustainable City Conference, held at Rio de Janeiro, in 2000: “The concept of sustainability, as applied to a city, is the ability of the urban area and its region to continue to function at levels of quality of life desired by the community without restricting the options available to the present and future generations and causing adverse impacts inside and outside the urban boundary” (Brebbia et al. 2000).

The economic, environmental and social repercussion of each investment will be considered here, in order to consider all these aspects. The coherence, representativeness, and objectivity of the criteria and indicators under consideration in each requirement will guarantee the goodness and credibility of its results. With this purpose the most significant and discriminatory indicators have exclusively been considered. Table 2 shows the detailed list of the decision framework, constituted by the 3 aforementioned requirements, 5 criteria, and 8 indicators (the weight of each requirement, criterion and indicator is presented in brackets).

Table 2 – Decision framework for the Investment Prioritization Index

REQUIREMENTS	**CRITERIA**	**INDICATORS**
R1. Economic (20%)	C1. Investment (80%)	I1. Annual Unitary Cost (70%)
		I2. Exploitation Cost (30%)
	C2. Cofinancing (20%)	I3. Co-funding (100%)
R2. Environmental (40%)	C3. Environmental Contribution (100%)	I4. Environmental Contribution (100%)
R3. Social (40%)	C4. Service Change (50%)	I5. Service Quality Improvement (50%)
		I6. Service Capacity Improvement (50%)
	C5. Surrounding Impacts (50%)	I7. Creation of Employment (30%)
		I8. Social Agreement (70%)

Economic Requirement

In the Economic Requirement, two different criteria (investment balance (C1) and investment return (C2)) are considered, to evaluate the economic impact of each investment project.

C1 is at the same time divided into two indicators. Indicator I1 is the annual unitary cost (AUC) and is based on Pardo-Bosch, F. and Aguado, A. (2015). It evaluates the implementation costs (ImC) of each investment project considering its expected lifetime (LT) and its HC according to eq. 7.

$$AUC = \frac{ImC}{LT \cdot HC} \qquad [7]$$

Apart from the annual unitary cost, C1 also measures the annual economic effort needed to maintain the service provided by the investment project (indicator I2). A score of 1 to 5 is assigned to the variable exploitation cost or ExC (according to the attribute-criteria defined in Table 3). This value, affected by the HC yields annual maintenance effort or AME (see eq. 8).

$$AME = \mathrm{ExC} \cdot \mathrm{HI} \qquad [8]$$

C2 is constituted only by Indicator I3 which aims to measure the possibility of obtaining external funding to develop the investment. The variable for the calculation of I3 is calculated as the product of the probability of obtaining funding (PrF), the quantity of probable funding (QuF) and the HC. The variables PrF and QuF are directly obtained assigning a 1-to-5 score according to the attribute-criteria of table 3.

$$CoF = PrF \cdot QuF \cdot HI \qquad [9]$$

Table 3 – Attribute-criteria for the variables defining the Economic Requirement

Variable	ExC	Points
AME	Very high	5
	High	4
	Medium	3
	Low	2
	Very low	1

Variable	PrF	QuF	Points
CoF	Very high	QuF >80%	5
	High	60% <QuF ≤ 80%	4
	Medium	40% < QuF ≤ 60%	3
	Low	10% < QuF ≤40%	2
	Very low	QuF ≤ 10%	1

Environmental Requirement

Barcelona has a strict green policy, promulgating only environmental friendly investments. Consequently, in this decision framework, the environmental requirement is assessed as the level of positive environmental contribution of each investment project. The only indicator used, I4, measures this contribution through the evaluation of 7 environmental key-issues (EKI_i). The 7 key issues considered are: (1) waste management; (2) energy efficiency; (3) water use efficiency; (4) air quality; (5) acoustic quality; (6) biodiverse city; and, (7) acceptable landscaping.

A score ranging from 1 (very poor) to 5 (very high) depending on the level of improvement provided by the investment projects is assigned to each issue. The average of the 5 most highly scored environmental key-issues affected by the HC (see eq. 10) is used to calculate the environmental contribution (EnC) variable.

$$EnC = \left(\sum_{i=1}^{5} EKI_i \right) \cdot HC \qquad [10]$$

Social Requirement

The Social Requirement evaluates the direct and indirect consequences that any investment project can generate on the people that use or live with it. With the aim of having a complete analysis, two criteria were used: C4. Service change and C5. Surrounding impacts.

The service change criterion (C4) represents the idea that any investment should aim to change the service given by either improving its quality (Service Quality Improvement or SQI) or increasing its amount of users (Service Capacity Improvement or SCI), which corresponds to indicators I5 and I6, respectively.

Indicator I5 (SQI) evaluates the service quality improvement in 5 different key-issues: (1) security; (2) accessibility/comfort/mobility; (3) culture/education; (4) health/sport; and (5) social cohesion. A score of 1 to 5, depending on the level of improvement provided by the investment (according to the attribute-criteria defined in Table 4 that is assigned to each quality key-issue (QKI_i). The average of the 4 most highly scored key-issues (QKI_i) affected by the HC yields SQI (see eq. 11), which is used to calculate I5.

$$SQI = \left(\sum_{i=1}^{4} QKI_i\right) \cdot HC \qquad [11]$$

Similarly, the level of user increment (UIn, according to the 1-to-5 attribute-criteria defined in Table 4) affected by the HC is used to calculate the SCI (see eq. 12).

$$SCI = UIn \cdot \mathrm{HC} \qquad [12]$$

The surrounding impacts criterion (C5) is constituted by two indicators, I7 is the Creation of Employment (CrE) and the I8 is Social Agreement (SoA). The first one represents the amount of direct and indirect job positions that would be created due to the implementation and use of the service or infrastructure under analysis (see eq. 13). The latter somehow evaluates the social acceptance of the proposed investment. The 1-to-5 attribute-criteria affected by the HC and defined in Table 4) are used to calculate I7 (CrE) and I8 (SoA) by means of the value function presented in table 4.

$$CrE = \rho_1 \cdot DEI + \rho_2 \cdot DES + \rho_3 \cdot IES \qquad [13]$$

Table 4 – Attribute-criteria for the variables defining the Social Requirement

Variable	**Level of improvement in the service quality**		**Points**
	Key issues QKI_i	**Attribute**	
SQI	security accessibility/comfort/mobility culture/education health/sport social cohesion	Very high	5
		High	4
		Medium	3
		Low	2
		Very low	1

Variable	**Level of users increment (UIn)**	**Points**
SCI	Very high	5
	High	4
	Medium	3
	Low	2
	Very low	1

Variable	**DEI** $\boldsymbol{\rho_1 = 0,2}$	**DES** $\boldsymbol{\rho_2 = 0,2}$	**IES** $\boldsymbol{\rho_3 = 0,6}$	**Points**
CrE	DEI> 100	DES> 20	IES> 200	5
	50 <DEI≤ 100	10 <DES≤ 20	100 <IES≤ 200	4
	30 <DEI≤ 50	6 <DES≤ 10	60 <IES≤ 100	3
	10 <DEI≤ 30	2 <DES≤ 6	20 <IES≤ 60	2
	0 ≤ DEIx≤ 10	0 ≤ DES≤ 2	0 ≤ DES≤ 20	1

Variable	**Level of social agreement**	**Points**
SoA	Very high	5
	High	4
	Medium	3
	Low	2
	Very low	1

Value Functions

A value function is proposed for each indicator, in order to transform each evaluation to a number from 0 to 1, thereby defining equivalences between the different units of the indicators. The decision-making satisfaction criteria of each indicator involved in the present study can be satisfactorily represented with decreasing (D) or increasing (I) functions, these being linear (Lr), concave (Ce), convex (Cx) or S-shaped (S). Accordingly, Table 5 shows the data and the form of each value function.

Table 5. Parameters and coefficients for each indicator value function

INDICATORS	X	X_{min}	X_{max}	P_i	C_i	K_i	B_i	Shape
I1. Annual Unitary Cost	AUC	0.0	5.E5	2.50	2.5E5	0.50	1.06	D-S
I2. Implementation Cost	ImC	1.0	25.0	1.0	25.0	3.0	1.05	I-Ce
I3. Co-funding	CoF	1.0	125.0	2.0	60.0	1.0	1.01	I-S
I4. Environmental Contribution	EnC	5.0	125.0	2.0	100.0	2.0	1.05	I-S
I5. Service Quality Improvement	SQI	4.0	100.0	2.0	50.0	1.0	1.02	I-S
I6. Service Capacity Improvement	SCI	1.0	25.0	1.0	20.0	2.0	1.09	I-Ce
I7. Creation of Employment	CrE	1.0	5.0	1.5	5.0	1.0	1.95	I-Cx
I8. Social Agreement	SoA	1.0	5.0	1.0	1E4	1.0	2.5E3	I-Lr

Prioritization Index for Heterogeneous Urban Investments (PIHUI)

The final result of the PIHUI for each investment project is calculated according to equation 2 as the weighted sum of each indicator, IVj(Pi,x); see eq. 14. As previously mentioned in section 2, the relative weights of each indicator(w_{I_j}), criterion (w_{C_y}) and requirement (w_{R_t}) were calculated by means of the Analytic Hierarchy Process (AHP), and the indicator IVj(Pi,x) with function values (see Appendix A and B, respectively).

$$\mathrm{PIHUI}\ (\mathrm{P}_x) = 100 \cdot \sum \mathrm{w}_{\mathrm{R_t}} \cdot \mathrm{w}_{\mathrm{C_y}} \cdot \mathrm{w}_{\mathrm{I_j}} \cdot \mathrm{IV_j}(\mathrm{P}_x)$$ [14]

A PIHUI value ranging between 0 (low priority) and 100 (high priority) prioritizes the investment projects under evaluation. A qualitative assessment may be assigned to each project according to the five PIHUI categories presented in table 6 (Pardo-Bosch, F. and Aguado, A., 2015). The maximum and the minimum contributions to sustainability are represented by levels A and E, respectively. According to Pardo-Bosch, F. and Aguado, A. (2015), investment projects can hardly score over 80 due to the highly demanding requirements of a multi-criteria analysis. Following the same logic, projects with an E level score are in all likelihood directly rejected beforehand, because of their very low contribution to sustainable development. Therefore, the projects will generally be classified at the B, C, and D levels.

Table 6. Levels of PIHUI to classify the projects, ICE (2010) and ASCE (2013).

Level A	Level B	Level C	Level D	Level E
100≤ PIHUI <80	80≤ PIHUI <60	60≤ PIHUI <40	40≤ PIHUI <20	20≤ PIHUI <0

Sometimes the contribution of projects to the overall benefit of different scenarios is highly intertwined and interdependent. According to Bagloee, S. A. and Asadi, M. (2015), interdependency appears to be an intractable problem, when assessing the contribution of projects to overall benefits. Thus, earlier studies have generally ignored this issue or at best, have considered it indirectly, falling short of considering interdependency.

However, the methodology presented here can be adjusted to account for project inter-dependence by consecutive iteration once a project has been prioritized. Moreover, using game-theory, instead of prioritizing individual projects one by one, the most sustainable group or combination of projects can be prioritized.

4.- CASE STUDY

The feasibility, robustness, and coherence of the PIHUI - MIVES multi-criteria approach is assessed in this section. To do so, 15 heterogeneous investment projects under consideration at the Ecology, Urban Planning and Mobility Area of the Municipal Council of Barcelona are evaluated and prioritized. A complete list of the 15 investment projects together with a brief description may be found in table 7.

Table 7. List of the 15 heterogeneous public investment projects.

LIST OF INVESTMENTS TO EVALUATE		
Nº	**INVESTMENT PROJECT DESCRIPTION**	**DISTRICT LOCATION**
I-1	Urbanization of area around the new building for social rehousing.	SANT ANDREU
I-2	Enlargement of the sidewalk area, moving bar terraces and motorbikes parking closer to the road	EIXAMPLE
I-3	Increase the number and variety of the flora and fauna in Collserola area.	BARCELONA CITY
I-4	Optimization of the number and the distribution of the lights around the city.	BARCELONA CITY
I-5	Soil expropriation program to develop the larger project of neighborhood transformations.	LES CORTS
I-6	Initial project to collect all the different points of view of stakeholders, with special social and environmental dimensions.	EIXAMPLE
I-7	Works to consolidate the sewer system in the area.	SANTS MONTJUÏC
I-8	Listing the main issues to create a new methodology to evaluate street variety in the city.	BARCELONA CITY
I-9	City council program to resolve housing soil problems.	BARCELONA CITY
I-10	Creating a new methodology with a Smart City perspective to rethink the social space	BARCELONA CITY
I-11	Implementation of measures to evaluate the efficiency of actual actions for air quality evaluation.	BARCELONA CITY
I-12	Social plan for citizens to promote an energy saving culture.	BARCELONA CITY
I-13	Reorganization of public spaces, improving gardens and subway entrances.	GRÀCIA
I-14	Urban road tunnel to redirect Barcelona's traffic at one of the points of highest traffic density.	SANT MARTÍ
I-15	Organization of the area with sustainable and equity perspective incorporating all stakeholder perspectives.	SANT MARTÍ

4.2- Coefficient for the homogenization of the investment alternatives

Figure 1 presents the HC results for each of the 15 investment projects. Note that the HC values that were obtained ranged between a minimum of 2.7 (for I-7) and a maximum of 3.9 (for I-1).

Figure 1- Comparison of the HC values obtained for each investment

Among the four variables involved in the evaluation of the HC, the CRB (contribution to regional balance) makes (according to the decision-makers) the most important contribution. This variable is defined by the rent level (RL), population density (PD), and the investment over the last 8 years (Inv). Therefore, the CRB, and consequently the HC affects the decision in a way that: (1) the greater the investment in recent years in a specific district, the lower its future investments will be; (2) the higher the density of the district, the higher the need for future investment; and, finally, (3) the higher the average district rent, the lower the required investment.

4.3- Decision framework

The decision framework is based on the economic, environmental and social requirements previously developed in section 3.3. The weights the decision makers assigned to these requirements using AHP were: 0.20; 0.40 and 0.40, respectively. Figure 3 the results of prioritization ranking from highest to lowest priority.

Figure 2- Prioritization ranking of the 15 heterogeneous public investment projects.

4.3- Sensitivity study

This section aims to analyze the sensitivity of the methodology that has been developed. A comparison of the investments ranking is assessed when the assigned weights ($w_{HC,n}$) change, in order to study the influence of HC on the prioritization. Table 8 summarizes the 3 cases under study. (Case A represents the current weights chosen by Barcelona City Council decision makers). As shown in Figure 3, changing the weights of the four variables involved in defining index HI (CBR, InS, ECS and VaC), within a range of reasonable values, leads to no major changes in the PIHUI outcome. Some of the investments changed their priority ranking with the investment immediately above or below. However, these changes are not significant, which reaffirms the robustness of the approach.

Table 8- HC variable weights used for the sensitivity analysis

	CRB	**InS**	**ECS**	**VaC**
case A	0.48	0.21	0.10	0.21
case B	0.25	0.25	0.25	0.25
case C	0.35	0.35	0.20	0.10

Figure 3- Comparison of the prioritization ranking following changes to the weights of the HC variables.

The comparison of the ranking of the investments is assessed when the assigned weights of each requirement (see Table 9) change, in order to study the influence of the decision-making criteria on the prioritization. In all the cases under study, the HC value of case A was used. Case A.1 corresponds to the reference case (see section 3) with the economic, environmental and social weights originally proposed by the administration. Alternatively, case A.2 considers a more balanced distribution, in which all the requirements have the same weight in the final decision. Finally, in case A.3, the environmental requirement was assigned a small weight, as it was assumed that all investments are acceptable and compatible with the criteria and environmental concerns of the city.

Table 9- Requirement weights used for the sensitivity analysis

	Economic Req.	**Environmental Req.**	**Social Req.**
case A.1	0.20	0.40	0.40
case A.2	0.33	0.33	0.33
case A.3	0.35	0.20	0.45

These differences result in small changes in the priority ranking order (Figure 4). Investment I-10 changes from 3rd position in the case of A.1 to 8th position in the cases of both A.2 and A.3 (in which the economic requirement has the major weight), while the other investments underwent not significant changes.

Figure 4- Comparison of the prioritization ranking following changes to the requirement weights

5- CONCLUSIONS

The simple and straightforward methodology presented in this paper has meant that the alternatives may be sorted and prioritized on the basis of homogeneous criteria. The

PIHUI index provides a step towards sustainable urban planning in which decisions are made according to clear, consistent, and transparent criteria.

The MIVES methodology has proven itself to be a proper approach, in order to consider the main economic, environmental and social aspects in the decision framework. Moreover, the HC coefficient has been developed, which measures the need of the society to invest in each public project on the basis of its contribution to the regional balance of investments, its investment scope, the evaluation of the current situation, and the values of the city. This represents a meaningful contribution for the evaluation of heterogeneous investments.

The case study conducted for the Barcelona Ecology, Urban Planning and Mobility Area has yielded very satisfactory results, showing that accurate, consistent, and repeatable evaluations can be performed. The method can be simply adapted, if the decision-makers change the criteria by modifying the weights and the value functions that are assigned to them. Moreover the robustness of the proposed approach would make it easily applicable to other cities.

Appendix A.: Analytic Hierarchy Process

Construction of the pairwise comparison matrix

To build the pairwise comparison matrix, the decision maker is asked to rate the importance of one particular criterion in relation to another in the context of the decision that is addressed.

Checking the consistency of the pairwise comparison matrix.

Typically, some inconsistencies may arise during the assessment of the comparison of each alternative (which may cause errors and uncertainty over logical results). The AHP incorporates an effective technique for checking the consistency of the evaluations made by the decision maker when building each of the pairwise comparison matrices involved in the process. In this sense, Saaty introduced the Consistency Ratio (CR) for the pairwise consistency matrix. If the CR exceeds 10%, it is recommended that the decision maker revise the elicited preferences. The CR may be calculated using the Consistency Index (CI) and the Random Index (RI), according to ec.A1.

$$CR = \frac{Consistency\ Index}{Random\ Index} = \frac{CI}{RI} \qquad [AA.1]$$

Saaty proposed to compute the Consistency Index (CI) by means of the largest eigen value (λ_{max}) and the size (m) of the pairwise comparison matrix, according to eq. AA.2.

$$IC = \frac{\lambda_{max} - n}{n - 1} \qquad [AA.2]$$

The Random Index, i.e. the consistency index when the entries of A are completely random. The values of RI for small problems ($n \leq 10$) are shown in Table AA.1.

Table AA.1 Random Consistency Index (RI)

Matrix size n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.51

Calculate the weights of the variables

A number of methods can be used to estimate the set of weights that are most consistent with the relativities expressed in the pairwise comparison matrix. Saaty's basic method of identifying the value of the weights depends on relatively advanced ideas in matrix algebra and calculates the weights as the elements in the eigenvector associated with the maximum eigenvalue of the matrix.

A more straightforward alternative, which also has some theoretical grounding, is to: (1) calculate the geometric mean of each row in the matrix; (2) total the geometric means; and, (3) normalize each of the geometric means by dividing each one by the total calculated in the preceding step. The weights estimated by the two different methods (taken to a number of significant figures for greater accuracy) are not identical, but it is common for them to be very close.

Appendix B.: Value Function

The parameters that define the type of function are: Ki, Ci, X max., X min. and Pi. The value of B that appears in equation 3 is calculated on the basis of the 5 earlier values (Equation AB.1).

$$\mathrm{IV_i} = \mathrm{B_i} * \left[1 - \mathrm{e}^{-\mathrm{Ki} * \left(\frac{|\mathrm{X} - \mathrm{X}_{\mathrm{min_i}}|}{\mathrm{C_i}}\right)^{\mathrm{P_i}}}\right] \qquad \text{[AB.1]}$$

where:

X_{mini}	is the minimum x-axis of the space within which the interventions take place for the indicator under evaluation.
X	is the quantification of the indicator under evaluation (different or otherwise, for each intervention).
P_i	is a form factor that defines whether the curve is concave, convex, linear or an “S” shape: concave curves are obtained for values of Pi < 1, convex and “S” shaped forms for Pi > 1 and almost straight lines for values of Pi = 1. In addition, Pi gives an approximation of the slope of the curve at the inflection point.
C_i	approximates the x-axis of the inflection point.
K_i	approximates the ordinate of the inflection point.
B_i	is the factor that allows the function to be maintained within the value range of 0 to 1. This factor is defined by equation AB.2.

$$B_i = \left[1 - e^{-Ki*\left(\frac{|X_{max_i} - X_{min_i}|}{C_i}\right)^{P_i}}\right]^{-1} \qquad [AB.2]$$

where: X_{max} is the x-axis of the indicator that generates a value equal to 1 (in the case of functions with increasing values).

Alternatively, functions with decreasing values may be used: i.e. they adopt the maximum value at X_{min}. The only difference in the value function is that the variable X_{min} is replaced by the variable X_{max}, adapting the corresponding mathematical expression.

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