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STUDY OF CRITERIA USED TO OBTAIN A SUSTAINABLE BRIDGE

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The sustainable development of bridges is mainly based on meeting the three pillars of sustainability (economic, social and environmental factors) which have different goals. Each main criterion groups a large number of subcritera. Therefore, achieve a sustainable bridge is a complicate problem that involves a high number of factors in each stage of bridge life-cycle. For this reason, decision-making is a helpful process to solve the sustainability problem. The objective of this work is to review the bridge life-cycle decision-making problems that involve criteria that represent the pillars of the sustainability. While some works only consider criteria related to one or two of these pillars, the most current works consider criteria that involve all the pillars of sustainability. Furthermore, most of the works reviewed only study one stage of bridge life-cycle. This study shows the criteria used in some revised journal articles in each bridge life-cycle phase and, the multi-attribute decision-making used to achieve the sustainability. In addition, a small explanation of the obtained information will be carried out.

Keywords: Multi-criteria, Life-cycle, Decision-making, MCDM, MADM.

1 INTRODUCTION

Nowadays, there is a sustainability trend in structures. This sustainable development is mainly based on meeting three main pillars: economic, social, and environmental. The economic and environmental factors have been widely studied, and the social factor is the least studied in structures. Thus, to achieve a consensus among these three main pillars, it is necessary to apply a process such as decision-making. This process facilitates the rational selection of a sustainable bridge solution based on certain information and judgment about the criteria chosen for each life-cycle phase.

Some authors (Balali *et al.* 2014) pointed that the different steps of bridges life-cycle can be categorized as: (a) planning and design, (b) construction, and (c) operation and maintenance. These phases and (d) demolition or recycling phase form all the phases considered in the bridge life-cycle.

The aim of this study is to classify and analyze the criteria used by different authors to evaluate the sustainability for each phase of the bridge life-cycle. First, a brief description of the most important multi-attribute decision-making (MADM) methods is carried out. After, at each bridge life-cycle phase, the criteria used for authors are classified into the three pillars of sustainability. Finally, a small explanation of the collected information will be carried out.

2 MADM METHODS

There are many methods and tools that can be used for MADM. Despite the large number of traditional MADM methods, none is perfect. Most of them make unrealistic assumptions hardly applicable to the real world. However, the traditional MADM methods can be classified into different groups according to similar characteristics (Penadés-Plà *et al.* 2016). Table 1 shows an outline of traditional MADM.

Table 1. Multi-attribute decision-making (MADM) methods description.

MADM group	MADM method	Reference
Scoring methods	Simple additive weighting (SAW)	(Podvezko 2011)
	Complex proportional assessment (COPRAS)	(Podvezko 2011)
Distance-based methods	Goal programming (GP)	(Tamiz *et al*. 1997)
	Compromise programming (CP)	(Ballestero 2006)
	Technique for order of preference by similarity to ideal solution (TOPSIS)	(Opricovic and Tzeng 2002)
	Multicriteria optimization and compromise solution (VIKOR)	(Opricovic and Tzeng 2002)
	Data envelopment analysis (DEA)	(Podinovski 2016)
Pairwise comparison methods	Analytic hierarchy process (AHP)	(Görener 2012)
	Analytic network process (ANP)	(Görener 2012)
	Measuring Attractiveness by a Categorical Based Evaluation Technique (MACBETH)	(Bana e Costa and Chagas 2004)
Outranking methods	Preference ranking organization method for enrichment of evaluations (PROMETHEE)	(Behzadian 2009)
	Elimination and choice expressing reality (ELECTRE)	(Govindan and Jespen 2015)
Utility/Valuate methods	Multi-attribute utility theory (MAUT)	(Sarabando and Dias 2010)
	Multi-attribute value theory (MAVT)	(Sarabando and Dias 2010)

3 LIFE-CYCLE STAGES OF THE BRIDGE

3.1 Planning and Design

The planning and design phase is the most important phase in which all the others can be included. A good decision-making at this stage can improve the sustainability of the bridge throughout it useful life with a lower cost. Therefore, it is necessary to select a set of criteria that assess the sustainability of the bridge over its useful life.

Table 2 shows the criteria used for different authors to select the most sustainable bridge. In some publications, the general cost is divided into different subtypes of cost (construction cost, maintenance cost, recycle or demolition cost…), in addition to including another criteria that indirectly affect these direct cost (speed of construction, durability…). The environmental factor, despite being widely considered, do not take into account a determined set of criteria. Some authors carried out an environmental impact assessment, (Gervasio and Da Silva 2012) using CML method to evaluate the environmental impact of the bridge. The social factor is, perhaps, the most subjective. The aesthetic is the most criterion considered for the authors (aesthetic feeling, architecture design, bridge geometry…), although there are others also important such as driving comfort and symbolism, among others.

Table 2. Criteria used in the planning and design phase.

Reference	Criteria			Method
	Economic	**Environmental**	**Social**	
(Jakiel and Fabianowski 2014)	Total investment cost, Project duration, Maintenance costs	Project area minimization, Minor interference on landscape and harmoniously integrated into landscape, Contamination during erection, use, and recycling	Bridge structure geometry adjustable to locality conditions	AHP
(Gervasio and Da Silva 2012)	Construction cost, Maintenance cost, End of life cost	CML impact assessment method	Vehicle operation cost, Driver delay cost, Safety cost	AHP and PROMETHEE
(Balali *et al.* 2014)	Cost, Construction speed, Inspection and maintenance	-	Architecture design, Symbolic, Aesthetics	PROMETHEE
(Martí *et al.* 2016)	Cost	Embodied energy	-	Mono-objective optimization
(García-Segura and Yepes 2016)	Cost	CO_2	Safety	Multi-objective optimization
(García-Segura *et al.* 2017)	Cost	-	Durability, Safety	Multi-objective optimization

3.2 Construction

The construction phase involves higher risk, so it is important to consider criteria that take into account this risk. Table 3 shows the criteria used by some authors for this phase. The economic factor is more fragmented than in planning and design phase. The direct cost of construction is a common criterion. Besides, some authors subdivide the speed of construction or duration into other criteria (constructability, weather condition, and site condition). Environmental factor is not sufficiently developed and only indicates that it is taken into account. The social factor is very important in this phase. On one hand, it is necessary to consider the safety during the construction of the bridge. On the other hand, the criteria of time loss (traffic conflict, traffic interference) must be considered when the construction of the bridge causes lost time for users of closer roads.

3.3 Operation and Maintenance

Table 4 shows some criteria used for authors in operation and maintenance phase. This phase is the most unclear phase because there are many criteria that could have associated a very large uncertainty. Therefore, it is difficult to assess which is the most sustainable way to maintain the bridge. The economic factor takes into account the cost of the material and the cost of the workers. CO_2 and energy used are common criteria. The social factor considers mainly the time lost by users and the extra travel distance as a result of the repair and maintenance of the bridge.

Table 3. Criteria used in the construction phase.

Reference	Criteria			Method
	Economic	**Environmental**	**Social**	
(Pan 2008)	Damage cost, Construction cost, Duration (Constructability and Weather condition)	Environmental preservation	Traffic conflict, Site condition, Geometry, Landscape	AHP
(Gu *et al.* 2011)	Cost, Duration	-	Safety	TOPSIS
(Mousavi *et al.* 2011)	Cost, Duration	-	Safety, Shape	AHP
(Balali *et al.* 2014)	Cost, Construction Speed	Environmental issues	Traffic interference	PROMETHEE
(Chen 2014)	Damage cost, Construction cost, Weather condition, Site condition	Environmental effect	Landscape, Traffic conflict, Durability	PROMETHEE

Table 4. Criteria used in the operation and maintenance phase.

Reference	Criteria			Method
	Economic	**Environmental**	**Social**	
(Abu Dabous and Alkass 2010)	Material cost, Labor cost, Equipment cost	Environmental impact	Delay cost, Cost of accident and crashes, Safety	AHP
(Bitafaran *et al.* 2013)	Performance costs	-	Reduce mortality and vulnerability, Performance speed	AHP
(Sabatino *et al.* 2015)	Rebuilding cost	CO_2 emissions, Energy consumption	Extra travel time, Extra travel distance, Fatalities	Other

3.4 Demolition or Recycling

The study of the sustainability of last bridge life-cycle phase has only been investigated by very few authors. However, the sustainability in this phase is important too, because this stage has an impact on each of the three pillars of sustainability. Table 5 shows the criteria used for one of the few authors who have studied the sustainability of this phase.

Table 5. Criteria used in the demolition or recycling phase.

Reference	Criteria			Method
	Economic	**Environmental**	**Social**	
(Chen *et al.* 2014)	Machinery, Manpower	Environmental impact	Safety risk, Acceptable level of noise, Proximity to adjacent structures	ANP

4 DISCUSSION

This investigation shows the use of different methods and criteria in the decision-making process at each life-cycle phase of sustainable bridges. The works shown in this study are a small sample of a larger review study. As in the works described in this study, there is a great variety both on the criteria and methods used in each bridge's life-cycle. In addition, some criteria are not enough disaggregated, so it cannot be deduced how was assessed.

In the future, the criteria used to assess the sustainability of each bridge's life-cycle should be unified, thus, a comparison of the results of the different studies could be made. Furthermore, the three pillars of the sustainability must be fragmented into the criteria and sub-criteria needed to make an assessment as objective as possible. The planning and design phase, must consider all phases of the bridge life-cycle. In this way, it will be possible to make a complete evaluation of the bridges and asses which is the most sustainable bridge.

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