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Bayesian network method for decision-making about the social sustainability of infrastructure projects

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A B S T R A C T

Nowadays, sustainability assessment tends to focus on the biophysical and economic aspects of the built environment. The social aspects are generally overestimated during an infrastructure evaluation. This study proposes a method to optimize infrastructure projects by assessing their social contribution. This proposal takes into account the infrastructure's interactions with the local environment in terms of its potential contribution in the short and long term. The method is structured in three stages: (1) preparation of a decision-making model, (2) formulation of the model, and (3) implementation of the model through optimization of infrastructure projects from the social sustainability viewpoint. The theory of Bayesian reasoning and a harmony search optimization algorithm are used to carry out the research. The paper presents the application to a case study of a set of alternatives for road infrastructure projects in El Salvador. This approach creates a model of participative decision-making. The results show that the method can distinguish socially efficient alternatives from the short and long-term contributions. In addition, the results suggest that some variables are less sensitive to the short and long-term maximization, while others vary their values to improve one objective or the other. The findings are directly applied to a real case. The method can be employed in the infrastructure formulation and prioritization phases and complemented with economic and environmental sustainability assessments.

1. Introduction

Sustainable development makes the economy, society and the environment compatible without jeopardizing either development or future generations (WCED, 1987). In the last 30 years of the 20th century, the discussion centered on ecology. Only at the end of the century did the international community begin to understand the importance of enhancing human abilities (Colantonio, 2011). In particular, the evaluation of social sustainability has been intertwined with assessment methods to make sustainable development measurable (Torres-Machi et al., 2015; Pellicer et al., 2016). Environmental assessments incorporate this condition; however, the social aspect is not taken sufficiently into account (Valdés-Vásquez and Klotz, 2013; Dendena and Corsi, 2015). In addition, social aspects have limitations to being evaluated in the same way as other sustainability dimensions. Social and cultural heterogeneity drives the divergence of measurement criteria (Vanclay, 2002; Colantonio, 2011). Moreover, the estimation of social sustainability also requires the assessment of qualitative aspects. Munda (2004, 2006) explains that the social development to achieve sustainability must consider the ethical sense of equity in both resource and cost distribution. Moreover, this author suggests that it is not enough to consider a development model based on economic and industrialized growth.

Infrastructure projects promote economic well-being, and they may complement many social interventions as well. For example, early maintenance investments improve the social contribution of services that require infrastructures (Schwarz et al., 2016). Thus, a complete infrastructure life-cycle review is crucial to assessing the impacts (Sierra et al., 2016; Zastrow et al., 2017). However, the social characteristics of a project have a high degree of uncertainty (Delgado and Romero, 2016). This is especially noticeable in the early stages of a project's development, prior to its construction

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(Gervásio and Simoes da Silva, 2012; Mel et al., 2015). Furthermore, the social contribution of an infrastructure project depends heavily on its interaction with the contextual conditions (Mostafa and El-Gohary, 2014; Dendena and Corsi, 2015). Contextual conditions refer to the development level of an area, such as the level of employability, public transport services, health and education services, and so forth.

In professional practice, Cost-Benefit Analysis is one of the most traditional methods used to evaluate infrastructures. However, non-monetary social externalities are not sufficiently considered. Bueno et al. (2015) and Mostafa and El-Gohary (2014) argue that the method does not include the distribution of cost, benefit or participation in the evaluation process. Social Life Cycle Assessment is another methodological framework that is still at an early stage of development and requires databases or inventories (van Haaster et al., 2017). In this sense, Benoit-Norris et al. (2012) have proposed social hotspot databases, which express social risks per country and productive sector. These databases provide information only for a limited set of sectors and there is no evidence of their use in infrastructure projects (Chhipi-Shrestha et al., 2015; van Haaster et al., 2017). By contrast, multicriteria decision-making methods are commonly used for assessing construction projects. Social Multicriteria Assessment is an alternative to represent a multidimensional and participatory evaluation of social aspects (Munda, 2004, 2006). Jato-Espino et al. (2014) and Soltani et al. (2015) present a review of both methodological and participatory approaches in the infrastructure multi-criteria assessment. This method gives considerable flexibility to deal with interconnected aspects and complement other appropriate techniques to evaluate each social aspect. Some recent studies have presented methods to prioritize specific projects of sustainable infrastructures (Sierra et al., 2017a, 2017b). However, a methodology to generate socially sustainable alternatives in a macro-context still requires additional efforts.

Investment in public infrastructure should be justified by the social contribution in the short and long term. In a short-term approach, the early return of the social benefits of an infrastructure will only be possible in a developed geographical context (Gannon and Liu, 1997). By contrast, a long-term approach will promote the social development in those contexts lacking in opportunities. In order to clarify these two periods (short and long term), two real examples are used. First, the second Penang Bridge, with a length of 24 km, connects Batu Kawan on mainland Malaysia to Batu Maung on Penang Island (Yadollahi et al., 2015); after commissioning (short-term) there was evidence of accident reduction and a reduced noise level in the area, which previously had high traffic congestion. In the long-term, there was an improvement in equity accessing and using city services, and the surrounding area flourished economically. Second, the Dam “Urra 1” (Egre and Senecal, 2003), which affects 350 km along the Sinú River in the northwestern part of Colombia, impacts a local area with low public investment. In the short term, there were impacts on the activities of the fishermen and ethnic conflicts; in the long term, quality of life improved in the area due to the increased private investment, leading to social segregation and a change in lifestyle and identity. It is likely that the short and long-term approaches will not be simultaneous; i.e., the projects that involve early efficiency do not necessarily benefit the population groups that require major development. Therefore, the distribution of public benefits should endeavor to achieve equality in society (Foth et al., 2013; Delgado and Romero, 2016). In light of this, governments must consider the initial local conditions that interact with the project's characteristics in the prioritization of infrastructure projects. Accordingly, it is necessary to identify a series of infrastructure project alternatives which have an early return on social well-being and create development opportunities (Foth et al., 2013).

The literature regarding the social sustainability of infrastructure projects is limited. Valdès-Vásquez and Klotz (2013) propose a range of aspects to consider during the planning of an infrastructure project: user-centered design, environmental safety elements, communication with stakeholders, and contextual conditions, among others. In global terms, social criteria have been more clearly defined since the 1990s; the most prevalent criteria are those proposed by Labuschagne et al. (2005) comprising a social sustainability framework. Furthermore, a criterion requires the determination of certain attributes of the infrastructure and its location context defined as decision variables (Gervásio and Simoes da Silva, 2012). In particular, the social contribution of a set of decision variables will depend on the type of infrastructure and the contextual condition.

Technically, the number of decision variables and evaluation criteria may be too high. The problem is daunting when there are several possible states for each variable and criterion. Given the computer time and resources required, a conventional multicriteria analysis by itself does not provide a solution to the problem domain. Using the techniques of Bayesian reasoning, experts can generate a decision-making model (Chen and Pollino, 2012; Mkrtchyan et al., 2016). Participatory approaches have already employed Bayesian networks in sustainable decisions-making (Bertone et al., 2016; Mkrtchyan et al., 2016). In addition, Bayesian statistics have demonstrated advantages over classical inference in the analysis of efficiency in the water sector in Portugal (Carvalho and Marques, 2016).

This paper uses a model to represent the relations among the variables of the infrastructure and the location context, the evaluation criteria and the short and long-term social contribution (Gannon and Liu, 1997; Labuschagne et al., 2005; Foth et al., 2013). In particular, this study employs the potential of Bayesian networks to establish probabilistic relationships between the infrastructure characteristics and the criteria that contribute to short and long-term social sustainability. Used as a decision-making model, the network allows evaluation of the infrastructure based on its contribution to the social goal. The decision-making model is used to determine a number of alternatives for infrastructure projects (Chen and Pollino, 2012). Through optimization, decision-makers can concentrate on the best alternatives from the social sustainability viewpoint. These alternatives will be the most likely to satisfy social improvement in the short and long term. These considerations are the point of departure for this study. The research reported in this paper proposes a method to optimize infrastructure project alternatives by assessing their social contribution; this proposal takes into account the infrastructure's interactions with the local environment in terms of its potential contribution in the short and long term.

This paper is organized as follows: It begins with the introduction of the techniques of Bayesian reasoning. Then, there is a description of the proposed method in order to prepare the decision-making model, to evaluate its connections and to apply an optimization algorithm in the multiple-criteria model. The sequence of the Bayesian network development model is established through a case study. Finally, the conclusions of the paper are presented.

2. Bayesian networks applied to decision-making

Bayesian networks are a well-established graphical representation for encoding conditional probabilistic relationships among uncertain variables using Bayes’ theorem (Chen and Pollino, 2012). In the literature there are solutions to both environmental and