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Ranking the sustainability performance of pavements: An intuitionistic fuzzy decision making method

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ABSTRACT

In this research, we proposed a fuzzy multi-criteria decision making method which is applied for ranking the life cycle sustainability performance of different pavement alternatives constructed with hot-mix and warm-mix asphalt mixtures. This method consisted of four different techniques such as the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method to select the best pavement alternative, the intuitionistic fuzzy entropy method to identify the importance of phases and criteria, the intuitionistic fuzzy weighted geometric averaging operator to establish a sub-decision making matrix based on weights of attribute, and the intuitionistic fuzzy weighted arithmetic averaging operator to build a super decision matrix depending on weights of different life cycle phases. Based on research findings, a synthetic wax-type warm-mix asphalt additive is selected as the best alternative among the pavement alternatives. In addition, conventional hot-mix asphalt is found to be the second best option compared to other mixtures.

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1. Introduction

As a solution for sustainable pavement systems, warm-mix asphalts (WMAs) have gained a tremendous interest and are considered one of the most environmental friendly technologies for producing asphalt pavements [1]. WMAs have gained popularity in terms of its eligibility of being produced at a lower temperature thus cutting process energy by 30% [2]. WMA technology shows benefits for the environment because it produces asphalt at temperatures 20–40° lower in comparison to conventional hot-mix asphalt [3]. The reduced fuel consumption of mixing processes during the production of WMA mixtures also decreased the atmospheric emissions [4]. Although earlier reports show the significance of using different WMA mixtures towards achieving reduced energy consumption, a life cycle based assessment model will be vital for understanding the real benefits of WMA in pavement construction.

1.1. Life cycle assessment and triple-bottom-line

Life cycle assessment (LCA) is a well-established decision-making tool that aims to quantify the environmental impacts of a product or a process by including several life cycle phases such as raw material extraction and processing, manufacturing, use, and end-of-life. It primarily consists of goal and scope definition, inventory analysis, impact assessment, and interpretation of results [5]. Several applications of LCA are available in the literature to analyze WMAs [6,7]. The findings of these studies indicated that the emissions and energy consumption of the mixing process were decreased during the production of WMAs when compared to HMA mixture. Despite of the fact that previous studies have successfully quantified the environmental impacts of WMAs in terms of emissions and natural resource consumption, the role of the upstream supply chain during the production of asphalt binders, minerals, and fossil fuels used in the construction of WMA pavements, and related social and economic impacts associated with utilization of these resources were generally excluded in the LCA studies.

Among the LCA methodologies, economic input–output (EIO) analysis is widely used for analyzing the supply chain wide resource requirements and environmental impacts of products or systems [8]. EIO analysis was also integrated with the Triple-Bottom-Line (TBL) concept which covers all three dimensions of sustainability including environment, economy, and society [9]. In the literature, Foran et al. [10,11] integrated the EIO analysis with environmental, economic, and social metrics for 135 sectors of the Australian economy. These studies presented the first examples of the EIO framework which is combined with sustainable supply chain management concept. Later on, researchers of the Integrated Sustainability Analysis at University of Sydney developed a TBL sustainability accounting software for the Australia, United Kingdom, and Japan economies using detailed input–output tables.

In this paper, TBL-based sustainability accounting model results have been considered to evaluate the environmental, economic, and

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social impacts of pavement construction. The selection of pavements using the aforementioned sustainability metrics creates trade-offs between TBL indicators and Multi-criteria Decision Making (MCDM) method becomes a suitable solution where conflicting objectives exist. To improve the MCDM method and facilitate sustainable pavement selection process, the paper will use an intuitionistic fuzzy approach to represent decision maker's judgments which is used to evaluate the weights of different life cycle phases, sustainability indicators, and alternatives. This approach allowed us to mathematically represent the uncertainty and vagueness and reflect the decision maker's perception to decision making process. The following section presents the use of fuzzy-based MCDM models developed by other researchers.

1.2. Multi-criteria decision making using fuzzy sets

Intuitionistic fuzzy sets (IFSs), which are extension of the concept of fuzzy sets, are proposed by Atanassov. For instance, Atanassov et al. [12] discussed the reflection of intuitionistic fuzzy approach in the evaluation process of multi-expert and of multi-measurement tool MCDM. Liu and Wang [13] presented novel methods for solving MCDM problem in an intuitionistic fuzzy environment. The researchers also defined a series of new score and evaluation functions which measure the degrees of decision maker's requirements. In other research, Wei [14] studied the intuitionistic fuzzy MCDM with the information about criteria weights which are completely unknown or incompletely known, and introduced a maximizing deviation method-based approach. In addition, Boran et al. [15] proposed TOPSIS method that combines intuitionistic fuzzy set and IFWAA operator for supplier selection problems. In addition, Li et al. [16] proposed a new methodology for handling multi-attribute group decision-making problems using IFS with TOPSIS. In the method they developed, to decide the relative closeness coefficient intervals of alternatives, that are computed for the group to determine the order of all candidates, two auxiliary fractional programming models were generated from the TOPSIS by taking their optimal degrees of membership (based on the ranking method of interval numbers) into account. Several studies also used MCDM methods based on fuzzy environment. For example, Doukas et al. [17] presented MCDM method that has direct and flexible aspect to issue. The researchers used linguistic variables in their method, while policy makers determined and evaluated priorities of sustainable energy technologies. Jaber et al. [18] introduced a new method to select the best space heating systems in Jordan using fuzzy AHP method. Salah et al. [19] proposed a new fuzzy algorithm to decide domestic apparatus on either the electrical grid or photovoltaic panel (PVP). Wang et al. [20] presented fuzzy MCDM algorithm to evaluate the optimal cool storage system. They utilized entropy weighted method in their proposed method. Afshar et al. [21] proposed fuzzy MCDM process employing TOPSIS and fuzzy environment for water resource system.

Shaw et al. [22] introduced an integrated approach that consists of fuzzy AHP and fuzzy multi-objective linear programming methods to select the eligible supplier in the supply chain considering the carbon emissions. In another work, Nieto-Morote addressed the selection of an appropriate contractor by using fuzzy set theory [23]. Bridge construction methods were also studied from an MCDM perspective by using fuzzy AHP models [24]. Govindan et al. [25] developed effective fuzzy MCDM approach in supplier selection problem based on TBL impacts considering economic, environmental, and social aspects of sustainability. The researchers used linguistic values linked with triangular fuzzy numbers to reach objective expert judgment. In terms of construction materials, Akadiri et al. [26] proposed a fuzzy extended AHP model for building material selection problem from sustainability impacts point of view. Yeh and Xu [27] created a fuzzy MCDM algorithm in order to evaluate alternative e-waste recycling scenarios considering their TBL impacts.

1.3. Motivation and organization of the research

Sustainability science requires a futuristic vision that encompasses the life cycle of products and processes from a TBL perspective. TBL considers both positive impacts such as social and economic sides of such activities along with associated environmental burdens. While assessing sustainability performance of different products or processes, negative environmental impacts and socio-economics benefits become conflicting objectives during decision making period. Therefore, MCDM approaches become a very robust and necessary approach for such circumstances that can overcome issues associated with such tradeoffs. Since this study addresses sustainability assessment and ranking of pavement alternatives for the United States from a TBL perspective, an expert evaluation-based MCDM method is utilized. The hierarchical methodology is illustrated in Fig. 1. First, sustainability impact assessment of the four pavement alternatives is performed with the TBL-LCA model. Four life cycle phases including material extraction and processing, transportation of pavement materials and ready-mixtures, asphalt mixing process and construction of pavements were included within the scope. The use phase was excluded since pavement sections with equivalent performances were designed. Next, life cycle assessment results are evaluated by experts by using fuzzy linguistic terms. In the third step, a TOPSIS-based decision making analysis is performed for the ranking of pavement alternatives considering social, environmental and economic dimensions of sustainability. In the final phase, results of the third phase are analyzed, interpreted and discussed in terms of their potential contribution to sustainable development initiatives.

2. EIO model for sustainability accounting

The EIO analysis is a well-known model, which was theorized and developed by Wassily Leontief in 1970s, based on his earlier works in the late 1930s, for which he received the Nobel Prize [28]. The EIO analysis uses a top-down approach, which considers financial flows and interdependencies between sectors that form the economic structure of a country [29]. In this paper, industry-by-industry EIO model has been utilized [30]. Then, a vector of total sustainability impacts is formulated as follows:

$$r = E_{dir}\left[(I - DB)^{-1}\right] f \tag{1}$$

In Eq. (1), r is the total impact vector that represents total sustainability impacts per unit of final demand, and E_{dir} represents a diagonal matrix, which accounts for the direct TBL impact values per dollar of output, I refers to the identity matrix, and f is the total final demand vector for industries. In addition, B is the input requirements for products per unit of output of an industry matrix, and D is the market-share matrix. Also, the term $[(I - DB)^{-1}]$ represents the total requirement matrix, which is also known as the Leontief inverse and DB is the direct requirement matrix, which is denoted as A matrix in the Leontief's model [28,31]. For more explanation about the integration of the supply and use tables into industry-by-industry input–output model and calculation of the total environmental, economic, and social impacts, please see the reference paper published by [30].

3. Pavement systems and sustainability indicators

The types of WMAs analyzed in this research involve: Aspha-min® WMA, Evotherm™ WMA, and Sasobit® WMA. 10 in was taken as reference value for all four sections as a thickness of the base course layer. In the surface layer of the first three sections, Aspha-Min®, Sasobit®, and Evotherm™ WMA mixtures were used. A conventional HMA mixture was used in the fourth section. Pavement analyses were conducted using the Mechanistic Empirical

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