



A Hybrid Decision Tool for Site Selection of Construction and Demolition Waste (CDW) Facilities in Developing Countries

Jonathan Soto-Paz¹ · Angélica Hernandez¹ · Cristian A. Mejía-Parada¹ · Viviana Mora-Ruiz¹ · Wilson Hernández¹ · Francisco Luna-Guevara¹ · Miguel Casallas-Ojeda² · Brayan A. Parra-Orobio³

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Abstract

Construction and demolition waste (CDW) is a growing waste stream in the world. The implementation of the circular economy for its management requires decision-making tools based on multiple criteria to identify the most appropriate location for a CDW recycling facility. However, technical, economic, and social criteria do not have the same objectives. This research proposes a hybrid decision tool for site selection for CDW facilities in developing countries applying a multi-criteria analysis complemented by an economic evaluation. To accomplish this purpose, Geographic Information Systems (GIS), Fuzzy-Analytical Hierarchy Process (FAHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and Monte Carlo simulation were used to rank the potential facility sites. Three criteria and nineteen sub-criteria were considered and weighted by experts. The results showed that: i) the technical criterion (55%) predominated over the social criterion (45%), with CDW quality (14.9%) and social acceptability (14.2%) sub-criteria, respectively; ii) the Monte Carlo simulation evidenced the feasibility of CDW treatment facility with a 94% probability that the Net Present Value (NPV) will be greater than \$147,518. The results provide a theoretical basis for site selection of CDW management facility and tools for defining public policies for CDW utilization.

Highlights

- A hybrid decision tool was developed for CDW recycling facility location.
- 19 social, technical and economic sub-criteria were defined.
- The tool was validated with a case study based in Colombia.
- CDW quantity and operational costs have the greatest uncertainty about the NPV.
- Economic indicators show feasibility of CDW with an NPV of \$989,634.

Keywords Construction and demolition waste · Circular economy · Decision-making · Facility location · Multicriteria analysis · Uncertainty analysis

1 Introduction

Approximately 3 billion tons of construction and demolition waste (CDW) are generated worldwide each year (Akhtar and Sarmah 2018). The quantity and composition of CDW are variable around the world with rates that fluctuate between 18 and 842 kg per capita/year (Ding and Xiao 2014), with a mean of 600 kg per capita/year. The quantity is expected to increase particularly in developing countries (Asgari et al. 2017).

Frequently, CDW are dropped in final disposal sites such as landfills or open dumps and it is estimated that 35% of them goes to these sites (Duan et al. 2019; Kabirifar et al. 2020), even though 75% have potential added value (Purchase et al. 2022). The generation of materials such as steel or cement is responsible for between 10 and 12% of global greenhouse gases emissions, increased energy consumption, depletion of resources, and deterioration of water and soil quality (Nasir et al. 2017; Leising et al. 2018; Purchase et al. 2022). The implementation of circular economy (CE) contributes to optimizing the consumption of raw materials and ensures the value of materials throughout their life cycle during construction projects (Bilal et al. 2020).

Previous studies have proposed specific tools to improve the CDW management within the circular economy. Nevertheless, few studies have focused on the location of CDW facilities as the last link in the management of this type of waste (Li et al. 2022). Therefore, different tools have been proposed for the optimal geographic selection of CDW recycling facilities. For instance, traditional, heuristic, and meta-heuristic optimization algorithms are used, which mainly consider cost indicators that are a function of location, capacity, and number of CDWs. Liu et al. (2019) proposed a planning model based on dual-objective genetic algorithms that seeks to minimize treatment costs and environmental effects. Lin et al. (2020) proposed a robust multi-time location model that considers uncertainty in the generation of CDW. With a similar approach, Li et al. (2022) suggested a decision-making model for disposal facility location under the uncertainty of waste supply and unit transportation costs. Some of the studies that examine these approaches are considered inappropriate and ineffective for large-scale problem-solving. In addition, site selection requires an evaluation process to give priority of one site over another. In this sense, the selection of these locations should be approached considering multiple criteria.

Multi-criteria analysis (MCDA) tools can provide a complementary and systemic framework for a situation of interest. Moreover, they are useful when different criteria are in total/partial conflict that affects the multidimensional analytical decision framework and have the versatility to be articulated with tools such as GIS or economic indicators (Soto-Paz et al. 2019). MCDA is widely applied to locate transfer stations and landfills for municipal solid waste, although it has also been successfully applied for the selection of CDW management alternatives (Afshin et al. 2020) and in the selection of materials for building demolition processes (Zoghi et al. 2021). For example, Baniyas et al. (2010) used decision-making tools (i.e., ELECTRE III) for CDW transfer site selection in Greece, considering environmental, economic, and social criteria. Coronado et al. (2011) applied typical MCDA tools such as ELECTRE II (E2), Weighted Summation (WS) and Evamix (EV) to select the best CDW management alternative in Spain. They used economic (i.e., income, management costs), social (i.e., social acceptability), and environmental (i.e., atmospheric and noise pollution) criteria finding that the best alternative is recycling. Likewise, in Spain, Dosal et al. (2012) evaluated the location of a CDW recycling facility as an alternative using MCDA such as EV,

Weighted Summation, ELECTRE II, and Regime. Finally, Coelho and de Brito (2013), in Portugal, considered criteria for CDW quantity and transportation costs.

On the other hand, Khadivi and Fatemi Ghomi (2012) applied an integrated analytical hierarchy process (AHP) and data envelopment analysis (DEA) for the selection of CDW facility locations in Iran. Demesouka et al. (2013) highlight the importance of articulating a geographic information system (GIS) with multi-criteria that are generally in conflict; in addition, uncertainty is rarely considered when assigning weighting to criteria and sub-criteria that have an impact on decision-making. Araiza-Aguilar et al. (2019) proposed a tool that considers technical criteria applied to the AHP for the selection of a CDW recovery facility in Mexico combined with the weighted sum method. However, in several studies, the selection parameters cannot be given with precision due to subjectivity from the judgment of the decision-maker when is evaluating criteria. Therefore, it is necessary to implement tools that effectively reduce uncertainty in the face of managerial preferences and subjective data.

Among MCDA tools, Fuzzy-AHP (FAHP) has a flexible structure that includes a pairwise comparison of criteria items and sub-criteria expressed with triangular fuzzy numbers, which can avoid imprecision and uncertainty, and determine their degree of importance. On the other hand, the Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) prioritizes the alternative that is the shortest distance from the one considered ideal and the furthest from the negative ideal solution (Soltani et al. 2015; Aghajani Mir et al. 2016). TOPSIS has the advantage of being able to use the study's own data to prioritize alternatives. Together, the tools allow prioritizing criteria and selecting the best among a set of alternatives available in a region. In economic terms, there are several studies on CDW recycling facilities (Singh and Ordoñez 2016). However, Wang et al. (2021) indicate that the economic analyses are mainly applied in one city and do not explain the mutual influence of the construction and demolition industry among various cities in an area. In this sense, to select the most appropriate location for a CDW utilization and valorization facility, multiple aspects must be considered that generally have different objectives.

The Monte Carlo Simulation is a mathematical tool that allows estimating a set of possible results of a phenomenon that has uncertainty. Thus, from a set of fixed input values, the method uses sequences of random numbers to determine the probability of occurrence of a system value that one wants to study (Alves et al. 2020). This tool is useful in the decision process for the location of CDW utilization facility under conditions of uncertainty. Therefore, in this research, a procedure for selecting the location and economic feasibility of a CDW facility in developing countries is presented using the FAHP-TOPSIS and Monte Carlo Analysis approaches. The novelty of the article lies in the proposal for integration of tools that prioritize cross-cutting criteria and sub-criteria that have opposing objectives and weights defined by industry and academic experts considering the uncertainty, an aspect few addressed in the literature (Li et al. 2022). In addition, the selection of the alternative is carried out through the TOPSIS tool that considers the data of the case study, an aspect that in other investigations is left to the expert who does not necessarily know the study area in detail. Additionally, the tool is articulated with GIS to find potential location sites that are then prioritized with multi-criteria tools and current financial feasibility studies are for level three CDW facilities (i.e., large-scale, and highly mechanized) and few are considered in developed countries. Finally, to the authors' knowledge, studies implementing these multicriteria tools to locate CDW facility in developing countries are limited. Finally, the tool is validated in a real case carried out in Colombia and can be used in other countries. The paper is organized as follows: Section 2 presents the related criteria to evaluate the alternative to the location of waste recovery facilities. Then, the model purpose is given

in Section 3. Section 4 introduces the use of the decision tool for the case of Bucaramanga Metropolitan Area, Colombia. In Section 5, the discussion of the results is presented. Finally, concluding remarks are presented in Section 6.

2 Literature Review for the Definition of Criteria and Indicators

Even though the importance of proper CDW management is highlighted in the scientific domain, few reports propose tools that transversally consider multiple criteria to locate waste recovery facilities in a geographic region. The characterization of criteria was carried out in specialized databases such as Scopus® and Web of Science®. Keywords were used, such as: i) CDW and facilities and valorization; ii) Multicriteria analysis and CDW; iii) Multicriteria analysis and CDW facilities; iv) CDW and developing countries and facilities; v) circular economy and facilities and CDW. The feasibility of using keywords was verified with the ScienceDirect® “Browse Topics” (i.e., Thesauri) tool. The characterization of criteria was obtained from the analysis of a group of 15 articles indexed in the consulted databases.

The most cited criteria were: accessibility to the collection site (Coelho and de Brito 2013), quantity generated (Ding and Xiao 2014; Asgari et al. 2017; Rondinel-Oviedo 2021), distance to the final disposal site (Abdelhamid 2014), distance to water bodies and reserve areas (Shah 2021), land use (Ding et al. 2018), direct costs of recollection (Ghisellini and Ulgiati 2020; Lederer et al. 2020), cost of separation and operation (Jung et al. 2015), cost of equipment acquisition (Purchase et al. 2022), savings due to diversion to landfills (Doan and Chinda 2016; Hao et al. 2019), noise, offensive odours, atmospheric emissions (Purchase et al. 2022), social acceptability (Abdelhamid 2014), degree of stakeholder participation (Companies) (Rondinel-Oviedo 2021). These criteria were grouped into clusters using Ward’s method with the SPSS® software, as shown in Fig. 1. The information was condensed into a screen plot that identifies the relationship between the keywords (i.e., criteria) (Gil et al. 2018). The proximity between the words indicates a higher correlation.

According to Fig. 1, three clusters are distinguished corresponding to aspects of a technical (red cluster), social (blue cluster), economic (purple rectangle), and environmental (green rectangle) type. In this study, the use of technical (red color) and social criteria is proposed (blue color). The environmental criterion, being dependent on the technician, is not considered directly in the tool, because when locating the CDW utilization facility with the same technology and at minimum distances to water sources, in urban and rural areas, the environmental impact is similar. In this case, the effect of the wind direction is not considered and is considered a limitation of the study. Likewise, the economic criterion is used as a complementary indicator of the technical and social criteria due to its influence on decision-making in developing countries as a “dictating criterion” (Soto-Paz et al. 2019). The description of criteria and indicators is given below:

2.1 Technical Criteria (C1)

These correspond to a multi-objective criterion that seeks to maximize or minimize distances, and establish accessibility (that is, road conditions) to the site, and land use, among others. However, alternatives generally do not meet all these sub-criteria. Therefore,

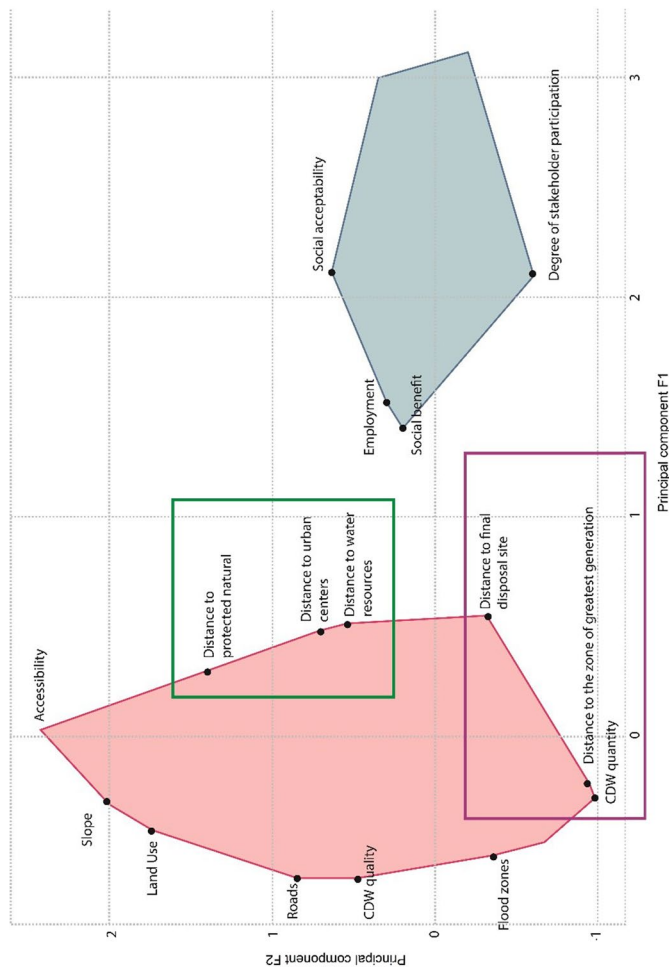


Fig. 1 Clusters identified for the definition of criteria and sub-criteria

cross-sectional comparisons between criteria, sub-criteria, and alternatives allow for determining the best location of exploitation facilities.

2.1.1 Accessibility (STC1)

Accessibility corresponds to the state of the roads where the vehicle will travel with the CDW to the potential facility location (i.e., alternatives) (Coelho and de Brito 2013). The roads can be primary, secondary, and tertiary roads that allow movement without the risk of the vehicle overturning due to instability. Therefore, the alternative to select should ideally have the best state of the roads and the closest to them (i.e., it is required to minimize the distance). Therefore, we propose a scale from 1 to 5, to give a quantitative grade to the evaluated alternatives:

- If the access road is less than 100 m: 1
- If the access road is between 100–1,000 m: 3
- If the access road is greater than 1,000 m: 5

2.1.2 Distance to the Zone of Greatest Generation (STC2)

The distance to the area with the highest generation of CDW is a relevant sub-criterion for the operation of the installation. It is required that the installation be as close as possible to the potential generation points without having to resort to mobile exploitation facilities (Li et al. 2022). The alternative to being prioritized must provide a sufficient and continuous flow of CDW. This contributes to the financial sustainability of the plant (Hao et al. 2019).

2.1.3 CDW Quality (STC3)

CDWs are required to be of the highest possible quality. According to Robayo-Salazar et al. (2020), the CDWs can be classified as usable (i.e., uncontaminated materials) and non-usable waste (i.e., CDWs contaminated with hazardous wastes, so their use is restricted by environmental regulations). This classification is adopted in Colombia and is taken in other contexts as a quality criterion for CDWs (Asgari et al. 2017; Rondinel-Oviedo 2021). However, highly mixed CDW affects the quality of the recycled products and requires more complex separation techniques (Galán et al. 2019). More separation of the CDW is ideal to improve its transformation into valuable products. Therefore, we propose a scale from 1 to 5, to give a quantitative grade to the evaluated alternatives:

- If CDW is mixed with hazardous waste: 1
- If CDW is not mixed with hazardous waste: 5

2.1.4 Distance from Water Resources Bodies (SC4)

A minimum distance must be maintained from water bodies (i.e., underground and surface) that may be susceptible to contamination in the event of a failure in the operation of the utilization facility (Shah 2021). For this sub-criterion, the minimum distance to be considered from the water source is 30 m or that indicated in the regulations of each country, for which the greater distance generates positive effect to locate the exploitation facility (Chen et al. 2021).

2.1.5 Distance to a Final Disposal Site (STC5)

The recovery facility must be close to the final disposal site to transport the discarded CDW to be transformed into a valuable product. Therefore, the facility must be close to the disposal site (Hao et al. 2019).

2.1.6 Reserve Areas (STC6)

Reserve zones correspond to protected areas such as natural reserve zones or cultural heritage zones (Shah 2021). The selected alternative must be far from these areas and guarantee the minimum proximity distances required by regulations. The minimum distance depends on the regulations of each country. The minimum distance adopted is 5 km, although the greater this distance, the more favorable it is to locate the waste recovery facility.

2.1.7 Land Use (STC7)

Land use is a key sub-criterion that helps define the location of the facility (Ding et al. 2018). This criterion is used to exclude land areas with significant socio-economic values, including agricultural lands, but the exploitation facility could be in areas such as grassland and barren land. This sub-criterion is verified with land use maps defined by authorities and is classified as suitable and unsuitable. Additionally, it is considered that the further away (i.e., at least 5 km) the exploitation facility is in the urban area, the better it is. Therefore, use and land cover in the study area were reclassified as unsuitable areas and highly suitable.

2.2 Social Criterion (C2)

It is a transversal multi-objective criterion that seeks to maximize the benefits it offers to the population and industry within the framework of the circular economy. It is made up of the following sub-criteria.

2.2.1 Social Acceptability (SSC9)

The location of the utilization facility must have the social acceptance of the community settled in proximity to it. Here a positive effect is considered if the food accepts the installation at a distance defined by the regulations of each country. In contrast, an adverse effect is considered if the community opposes the location of the waste recovery facility (Abdelhamid 2014). Therefore, it is considered an undesirable condition. We propose a scale from 1 to 5, to give a quantitative grade to the evaluated alternatives:

If people accept the plant at a distance equal to or greater than 5 km: 5

If people disagree with the location of the plant: 1

2.2.2 Degree of Stakeholder Participation (SSC10)

It refers to the participation of industries in the process of purchasing recycled materials that contribute to industrial symbiosis (Rondinel-Oviedo 2021). Likewise, it contributes to the circular economy. The alternative to prioritizing must consider the locations of the

companies and their interest in acquiring a valued product. Because the reincorporation of recycled materials is key in the CE (Hossain et al. 2020), the acceptance of construction industries close to the installation of taking advantage of the potential purchase of the product is essential. We propose a scale from 1 to 5, to give a quantitative grade to the evaluated alternatives:

The construction industry agrees to purchase a fraction of the recycled material from CDW: 5

The construction industry is not interested in buying recycled material: 1

3 Description of the Bi-stage Hierarchical Decision Model

The conceptual decision model contemplates four phases: i) Definition of criteria, sub-criteria, and alternatives; ii) Prioritization of alternatives with FAHP-TOPSIS; iii) Validation tool; iv) Economic evaluation. The economic analysis is carried out independently of the MCDA because the economic criterion is generally used in developing countries as the main one for decision-making. For this reason, it is considered a dictating criterion that can bias the process (Soto-Paz et al. 2019). In the first stage, GIS-FAHP and TOPSIS are used. The integration of both tools generates a ranking of alternative priorities from a technical and social perspective. In this study, the best alternative corresponds to the best location of the waste recovery facility. Subsequently, the economic analysis is carried out with cash flows and Monte Carlo simulation. Therefore, the decision model is of the hybrid type. Figure 2 shows how the decision model is conceptually constituted.

3.1 Definition of Criteria, Sub-criteria and Alternatives

The criteria and sub-criteria were evaluated by a group of 13 experts considering that the group of these should not be greater than 30 (Soltani et al. 2015). The experts were from Austria, Canada, Spain, Greece, Netherlands, United Kingdom, Colombia, Brazil, Mexico, India, and Taiwan. They were recognized in the scientific environment, government organizations and industries dedicated to the transformation of CDW into valuable products and consultants. The selection of each expert was made following the methodology of Tsyganok et al. (2012) which considers experience and knowledge on the subject as indicators. The use of experts has been widely documented in decision-making and municipal solid waste management processes, but it is scarce in the CDW issue.

The Fuzzy-AHP determined the weight of criteria and sub-criteria. The experts compared the criteria and sub-criteria in pairwise comparisons. The measurement scale was based on Saaty and was associated with a fuzzy triangular number (Eq. 1):

$$\mu_A = \begin{cases} (x-l)/(m-l); & l \leq x \leq m \\ (v-x)/(v-m); & m \leq x \leq v \\ 0; & \text{in other cases} \end{cases} \quad (1)$$

where μ_A is membership function; x , l , m and v are fuzzy parameters. Then, the geometric mean of each assessment provided by the experts through a survey consolidated the matrix P (Eq. 2):

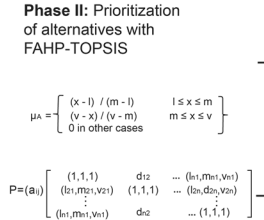
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Table 1 Fuzzy- AHP scale for pairwise comparisons of criteria and sub-criteria

Linguistic description of the variable	Fuzzy Numbers
Without preference	[1,1,2]
Moderate preference	[1,2,3]
Strong preference	[3,4,5]
Very strong preference	[5,6,7]
Full preference	[7,8,9]

$$P = (\alpha_{ij}) \begin{bmatrix} (1, 1, 1) & d_{12} & \dots (l_{n1}, m_{n1}, v_{n1}) \\ (l_{21}, m_{21}, v_{21}) & (1, 1, 1) & \dots (l_{2n}, d_{2n}, v_{2n}) \\ \vdots & \vdots & \ddots \vdots \\ (l_{n1}, m_{n1}, v_{n1}) & d_{n2} & \dots (1, 1, 1) \end{bmatrix} \quad (2)$$

Where P is fuzzy matrix; l , m and v are fuzzy parameters. The numbers 1, 3, 5, and 7 represent intermediate values, and the values 2, 4, 6, and 8 indicate a range from strong to low influence on another criterion, as presented in Table 1. The solution to finding the respective weights of the matrix P is done through Buckley's method to obtain a priority vector.

Equation (3) determines the consistency index (CI) estimate of the consistency of the pairwise comparison of the experts. In addition, the consistency ratio (CR) was quantified considering a value less than 0.1 as an acceptability criterion (Eq. 4):

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (3)$$

$$CR = \frac{CI}{IA} \quad (4)$$

where λ_{max} is the eigenvalue, n corresponds to the size of the matrix P and IA is the random index that also depends on the dimension of the matrix. Table 2 shows the weight of each criterion and sub-criterion.

The alternatives were defined from GIS considering potential sites with similar probabilities of being selected. For this, a pre-selection of alternatives was made overlapping shapefiles of land use, water sources, areas of instability due to landslides, and transit routes.

3.2 CDW Estimation and Data Collection

To estimate the amount of CDW, the tool considers information available from the government and private sources in the study area. It is recognized that the CDW generation rate is different among cities. In Colombia, official reports of the amount of CDW can be found on the official platform of the National Public Procurement Agency (known by its acronym in Spanish as SECOP). In this Platform, it is possible to extract information associated with CDW components from estimates based on the type of work built or demolished. Contracts with dates older than 2010 were sought. Priority was given to waste composed mainly of

Table 2 Weights of criteria and sub-criteria assigned by the panel of experts

Criteria	Weight of Criteria (%)	Sub-criteria	Weight of Sub-criteria (%)
Technical	55	CDW quantity	14.89
		Distance to the zone of the greatest generation	14.55
		Accessibility to the site where the plant will be located (roads, slope)	10.09
		Distance to final disposal site	6.29
		Distance to water resources	7.77
		Land Use	5.76
		Distance to urban centers	8.03
		Distance to protected natural areas	7.61
Social	45	Social acceptance	14.16
		Stakeholders' (Companies) participation	10.92

The value of $\lambda(\max)_{\text{average}}$ obtained by resolving the P matrix was 0.07 in both cases. Therefore, the CI was ≤ 0.1

stone, asphalt and clay aggregates that had an opportunity for reuse. The amounts reported are the product of explicit data in the contracts. In the case of other developing countries, it is possible to replicate. Here it is considered that the amount generated available in a geographic region corresponds to the sum of all the components of the CDW affected by a waste factor (F_r) due to the mixture of the waste that makes it difficult to fully use it (i.e., it was assumed between 10 to 15%) and an availability factor (F_d). In this study, the values of F_d of 0.95 are considered for areas where there is exploitation facility, 0.8 in places where there are collection centers that divert the flow of waste directly to landfills at distances, and 0.5 for regions whose distance is greater than 25 km from the plant, which could increase operating costs. On the other hand, the amount estimated in this study does not consider the excavated soil. The values of CDW_k are determined in the field (private sector) and from official information from government entities. Equation (5) presents the CDW estimation model adapted from other studies (Llatas 2011):

$$CDW_g = \sum CDW * F_r * F_d \quad (5)$$

where CDW_g is the global estimated amount of CDW; CDW corresponds to the different types of CDW generated (i.e., inert and organic material); F_r is the waste factor; and F_d corresponds to the availability factor. With the estimated amount of CDW, a heat map was created with the estimated amounts at different points of generation. Then, a neighborhood analysis is applied within the GIS environment for the analysis of the geographical dispersion of the CDW and the index of dispersion of residuals (IWD) is analyzed.

3.3 Influence of Weights of Criteria and Indicators on the Prioritization of Alternatives with the Hybrid Model FAHP-TOPSIS

The percentage evaluation of the criteria, sub-criteria and the characteristics of the alternatives are compared by pairs through the TOPSIS tool. Initially, the information of each

criterion and sub-criterion is normalized through the unit vector method (Eq. 6) in a range [0,1]:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}}; j = 1, 2, 3, \dots, n; i = 1, 2, 3, \dots, m \quad (6)$$

where r_{ij} is the normalized value of alternative i corresponding to criterion/sub-criterion j . Then, the distance to an optimal point (i.e., ideal solution or alternative) that is far from the Ideal Negative Solution (INS) and close to the Ideal Positive Solution (IPS) is determined. For each alternative, the calculation of INS and IPS is performed (Eqs. 7 and 8):

$$\{V_i^+ \dots V_n^+\} \{maxv_{ij}\}; j = 1, 2, 3, \dots, n \quad (7)$$

$$\{V_i^- \dots V_n^-\} \{minv_{ij}\}; j = 1, 2, 3, \dots, n \quad (8)$$

where V_{ij}^+ and V_{ij}^- correspond to the positive and negative ideal solution, respectively, of alternative i of criterion/sub-criterion j ; $maxv_{ij}$ corresponds to the criteria to maximize. For example, the distance to water sources and natural reserve areas seeks to be maximized because the CDW facilities must be as far away as possible. It is also desired to maximize the quality of the CDW and the distance from residential, commercial, or institutional sites (i.e., land use), the social acceptability, and the degree of stakeholder participation. In contrast, $\{minv_{ij}\}$ corresponds to the criteria to minimize, such as distance to the landfill, distance to the zone of the greatest generation, and road accessibility. Subsequently, the ideal positive (D^+) and negative (D^-) distance is calculated for the ij alternative (Eqs. 9 and 10) concerning the ideal solution (i.e., optimal point) that is close to the IPS and withdrawal from the INS:

$$D_i^+ = \left(\sum_{j=1}^n (v_{ij} - v^+)^2 \right)^{0.5}; i = 1, 2, 3, \dots, n \quad (9)$$

$$\{V_i^- \dots V_n^-\} \{minv_{ij}\}; j = 1, 2, 3, \dots, n \quad (10)$$

$$C_i = \frac{D_i^-}{D_i^- + D_i^+}; i = 1, 2, 3, \dots, n \quad (11)$$

where D^+ and D^- correspond to the positive and negative ideal distance; v_{ij} correspond to alternative set $\{V_1^+V_2^+V_3^+ \dots V_n^+\} \{maxv_{ij}\}$ $i=1$ or $\{V_1^-V_2^-V_3^- \dots V_n^-\} \{minv_{ij}\}$ $i=1 \dots m$ that identify the positive or negative ideal solution, and C_i is the relative closeness to the ideal solution. Finally, the alternative with the smallest distance from the optimum and the largest distance from INS is prioritized (Eq. 11). Therefore, a ranking of priorities is obtained at a technical and social level.

3.4 Characterization of Recycled Aggregate

The decision tool considers the characterization of the recycled aggregates from the transformation of the CDW once the geographical location of the installation has been selected. The characterization is carried out to determine the possible quality of the recycled material and its reincorporation into the supply chain and use them in more precise applications.

The CDW composition is determined by the Spain Normalization EN-933-11:2009 (2009). The parameters considered are: i) water absorption, where the sample is immersed in water for 24 h following ASTM C127 (2012); ii) density measured according to ASTM C29/C29M (2009); and iii) abrasion through the Los Angeles machine determined with ASTM C131 (ASTM 2006).

3.5 Economic Evaluation

The economic evaluation is carried out with the free cash flow methodology using indicators such as: i) net present value (NPV); ii) operating cash flow (OCF); and iii) minimum rate of return (OCF) (Hoang et al. 2021). In this study, the life of the project is 15 years and a Rate of Return (RR) of 8%. These indicators were applied to four proposed management scenarios: i) 90% of the recycled CDW income (i.e., optimistic scenario); ii) 50% of the recycled material income (i.e., moderate scenario); and iii) all at final disposal (i.e., pessimistic scenario). The scenarios are proposed and adapted from Souza et al. (2022). In all cases, it is assumed that a fraction of the material is not recyclable. The economic evaluation included the risk assessment of the project through Monte Carlo simulation (MCS) with the @Risk software trial version. On the other hand, the MCS was applied to estimate the probability of producing results considering the uncertainty of the generated amount of CDW, income, and expenses.

The input parameters considered correspond to the cost of acquisition (CAPEX) (Souza et al. 2022), operating costs (OPEX), the annual increase in labor costs, cost of infrastructure and machinery (Coelho and de Brito 2013), and transportation cost based on the concept of impedance determining the Euclidean distance between the generation point to the approach facility (Soto-Paz et al. 2019), number of operators, income tax rate, average inflation long-term and depreciation period (Oliveira Neto et al. 2017). As output parameters, indicators such as the value of the final product (Sheikh and Shah 2021), Earnings Before Interest Taxes Depreciation and Amortization (EBITDA), Earnings Before Interest and Taxes (EBIT), Net Profit After Taxes (NOPAT), Cash Flow from Operations (OCF) and Free Cash Flow. Each of these parameters is described in Table 3.

4 Validation of the Decision Model in the Colombian Context

The tool was validated in the metropolitan area of Bucaramanga, Colombia. This region was considered due to the availability of data registered in the public contracting agency SECOP on the amounts generated from CDW. The validation of the decision tool is developed in the following phases:

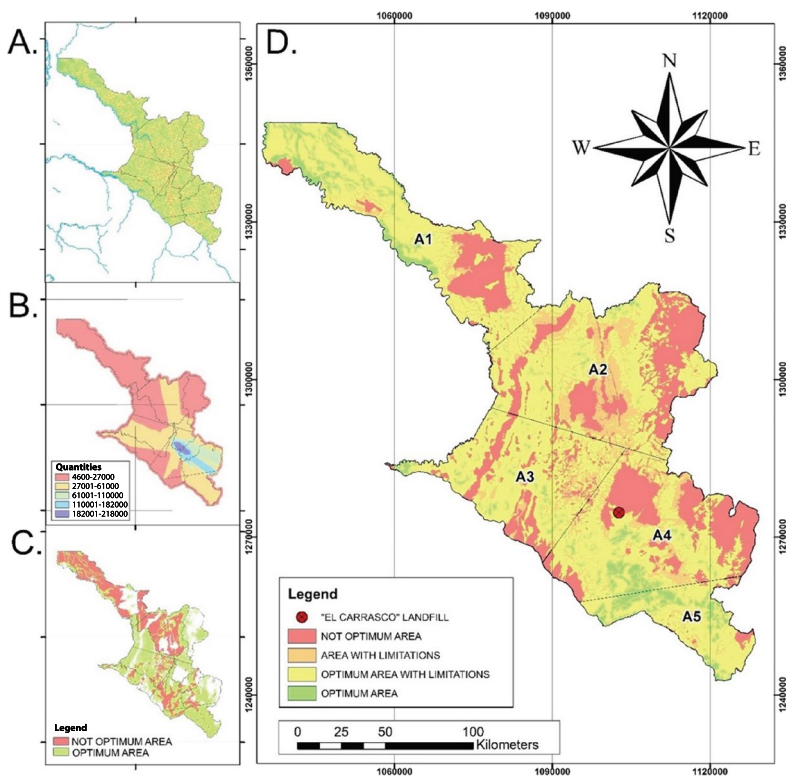
4.1 Phase I: Study Area and Selection of Information

The study area corresponds to the metropolitan area of Bucaramanga, Colombia, made up of the cities of Bucaramanga, Floridablanca, Piedecuesta, and Girón. The population in the metropolitan area is approximately 1,341,694 inhabitants. The region leads the industrial development of the department of Santander, characterized by the construction of buildings, updating of its road network, and incursion into the circular economy policy. Information was collected on land use, the water network, and roads, and digital maps (shape-file) were prepared from cartographic information from the Agustín Codazzi Geographical

Table 3 Equations used for economic evaluation

Expression	Equation
$I = PF \left(\frac{t}{\text{year}} \right) * PV(t)$	(12)
$OPEX = \left(\left(SA \left(\frac{s}{\text{month}} \right) * ON * \% \text{ working day} \right) \left(SS \left(\frac{s}{\text{month}} \right) * \% \text{ working day} \right) \right) * MS$	(13)
$\delta_{ij} = d_{ij} / v_{ij}$	(14)
$EBITDA = I - OP$	(15)
$\text{Depreciation} = \frac{\text{Infrastructure cost} + \text{Cost of machinery and equipment}}{\text{Depreciation period}}$	(16)
$EBIT = EBITDA - \text{Depreciation}$	(17)
$NOPAT = EBIT - TAX$	(18)
$OCF = NOPAT + \text{Depreciation}$	(19)
$\text{Investments} = \text{Infrastructure} + \text{Machinery and equipment}$	(20)
$FCF = OCF - \text{Investments}$	(21)

I: Income; PF is the amount of product obtained from the recycling of CDW; PV is sale price; SA: workers' salary; ON: operators numbers; SS is the salary of the supervisor; MS is months worked; OPEX is personnel operating costs; δ is impedance to move from site i to site j; d_{ij} corresponds to the distance between site i to site j; v_{ij} is the average speed (km/h) to travel from site i to site j; FCF is free cash flow

**Fig. 3** Cartographic information of the Metropolitan Area of Bucaramanga. **A** Water sources. **B** The amount of CDW generated. **C** Land uses. **D** Alternative selection map

Institute (IGAC) at a scale of 1:100,000 (Fig. 3). The maps were built with ArcGIS 10.4.1 software. The projected coordinate system of the MAGNA Colombia Datum in the Bogotá city was used. With the information from each map, restrictions were considered such as: i) minimum distances to water sources of 30 m (greater distance was considered as a positive effect to locate the exploitation plant); ii) proximity to tertiary road networks of less than 100 m (the greater the distance, the less desirable a place to install the plant); and iii) land use oriented towards pastures with no commercial value. Each of the maps with the potential sites defined following the restrictions was overlapped in a single map shown in Fig. 3D. The areas in green color were considered as optimum places. Therefore, the points in green represent the alternatives (A1, A2, A3, and A4) to consider. These areas were considered as alternatives for further evaluation with Fuzzy-AHP-TOPSIS. In contrast, red areas do not meet any of the preselection criteria set. In the yellow zones, show potential for selection, however, they present restrictions regarding some of the criteria considered.

4.2 Phase II: Estimation of the Amount and Composition of CDW Generated

There is no standardized procedure to quantify CDW generation in Colombia. The amount of CDW in the metropolitan area of Bucaramanga was estimated based on reports SECOP for the last ten years (i.e., 2012–2022) and private companies distributed throughout the country study area through systematic direct interviews with construction supervisors at generation points (Supplementary Material (SM), Table SM1). This study did not include CDW from maintenance and renovation of roads, not declared or registered.

Figure 3B shows the geographic distribution of different CDW generation points during 2021. The intensity of the color indicates the potential average income flow to the waste recovery plant in t/year. The average quantity in the Metropolitan Area of Bucaramanga between 2012 and 2022 was 24,738.2 t/year, lower than that reported in cities such as Shanghai, which are characterized by strong industrial development (Wang et al. 2021), and in Rio Branco Brazil with mean values of 159,300 t/year (Souza et al. 2021). On the other hand, highly concentrated areas and some scattered areas of CDW generation were observed. The largest CDW amounts were concentrated (i.e., 162,950–217,398 t/year) in the area close to the A4 and A5 alternatives, and to a lesser extent, the A3 and A2 (457–27,681 t/year). Likewise, the proximity to A4 and A5 means low logistics and transportation costs. The results are similar to those reported by Wang et al. (2021), who indicate that cities with a developed industrial chain drive the construction of surrounding cities. However, the values reported here are conservative and must be calculated for each case study accurately to generate reliable estimates.

Figure 4 shows the quantity and composition of CDW in the study area. According to the SECOP results, there was a predominance of road construction works, commercial (29%), and low-income and high-income housing (25.6%). These results were consistent with the interview conducted at different generation points in the private sector. The results are similar to those reported in the European Union, where 85% of the CDWs correspond to concrete, ceramics, and masonry (Gálvez-Martos et al. 2018), and to those reported by Ajayi et al. (2017) in China, where 50% of the CDWs are from the construction of new buildings.

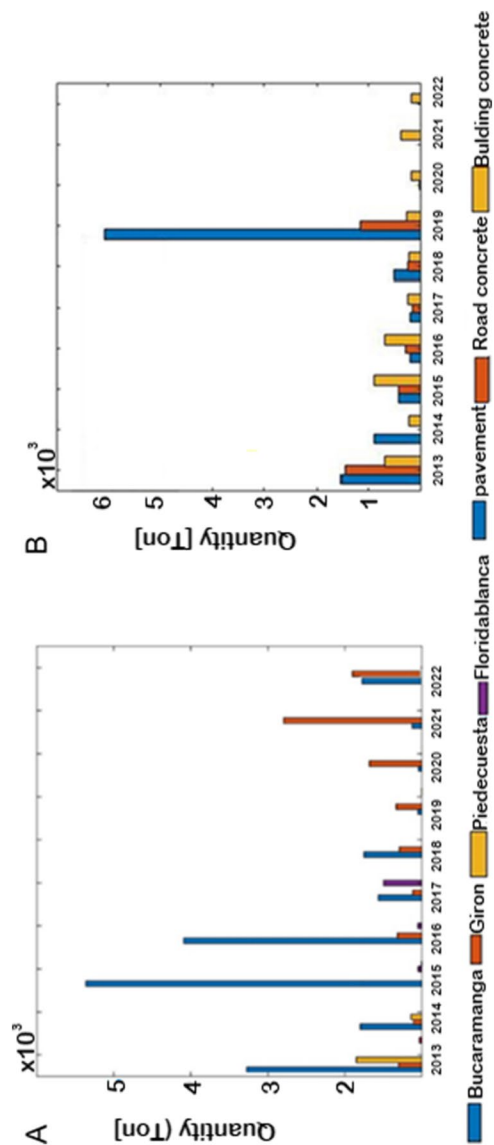


Fig. 4 A CDW amount over time for the study area. B CDW composition in the study area

Table 4 Selection of optimal site facilities based on technical and social criteria

Criteria	CDW quantity	Distance to the zone of the greatest generation	Accessibility	Distance to final disposal site	Distance to water resources	Distance to protected natural areas	Land use	Social acceptance	Stakeholders participation	D ⁺	D ⁻	Ri
A1	0.21	0.79	0.45	0.97	0.60	0.31	0.15	0.34	0.22	0.13	0.03	19%
A2	0.23	0.44	0.45	0.09	0.44	0.47	0.15	0.34	0.22	0.11	0.07	41%
A3	0.43	0.36	0.45	0.04	0.39	0.16	0.15	0.57	0.22	0.10	0.08	47%
A4	0.60	0.20	0.45	0.11	0.49	0.52	0.60	0.34	0.22	0.08	0.11	58%
A5	0.60	0.13	0.45	0.18	0.23	0.62	0.75	0.57	0.89	0.03	0.13	82%

The values reported in the criteria table correspond to those of the weighted matrix. D⁺: ideal distance positive; D⁻: ideal distance negative; Ri: ranking of priorities

4.3 Phase III: Implementation of the Decision Model

Table 4 shows the results of the evaluation of the alternatives with the hybrid tool (SIG-Fuzzy-AHP-TOPSIS) considering the weights given to criteria and sub-criteria by the experts (Table 2). The alternative that obtained the highest score in the ranking of priorities corresponds to the best option among the alternatives considered. The A5 alternative took first place in the ranking due to its proximity to the area with the highest generation of CDW, greater distance from water sources, land use oriented towards grassland, social acceptance, and the existence of construction industries with potential interest for the purchase of recycled material.

According to Li et al. (2022), the lesser proximity to the CDW generation points may favor the economic viability of the exploitation facility. Therefore, the A5 location offers greater economic advantages over the other alternatives. Regarding alternatives A3 and A4, the lowest score in the priority ranking was associated with the distance to the generation points, and therefore, their accessibility to greater amounts of CDW. This is because both sub-criteria had the highest weights among the technical criteria. In the case of Alternatives A1, A2, and A3, in addition to the limitations regarding the generation points, social acceptance was one of the sub-criteria that affected the decision process. This is associated with the resistance of some industries to the purchase of recycled CDW. This last aspect is key since the main documented obstacles are the participation and relationship of the actors involved (Leising et al. 2018). Schiller et al. (2019) explain that the articulation of the actors is key to prolonging the useful life of materials or their subsequent use.

4.4 Phase IV: Characterization of Recycled Aggregate

The study considered a representative sampling of works in the study area. The places were selected due to the availability of taking a defined sample from the interview carried out with the construction supervisors. Samples were taken from stationary containers where CDWs were stored 80 kg of random samples were taken inside the containers. The CDWs were manually classified according to the type of material following Spain Normalization EN-933-11:2009 (2009). In the CDW composition, materials based on concrete (45%), masonry (38%), ceramics such as tiles (15.6%), and others (1.4%) were predominant. Similar results are reported by Souza et al (2022) in Brazil. Investigations carried out document obtaining the recycled aggregate from crushed concrete waste. Phyco-mechanical characteristics showed that the percentage of water absorption was $3.2 \pm 0.5\%$, a value lower than that recommended by American Society for Testing and Materials (ASTM C127) (ASTM 2015). This result excludes the use of the fine fraction due to its interference, its greater absorption capacity, and the potential presence of impurities that reduce the quality of the recycled concrete. On the other hand, the values found here are similar to those indicated (i.e., between 3.7% and 7.1%) by Agrela et al. (2011) and indicate that the ratio of pores and voids is adequate, which increases the quality of the aggregates. Like water absorption, saturated surface dry density is another key property that defines aggregate quality. The mean density was $2,310 \pm 39 \text{ kg m}^{-3}$ and differed from that reported in other studies that indicate values between $1,340 \text{ kg m}^{-3}$ and $2,400 \text{ kg m}^{-3}$ (Zaetang et al. 2016). On the other hand, in Los Angeles, abrasion was $37 \pm 2.5\%$, a value lower than that reported (i.e., 43.3%) in other studies (Souza et al. 2021). The results found indicate that the recycled material may be suitable for

reincorporation into the supply chain. Among the potential uses, is its mixture with natural aggregates for the manufacture of concrete, in at least 60% by mass of the total mixture, to be used as subbase of highways and rural roads (Xu et al. 2022).

4.5 Phase V: Economic Evaluation

The utilization CDW facility considered in this study will be of Level 2 because it will receive a complete mixture of CDW and will include crushing machines, screens, screens, and conveyor belts. The plant will have a capacity of 72 ton/day. Due to the CDW composition, the products that can be obtained are diverse and the applications are focused on the geotechnical level, pipe bed, asphalt concrete, vitreous materials, and concrete blocks (Alexandridou et al. 2018). The recycled aggregate is expected to have a sale price of \$7.0/ton, a value that corresponds to 70% of the average value of virgin aggregates in Colombia, and which corresponds to the percentage suggested in facilities in developing countries (Hoang et al. 2021). The sale price adopted is similar to that proposed between 2013 and 2021 in other investigations (i.e., \$4.8 – \$6.7/ton) (Coelho and de Brito 2013; Souza et al. 2022).

The annual growth rate for labor costs was taken by the increase in the minimum wage for the year 2022 (i.e., 10.1%) and the long-term average inflation was determined by the growth of inflation from June 2021 to June 2022 (i.e., 4%). This same percentage was used for the increase in sales prices. The costs of infrastructure, machinery, equipment and operating costs were based on other studies (Hoang et al. 2021), considering expenses to adapt the infrastructure to its operation. The entry value for machinery and equipment was obtained from the sum of the purchase of a shaker, conveyor belt, collection vehicle, floor scale and others reported in the literature (Oliveira Neto et al. 2017). Along with the cost of machinery and equipment, the depreciation period of 20 years was taken into account. The operating costs were estimated considering the salary of the operators and administrative staff in Colombia. Table 5 presents the results of economic viability.

Regarding the optimistic scenario, the MCS showed that the NPV is positive in cash flow during the projected time threshold. The NPV was \$989,634 with a 95% probability of this value occurring. The results were found to differ from those reported by Souza et al (2022) who indicate an NPV of 11.67 million dollars. The difference between the two studies can be associated with the scale of exploitation facilities considered. Likewise, when considering that the CDW is no longer taken to final disposal sites, an approximate saving of \$6,030,000 would be incurred at the end of the projected period. Therefore, the results found suggested that the use and valorization of CDW are technically and economically viable. Regarding the moderate scenario, the MCS showed that there is a 94% probability that the NPV will be greater than \$147,518. These results are consistent with those indicated by different authors (Coelho and de Brito 2013; Souza et al. 2022), who indicate that even under these conditions, the waste recovery installation continues to be profitable. In these cases, greater government support is required to guarantee financial sustainability and an alternative would be through the savings generated by sending the material to the landfill.

5 Discussion of Results

The decision tool showed that the technical criterion (55%) is considered more relevant than the social one (45%). This result is consistent with what has been indicated in recent research where the amount of CDW and logistical aspects such as the proximity of recycling facility to construction sites and the market for recovered products are the focus of interest. However,

Table 5 Results of the economic evaluation for the proposed scenarios

Scenario	Indicator	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Optimist	Income	\$155,851	\$160,830	\$165,985	\$171,296	\$176,778	\$182,435	\$188,273	\$194,298	\$200,515	\$206,932	\$213,553	\$220,387	\$227,439	\$234,717	\$242,228
	Operating costs	\$7,200	\$7,625	\$8,075	\$8,551	\$9,056	\$9,590	\$10,156	\$10,755	\$11,389	\$12,061	\$12,773	\$13,527	\$14,325	\$15,170	\$16,065
	EBITDA	\$148,651	\$153,213	\$157,910	\$162,745	\$167,722	\$172,845	\$178,117	\$183,543	\$189,126	\$194,870	\$200,780	\$206,860	\$213,115	\$219,548	\$226,164
	Depreciation	\$38,667	\$38,667	\$38,667	\$38,667	\$38,667	\$38,667	\$38,667	\$38,667	\$38,667	\$38,667	\$38,667	\$38,667	\$38,667	\$38,667	\$38,667
Moderate	EBIT	\$109,984	\$114,547	\$119,244	\$124,079	\$129,056	\$134,178	\$139,450	\$144,876	\$150,459	\$156,203	\$162,114	\$168,194	\$174,448	\$180,881	\$187,497
	OCF	\$148,651	\$153,213	\$157,910	\$162,745	\$167,722	\$172,845	\$178,117	\$183,543	\$189,126	\$194,870	\$200,780	\$206,860	\$213,115	\$219,548	\$226,164
	Income	\$77,925	\$80,419	\$82,992	\$85,648	\$88,389	\$91,217	\$94,136	\$97,149	\$100,258	\$103,466	\$106,777	\$110,194	\$113,720	\$117,359	\$121,114
	Operating costs	\$7,200	\$7,625	\$8,075	\$8,551	\$9,056	\$9,590	\$10,156	\$10,755	\$11,389	\$12,061	\$12,773	\$13,527	\$14,325	\$15,170	\$16,065
Pessimistic	EBITDA	\$70,725	\$73,659	\$76,680	\$79,789	\$82,989	\$86,283	\$89,674	\$93,163	\$96,753	\$100,447	\$104,247	\$108,157	\$112,179	\$116,316	\$120,570
	Depreciation	\$38,667	\$38,667	\$38,667	\$38,667	\$38,667	\$38,667	\$38,667	\$38,667	\$38,667	\$38,667	\$38,667	\$38,667	\$38,667	\$38,667	\$38,667
	EBIT	\$32,995	\$34,364	\$35,773	\$37,224	\$38,717	\$40,254	\$41,835	\$43,463	\$45,138	\$46,861	\$48,634	\$50,458	\$52,334	\$54,264	\$56,249
	OCF	\$70,609	\$72,776	\$75,007	\$77,304	\$79,668	\$82,101	\$84,606	\$87,183	\$89,835	\$92,563	\$95,371	\$98,259	\$101,230	\$104,285	\$107,428
	Income	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0	\$0
	Operating costs	\$371,074	\$392,967	\$416,152	\$440,705	\$466,707	\$494,242	\$523,403	\$554,283	\$586,986	\$621,618	\$658,294	\$697,133	\$738,264	\$781,821	\$827,949
	EBITDA	-\$371,074	-\$392,967	-\$416,152	-\$440,705	-\$466,707	-\$494,242	-\$523,403	-\$554,283	-\$586,986	-\$621,618	-\$658,294	-\$697,133	-\$738,264	-\$781,821	-\$827,949
	Depreciation	\$27,487	\$27,487	\$27,487	\$27,487	\$27,487	\$27,487	\$27,487	\$27,487	\$27,487	\$27,487	\$27,487	\$27,487	\$27,487	\$27,487	\$27,487
	EBIT	-\$398,561	-\$420,454	-\$443,639	-\$468,192	-\$494,193	-\$521,729	-\$550,889	-\$581,770	-\$614,473	-\$649,105	-\$685,781	-\$724,620	-\$765,751	-\$809,308	-\$855,436

the sub-criteria of social acceptance and interest of the industrial sector in acquiring recycled materials must be considered key factors to promote the circular economy and environmental benefit. In this study, it is not appropriate to indicate whether the tool is better than others due to the heterogeneity of criteria considered due to differences in geographic context, but it does provide a comprehensive approach when considering multiple criteria and uncertainty (i.e., that of the panel of experts to assess criteria and sub-criteria as in economic analysis). In this study, the greatest uncertainty was found in the cost analysis in terms of the amount of CDW and the operating costs that significantly influenced ($p=0.037$) the economic viability of CDW utilization facility in terms of NPV. This result is similar to that reported by Li et al. (2022) who indicate that fluctuations in the amount of CDW strongly change the trends of the total cost.

The validation of the tool in the case study evidenced its benefits. In the metropolitan area of Bucaramanga, the generation of CDW during the last decade is estimated at about 24,738 ton/year. The estimated quantity is lower than that reported in other developing countries such as Mexico (i.e., 10,000 ton/year in 2019) and Brazil (i.e., 159,300 ton/year in Brazil) (Souza et al. 2021). This is associated with the fact that Colombia has lower infrastructure growth and is not characterized by strong industrial development like Shanghai (Wang et al. 2021). In addition, it is also associated with the fact that CDW is illegally deposited in landfills and its generation is not quantified. According to the SECOP results, there was a predominance of road construction works, commercial (29%), and low-income and high-income housing (25.6%). Ajayi et al. (2017) reported for China that a predominance of CDWs is from the construction of new buildings (i.e., 50%). Regarding the composition of the CDW, a predominance of materials based on concrete (45%), masonry (38%), ceramics such as tiles (15.6%), and others (1.4%) was found. Similar results are reported by Souza et al. (2022) for Brazil. According to Suárez-Silgado et al. (2017), proper sorting is a condition that must be met to ensure the recycling of CDWs.

Regarding the selection of the location of the exploitation plant for the case study, the tool showed that at a technical and social level, the best alternative was to locate it in the Piedecuesta city, which is located in the metropolitan area of Bucaramanga. This was associated with the smaller Euclidean distance that this municipality has to generation points, upgrading of the infrastructure that the municipality has due to population growth, and the available area for the exploitation plant. Regarding the economic analysis, the scenarios considered showed that a plant with a processing capacity of 72 ton/day is viable. The NPV values were \$989,634 with a 95% probability of this value occurring and \$147,518 for the optimistic and moderate scenarios, respectively. The NPV values are lower than those reported for a plant in Brazil where values of \$11.67 million are indicated (Souza et al. 2022). However, the difference may be due to the treatment capacity of the recovery facility. In addition, the differences between the optimistic and moderate scenarios are associated with the uncertainty in the supply of CDW that significantly affect the costs and the NPV. In contrast, when the CDW goes directly to landfills (i.e., Pessimistic scenario) the NPV is negative, indicating that there is not any economic benefit and the environmental dimension will be affected, for which the use of CDW is viable. Finally, the results show that in small cities such as the study area, the CDW recovery facility should be concentrating in urban areas where the generation of this waste stream is high.

6 Conclusions

The decision model systematically showed the importance of cross-sectional analysis of multiple criteria to locate a CDW utilization facility and determine its technical and economic feasibility. Therefore, the following conclusion is derived: The proposed decision

tool makes it possible to select the best location for a waste recovery facility considering both the uncertainty on the part of the experts who assign weights to criteria and sub-criteria, as well as fluctuating parameters at an economic level. In this study, the technical criterion had greater preference over the social one, and among the economic indicators, the income from CDW was the one giving the greatest uncertainty. It also revealed that the implementation of a CDW recovery facility in Santander, Colombia, is viable with a potential net present value of \$989,634. Therefore, the results of this study are significant because they provided the most appropriate location for CDW management in the study area. The limitation of the tool is that its applicability is conditioned by time, that is, it is in a stationary state because the judgments of the experts change according to the context due to external factors such as politics, the environment, and the economy. This leads to the need to adjust the weight of criteria and sub-criteria in the face of changes in any of these elements, such as at the level of country policies that promote or do not guidelines for the use of CDW and the incorporation of recycled CDW by the industries. Therefore, future work can address the development of a tool that considers the updating of weights dynamically over time as the study context changes.

Acronyms *AHP*: Analytical hierarchical process; *EBIT*: Earnings before interest and taxes; *EBITDA*: Earnings before interest taxes depreciation and amortization; *CAPEX*: Capital investment cost; *CE*: Circular economy; *CDW*: Construction and demolition waste; CDW_k : Construction and demolition waste quantity; C_j : Relative closeness to the ideal solution; C_r : Consistency ratio; D_i^+ : Distance to the positive ideal solution; D_i^- : Distance to the negative ideal solution; *EV*: Evamix; *OCF*: Operating cash flow; *FCF*: Free cash flow; F_d : Availability factor; *FUZZY*: Diffuse logic; *FAHP*: Fuzzy- Analytical hierarchy process; *GIS*: Geographic information system; *INS*: Ideal negative solution; *IPS*: Ideal positive solution; *WDI*: Waste dispersion index; *MCDA*: Multicriteria analysis; *MCS*: Monte Carlo simulation; *Mt*: Millon of tons; *NOPAT*: Net profit after taxes; *NPV*: Net present value; *OPEX*: Operating costs; *ton*: Tonne; *TOPSIS*: Technique of order of preference by similarity to the ideal solution; *RR*: Rate of return; *WS*: Weighted sum

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Declarations

Competing interests The authors declare no competing interests.

Ethics Approval The study did not involve humans or animals.

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Authors and Affiliations

**Jonathan Soto-Paz¹ · Angélica Hernandez¹ · Cristian A. Mejía-Parada¹ ·
Viviana Mora-Ruiz¹ · Wilson Hernández¹ · Francisco Luna-Guevara¹ ·
Miguel Casallas-Ojeda² · Brayan A. Parra-Orobio³**

✉ Jonathan Soto-Paz
jsoto3@udi.edu.co

¹ Faculty of Engineering, Research Group On Threats, Vulnerability and Risks to Natural Phenomena, Research and Development University (UDI), Cl. 9 # 23-55, Bucaramanga, Santander, Colombia

² Faculty of Engineering, Research Group Energy, Materials and Environment, Sabana University, Campus Universitario Puente del Común, Km. 7 Autopista Norte, Bogotá, Chía, Colombia

³ Department of Environmental and Health Sciences, GE&TES Research Group, Popular University of Cesar-Aguachica Section, Cra. 40 #1 Norte-2 a 1 Norte-58, Aguachica, Cesar, Colombia