Environ Res Tec, Vol. 6, Issue. 2, pp. 83–93, June 2023

Environmental Research and Technology
https://ert.yildiz.edu.tr - https://dergipark.org.tr/tr/pub/ert
DOI: https://doi.org/10.35208/ert.1244563

Research Article

Prioritization of upcycling and recycling applications for the management of waste printed circuit boards by using S-LCA and MCDM

Zerrin GÜNKAYA*, Zehra Gizem ERİS, Aysun ÖZKAN, Müfide BANAR

Department of Environmental Engineering, Eskişehir Technical University, Eskişehir, Türkiye

ARTICLE INFO

Article history
Received: 31 January 2023
Revised: 07 April 2023
Accepted: 18 April 2023

Key words:
Life cycle assessment; Multi-criteria decision methods; Printed circuit board; Recycling; Upcycling

ABSTRACT

In this study, the upcycling and recycling applications for the management of waste printed circuit boards (PCBs) were compared through the sequential application of Streamlined Life Cycle Assessment (S-LCA) and Multi-Criteria Decision Making (MCDM) techniques. Upcycling applications were determined as gold, copper-tin alloy, lead, copper recovery and activated carbon production. And, portland cement, aggregate, sawdust, fiberglass and styrene butadiene rubber (SBR) productions were taken account as recycling applications. At the S-LCA stage, CML-IA baseline and ReCiPe 2016 methods were used for the characterization. For the MCDM study, environmental, technical and economic criteria were determined. Remarkable characterization results of S-LCA were used as the environmental criteria of MCDM. The Entropy method was used for the weighting of the criteria. TOPSIS method was used to compare the alternatives based on weighted criteria. S-LCA study shows that impact categories of Abiotic Depletion Potential (element basis), Total Ecotoxicity Potential and Human Toxicity Potential are the major impact categories. MCDM study shows that the gold recovery (0.9845) as an upcycling application and SBR production (0.7361) as a recycling application have been determined as the first applications to be applied to waste PCBs in terms of environmental, technical and economic aspects.

Cite this article as: Günkaya Z, Eris ZG, Özkan A, Banar M. Prioritization of upcycling and recycling applications for the management of waste printed circuit boards by using S-LCA and MCDM. Environ Res Tec 2023;6:2:83–93.

INTRODUCTION

Rapid changes in technological devices and the decline in their lifespan has become a problem in the management of waste electrical and electronic equipment (WEEE). In 2019, the world generated a striking 53.6 million metric tons (Mt) of e-waste and is projected to expand to 74.7 Mt in 2030 [1]. WEEE is often referred to as urban mine, and the estimated value of all raw materials in global e-waste generated in 2019 was approximately USD 57 billion. This monetary value is largely concentrated in printed circuit boards (PCBs), which are the most valuable component of e-waste, comprising approximately 4–7% of the total mass of WEEE [2, 3]. The PCBs are composed of a mixture of metals (40%), plastics (30%) and ceramics (30%) (Van Yken et al. [2]). In addition to non-metal components, such as plastics, glass fibers and ceramics, there are a large number of valuable metals in waste PCBs, which have high economic value and industrial value [4]. Base metals such as copper, iron, aluminum, nickel, lead, chromium, and antimony are present in percentage levels, while other valuable elements such

---

***Corresponding author.**
*E-mail address: zcokaygil@eskisehir.edu.tr

This paper has been presented at Sixth EurAsia Waste Management Symposium (EWMS 2022)/İstanbul, Türkiye / 24–26 October 2022.

Published by Yıldız Technical University Press, İstanbul, Türkiye

as gold, silver, and palladium appear at minute, but not negligible, ppm levels [5]. From that point of view, managing of the waste PCBs are a critical concern and should be realized based on circular economy principles because of their valuable metallic/non-metallic content. At that point, recycling and upcycling come to the fore.

Recycling is generally described as the reuse of waste materials and sometimes different process are required for waste recovery or converting into products, materials, or ingredients [6]. Recycling can reduce the use of raw materials and reduce waste through a closed loop system [7]. On the other hand, upcycling has been defined as "the enhancement of the value of waste material or discarded products through the recycling process. Upcycling converts waste streams into products of higher value than their starting forms [8, 9]. Upcycling of waste PCBs has more importance for the metallic parts of PCBs. WEEE, and also waste PCBs, can be candidate for sustainable resources since they contain precious and rare earth metals. For example, the concentration of Au in WEEE is higher than that in mined Au ores. The recovery of these valuable metals from solid wastes offers an alternative as critical resources become exhausted, and mitigates the negative environmental impact of traditional mining from ores and downstream solid waste disposal [8]. At that point, upcycling of waste PCBs supports urban mining which is also based on the value recovery of secondary raw materials from anthropogenic sources through biological, chemical, or physical procedures and technological input [10]. Traditional urban mining methods use extractive metallurgy, mainly pyrometallurgical and hydrometallurgical processes to liberate metals from encased platforms like waste PCBs [4, 8]. Pyrometallurgy is the traditional and most common approach for base metal and precious metal extraction from e-waste. However, pyrometallurgical facilities are complex and represent a significant economic investment [2]. Hydrometallurgical processes are more selective and leach metals from waste materials using specific strong acid mixtures known as lixiviants, but secondary aqueous waste streams of strong acid are generated [8, 11].

There are various upcycling and recycling applications to be applied to waste PCBs. On the other hand, it is difficult to determine in advance which of these applications would be more environmentally, technically, and economically viable. At that point, sequential application of Life Cycle Assessment (LCA) and Multi-Criteria Decision-Making (MCDM) techniques is very helpful to manage this problem. LCA is a useful tool to determine the environmental impacts resulted from products and services. An LCA allows for an evaluation of how impacts are distributed across processes and life cycle stages [12]. In the literature, there are various LCA studies for waste PCBs. Rezaee et al. [13] designed a study to investigate the environmental aspects of step-wise glycine leaching for precious metals recovery from waste PCBs. A comprehensive LCA focusing on metal recovery from low-grade PCBs was undertaken by Kouloumpis and Yang [14]. Pokhrel et al. [15] assessed the environmental and economic performance of recovering nine metal elements (aluminum (Al), copper (Cu), gold (Au), lead (Pb), nickel (Ni), silver (Ag), tin (Sn), zinc (Zn), and iron (Fe)) and two non-metal materials (resin and glass-fiber) from the waste PCBs. Another LCA study providing an environmental impact assessment of the black copper smelting route for the recovery of valuable metals from PCB was performed by Ghodrat et al. [16]. MCDM is a sub-branch of Decision Sciences and is based on the process of modeling and analyzing the decision process according to its criteria. MCDM techniques have been used in areas of energy-environment-sustainability, supply chain and quality management, materials, project management, security and risk management, manufacturing systems, production management, operational research and soft computing, technology management, strategic management, tourism management, knowledge management, and other areas. Among these, the application field of energy-environment-sustainability had a maximum share with 13% [17]. There are many MCDM studies regarding WEEE management [18–22]. Among them, the study of Grimes and Maguire (2021) [23] stands out regarding the subject of this study. They have used MCDM for critical metal recovery priorities from WEEE from the points of economic availability, political influences, ease of recycling, potential for substitution and likely development of new raw material sources. Their study did not consider environmental concerns and so on LCA. Le et al. [24] proposed a new model for evaluating metal recycling efficiency from PCBs. They used three criteria: mass, environmental impacts and natural resources conservation. They weighted the criteria by Entropy method and used LCA for environmental impacts (damage to ecosystems and damage to human health from Eco-Indicator 99 method) data. On the other hand, their study was limited with the metals and did not consider non-metallic end products. Different from the study of Le et al. (2013) [24], this study aims to prioritize the upcycling and recycling applications of based on metallic and non-metallic parts of waste PCBs by using LCA and MCDM techniques sequentially.

MATERIALS AND METHODS

For the purpose of the study, firstly five different materials replacements were determined for both upcycling and recycling. A Streamlined LCA (S-LCA) and MCDM studies were sequentially realized to evaluate these replacements.

Streamlined LCA (S-LCA) Study

A S-LCA was applied to less the data requirement for complex products that can be produced by upcycling and recycling methods. The S-LCA methodology used in this study follows the International Organization for Standardization (ISO) 14040 (2006) [25] and ISO 14044 (2006) [26] guidelines, which comprise four stages; Goal and Scope Definition, Life Cycle Inventory (LCI) Analysis, Life Cycle Impact Assessment (LCIA), and Interpretation.

Table 1. Material replacements by upcycling

Code	Parts of PCB to be processed	Material to be obtained by upcycling	Material to be replaced	Reference
U1	Metallic parts	Gold	Gold mine	[27]
U2	Metallic parts	Copper-tin alloy	Bronze production	[28]
U3	Metallic parts	Lead	Lead mine	[29]
U4	Non-metallic parts	Activated carbon	Activated carbon	[30]
U5	Metallic parts	Copper	Copper mine	[31]

Table 2. Material replacements by recycling

Code	Parts of PCB to be processed	Material to be obtained by recycling	Material to be replaced	Reference
R1	Non-metallic parts	Filling material to be used for self-compacting concrete	Portland cement (PC)	[32]
R2	Non-metallic parts	Filler to be used in the cement and construction industries	Aggregate	[33]
R3	Non-metallic parts	Performance enhancing agent for wood plastic composite	Sawdust	[34]
R4	Non-metallic parts	Soundproofing material	Fiberglass (FB)	[35]
R5	Non-metallic parts	Asphalt modifier product	Styrene butadiene rubber (SBR)	[36]

Table 3. Ecoinvent data for material replacement by upcycling

Material to replaced	Corresponding ecoinvent data	Reference
Gold mine	Gold production	[37]
Bronze	Bronze production	[38]
Lead mine	Primary lead production from concentrate	[39]
Activated carbon	Activated carbon production, granular from hard coal	[40]
Copper mine	Copper production, cathode, solvent extraction and electrowinning process	[41]

Table 4. Ecoinvent data for material replacement by recycling

Material to replaced	Corresponding ecoinvent data	Reference
Portland cement	Cement production, Portland	[42]
Aggregate	Sand quarry operation, open pit mine	[43]
Sawdust	Suction, sawdust	[44]
Fiberglass	Glass fibre production	[45]
Styrene butadiene rubber	Synthetic rubber production	[46]

Goal and Scope Definition

The purpose of this S-LCA study is to compare the material replacements obtained by upcycling and recycling applied/can be applied to waste PCBs from an environmental point of view. Functional unit was applied as a 1 ton of waste PCB. The system boundaries cover the direct replacement of the new material to be obtained by the upcycling and recycling, which will be applied to the waste PCB, with the existing material. The system boundaries are considered as cradle-to-gate, starting from the raw material acquisition for the existing material that the new product will replaced, and covering the production process of the material. The material replacements that can be obtained by upcycling and recycling applications are shown in Table 1 and 2, respectively.

Life Cycle Inventory

Ecoinvent data embodied in SimaPro 9.2 was used for the background data. The data sets corresponding to the materials to be replaced through upcycling and recycling were selected (Table 3 and Table 4).

Life Cycle Impact Assessment

Characterization calculations were performed by using CML-IA baseline (v3.06) and ReCiPe 2016 Midpoint (V1.04) characterization methods. Impact categories taking place in characterization methods were given in Table 5. Characterization results were normalized by using EU25+3, 2000 and World (2010) (which are included in CML and ReCiPe methods, respectively) normalization methods.

Table 5. Impact categories of the characterization methods

Impact categories	CML	ReCiPe
Abiotic depletion (element)	x	x
Abiotic depletion (fossil fuel)	x	x
Global warming potential	x	x
Ozon depletion potential	x	x
Human toxicity potential	x	x[a]
Freshwater aquatic ecotoxicity	x	x
Marine aquatic ecotoxicity	x	x
Terrestrial ecotoxicity potential	x	x[b]
Photochemical oxidation potential	x	x
Acidification potential	x	x[c]
Eutrophication potential	x	x[d]
Ionization radiation potential		x
Particulate matter formation potential		x
Land use		x
Water depletion		x

a: Carcinogenic and noncarcinogenic; b: Human health and terrestrial ecosystem; c: Terrestrial; d: Freshwater and marine.

MCDM Study

The flow chart followed for the MCDM study given in Figure 1. According to this flow chart, firstly criteria were determined (Table 6). The criteria of environmental criteria category will be the impact categories of the LCA study that have the higher results.

The importance weights of criteria were determined by using the entropy method. The entropy method evaluates the uncertainty in the information using probability theory. It shows that there is a wide distribution that presents more uncertainty than that of a sharply peaked one [47, 48]. Compared with various subjective weighting models, the biggest advantage of the EWM (….) is the avoidance of the interference of human factors on the weight of indicators, thus enhancing the objectivity of the comprehensive evaluation results [49]. This method includes first deciding objectives (decision matrix) and then calculations of the normalized decision matrix, probability of the attribute/response to take place, the entropy value of attribute/response, degrees of divergence (average information contained) by each response and after that entropy weight [50]. The smaller the entropy of the evaluated information criterion, the greater the weight of the information criterion [51].

The comparison of the upcycling and recycling applications was realized with TOPSIS method. The method is a technique to order preference by similarity to ideal solutions. This method determined the alternative closest to the positive ideal solution (PIS) and the farthest to the negative ideal solution (NIS) [52]. The method calculates the distances by using the n–dimensional Euclidean distance according to the number of the criteria of the problem [53]. Firstly, the normalized decision matrix by vector normalization is computed. The weighted normalized decision matrix is calculated. Positive and negative ideal solution sets are detected. For positive ideal solution, maximum and minimum criteria values are used for ascending order and descending order, respectively. For the negative ideal solution, the opposite approach is used. After then, the distance to the PIS and NIS from each alternative as separation values (Si^+ and Si^-) is computed by applying the Euclidean distance theory and the closeness coefficient for each alternative by using separation values is calculated. Finally, alternatives are ranked based on higher closeness coefficient [54, 55].

Table 6. The criteria for MCDM study

Criteria category	CN	Criteria	Ascending/ descending order
Environmental	c1	LCA impact categories	Descending
	c2		
	c3		
Technical	c4	Ease of operation	Ascending
	c5	Operation time	Descending
	c6	Quality of material	Ascending
Economical	c7	Cost of energy	Descending
	c8	Operational cost	Descending
	c9	The value of product	Ascending

CN: Criteria number.

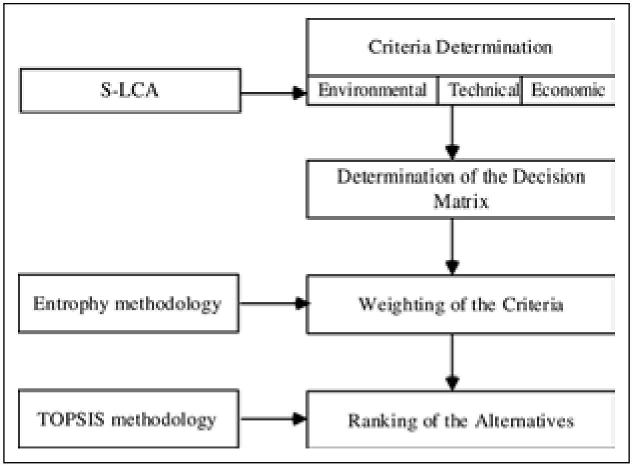

Figure 1. Flowchart of the MCDM study.

RESULTS

The characterization tables of material replacements that can be obtained by upcycling and recycling applications for CML according to impact category (IC) were given in Table 7 and 8. All the values in these tables are negative values which means these impacts will be avoided in the case of upcycling and recycling realized. The magnitude of negative values for upcycling applications are higher those of recycling applications. This situation depicts that, upcycling applications would be more environmentally effective than recycling applications.

Table 7. CML characterization results of upcycling applications

IC	Unit	Gold	Copper-tin alloy	Lead	Activated carbon	Copper
ADPe	kg Sb eq.	-5.81E+01	-2.05E-03	-6.81E-03	-9.97E-07	-2.02E-03
ADPff	MJ	-2.27E+05	-2.97E+01	-1.75E+01	-9.33E+01	-3.22E+01
GWP	kg CO_2 eq.	-1.80E+04	-2.57E+00	-1.99E+00	-8.29E+00	-2.79E+00
ODP	kg CFC-11 eq.	-1.69E-03	-1.91E-07	-7.02E-08	-1.14E-07	-2.21E-07
HTP	kg 1.4-DB eq.	-1.01E+04	-2.62E+01	-1.69E+00	-1.35E+00	-1.34E+02
FAEP	kg 1.4-DB eq.	-4.85E+03	-4.65E-01	-1.32E-01	-2.88E-02	-2.19E+00
MAEP	kg 1.4-DB eq.	-1.30E+07	-3.41E+03	-8.26E+02	-4.48E+03	-1.35E+04
TEP	kg 1.4-DB eq.	-5.96E+02	-7.30E-02	-9.78E-03	-7.27E-03	-3.62E-01
POP	kg C_2H_4 eq.	-4.53E+00	-5.80E-03	-1.99E-03	-2.41E-03	-2.08E-02
AP	kg SO_2 eq.	-1.63E+02	-1.57E-01	-5.28E-02	-5.24E-02	-5.47E-01
EP	kg PO_4 eq.	-4.36E+02	-6.46E-02	-5.38E-03	-3.74E-03	-2.19E-01

ADPe: Abiotic depletion (element); ADPff: Abiotic depletion (fossil fuel); GWP100: Global warming potential; ODP: Ozon depletion potential; HTP: Human toxicity potential; FAEP: Freshwater aquatic ecotoxicity potential; MAEP: Marine aquatic ecotoxicity potential; TEP: Terrestrial ecotoxicity potential; PbOP: Photochemical oxidation potential; AP: Acidification potential; EP: Eutrophication potential.

Table 8. CML characterization results of recycling applications

IC	Unit	PC	Aggregate	Sawdust	FB	SBR
ADPe	kg Sb eq.	-1.19E-08	-4.54E-10	-7.28E-08	-1.87E-06	-6.88E-05
ADPff	MJ	-2.35E+00	-2.54E-02	-2.69E+01	-3.22E+01	-7.42E+01
GWP	kg CO_2 eq.	-7.14E-01	-1.90E-03	-2.00E+00	-2.57E+00	-2.52E+00
ODP	kg CFC-11 eq.	-2.02E-08	-2.50E-10	-2.44E-07	-2.22E-07	-6.31E-07
HTP	kg 1.4-DB eq.	-1.82E-02	-1.86E-04	-2.26E-01	-1.49E+00	-2.34E-01
FAEP	kg 1.4-DB eq.	-6.30E-04	-8.69E-06	-1.33E-02	-1.31E-02	-1.54E-02
MAEP	kg 1.4-DB eq.	-1.03E+01	-2.27E-01	-3.24E+02	-1.97E+03	-4.70E+02
TEP	kg 1.4-DB eq.	-7.84E-04	-9.34E-07	-1.21E-03	-1.72E-03	-1.07E-03
POP	kg C_2H_4 eq.	-3.61E-05	-3.50E-07	-5.76E-04	-5.66E-04	-5.32E-04
AP	kg SO_2 eq.	-9.92E-04	-1.23E-05	-1.29E-02	-1.52E-02	-9.81E-03
EP	kg PO_4 eq.	-1.53E-04	-2.44E-06	-3.37E-03	-1.45E-03	-1.01E-03

ADPe: Abiotic depletion (element) (kg Sb eq.); ADPff: Abiotic depletion (fossil fuel); GWP100: Global warming potential; ODP: Ozon depletion potential; HTP: Human toxicity potential; FAEP: Freshwater aquatic ecotoxicity potential; MAEP: Marine aquatic ecotoxicity potential; TEP: Terrestrial ecotoxicity potential; POP: Photochemical oxidation potential; AP: Acidification potential; EP: Eutrophication potential.

Characterization tables of materials replacements by upcycling and recycling applications for ReCiPe were given in Table 9 and 10. These values are differing from CML results since the units are different except GWP. Total GWP values for upcycling and recycling applications calculated by CML and ReCiPe are the almost same (-1.8 E+04 kg CO_2 eq. and -7.81 E+00 kg CO_2 eq. for CML; -1.83 E+04 kg CO_2 eq. and 6.60 E+00 kg CO_2 eq. for ReCiPe, respectively). As same for the CML results, according to the ReCiPe results, gold recovery is the major replacement that can be the most effective from the environmental point of view.

Normalization results of upcycling and recycling applications were presented in Figures 2–5. Percentile distribution of the normalization values were used to determine which impact category and characterization result (between CML and ReCiPe) are going to be used for MCDM.

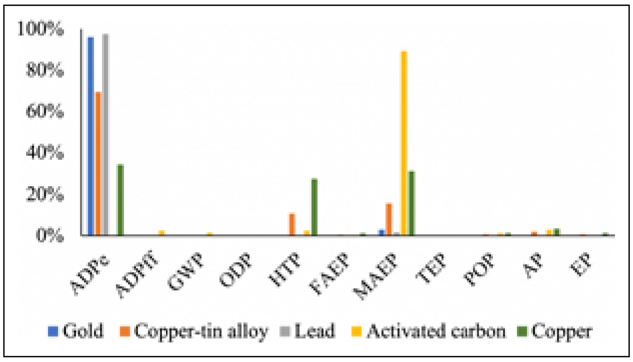

Figure 2. CML normalization results of upcycling applications.

Table 11 shows the impact category determination for MCDM. This determination was made based on the percentile distribution of upcycling and recycling applications calculated by CML and ReCiPe normalization methods. For upcycling,

Table 9. ReCiPe characterization results of upcycling applications

IC	Unit	Gold	Copper-tin alloy	Lead	Activated	Copper
GWP	kg CO$_2$ eq.	-1.83E+04	-2.61E+00	-2.02E+00	-8.54E+00	-2.84E+00
ODP	kg CFC-11 eq.	-1.32E-02	-3.19E-06	-9.96E-07	-1.59E-06	-6.70E-06
IRP	kBq Co-60 eq.	-1.57E+02	-5.76E-02	-1.76E-02	-1.29E-02	-5.36E-02
OFPhh	kg NO$_x$ eq.	-1.65E+02	-2.74E-02	-1.07E-02	-1.82E-02	-5.20E-02
PMFP	kg PM 2.5 eq.	-4.83E+01	-4.85E-02	-1.34E-02	-1.67E-02	-1.59E-01
OFPte	kg NO$_x$ eq.	-1.67E+02	-2.79E-02	-1.09E-02	-1.83E-02	-5.30E-02
TAP	kg SO$_2$ eq.	-1.34E+02	-1.31E-01	-4.40E-02	-4.28E-02	-4.58E-01
FEP	kg P eq.	-1.35E+02	-1.97E-02	-1.19E-03	-4.23E-04	-6.90E-02
MEP	kg N eq.	-6.84E-01	-3.31E-04	-9.39E-05	-1.10E-05	-1.09E-03
TEP	kg 1.4-DCB	-9.60E+04	-1.16E+03	-3.49E+01	-3.81E+00	-5.37E+03
FAEP	kg 1.4-DCB	-2.83E+03	-2.27E-02	-2.42E-02	-1.56E-03	-8.06E-02
MAEP	kg 1.4-DCB	-6.56E+03	-5.38E-01	-4.53E-02	-3.95E-03	-2.44E+00
HTPcar	kg 1.4-DCB	-1.36E+02	-3.29E-01	-1.89E-01	-2.29E-02	-1.60E+00
HTPncar	kg 1.4-DCB	-1.11E+05	-4.72E+01	-4.78E+01	-1.13E+00	-2.31E+02
LU	m^{2}a crop eq.	-6.67E+02	-1.43E-01	-2.05E-02	-5.44E-01	-3.28E-01
ADPe	kg Cu eq.	-4.26E+03	-1.31E+00	-5.31E-01	-5.32E-04	-1.89E+00
ADPff	kg oil ed	-5.41E+03	-7.00E-01	-4.07E-01	-2.14E+00	-7.61E-01
WD	m^3	-8.21E+04	-5.12E+01	-3.58E+00	-1.58E-02	-1.17E+02

GWP: Global warming potential; ODP: Ozon depletion potential; IRP: Ionization radiation potential; OFPhh: Ozone formation potential, human health; PMFP: Particulate matter formation potential; OFPte: Ozone formation potential, terrestrial ecosystem; TAP: Terrestrial acidification potential; FEP: Freshwater eutrophication potential; MEP: Marine eutrophication potential; TEP: Terrestrial ecotoxicity; FAEP: Freshwater ecotoxicity potential; MAEP: Marine ecotoxicity potential; HTPcar: Human toxicity potential (carcinogenic); HTPncar: Human toxicity potential, noncarcinogenic; LU: Land use; ADPe: Mineral depletion potential; ADPff: Fossil depletion potential; WD: Water depletion.

Table 10. ReCiPe characterization results of recycling applications

IC	Unit	PC	Aggregate	Sawdust	FB	SBR
GWP	kg CO$_2$ eq.	-7.01E-01	-1.85E-03	-1.88E+00	-2.39E+00	-2.33E+00
ODP	kg CFC-11 eq.	-4.89E-08	-1.48E-09	-3.27E-06	-4.99E-06	-2.76E-06
IRP	kBq Co-60 eq.	-2.94E-02	-9.14E-04	-3.73E-01	-3.40E-01	-2.56E-01
OFPhh	kg NO$_x$ eq.	-1.05E-03	-1.71E-05	-1.88E-02	-7.79E-03	-4.95E-03
PMFP	kg PM 2.5 eq.	-2.65E-04	-4.33E-06	-5.52E-03	-3.98E-03	-3.03E-03
OFPte	kg NO$_x$ eq.	-1.07E-03	-1.74E-05	-1.93E-02	-7.90E-03	-5.38E-03
TAP	kg SO$_2$ eq.	-7.83E-04	-9.30E-06	-9.78E-03	-1.23E-02	-7.97E-03
FEP	kg P eq.	-2.49E-06	-3.61E-08	-2.32E-05	-1.03E-04	-9.72E-05
MEP	kg N eq.	-3.31E-07	-7.48E-09	-5.29E-04	-3.43E-05	-9.34E-06
TEP	kg 1.4-DCB	-1.73E-01	-1.58E-03	-6.31E+00	-1.24E+01	-1.76E+00
FAEP	kg 1.4-DCB eq.	-7.11E-05	-7.41E-07	-3.07E-03	-3.71E-03	-1.66E-03
MAEP	kg 1.4-DCB	-1.04E+00	-1.19E-02	-5.69E+01	-2.47E+01	-2.11E+01
HTPcar	kg 1.4-DCB eq.	-8.06E-03	-3.34E-04	-1.40E-01	-1.64E+00	-4.61E-01
HTPncar	kg 1.4-DCB eq.	-9.95E-01	-1.10E-02	-4.86E+01	-1.25E+02	-1.86E+01
LU	m^{2}a crop eq.	-3.92E-04	-2.12E-04	-9.26E+01	-4.91E-03	-3.18E-02
ADPe	kg Cu eq.	-1.28E-04	-3.69E-06	-1.49E-03	-2.58E-03	-3.33E-03
ADPff	kg oil eq.	-5.40E-02	-5.93E-04	-6.38E-01	-7.77E-01	-1.74E+00
WD	m^3	-1.21E+00	-2.30E-02	-1.61E+01	-7.31E+00	-5.44E+00

GWP: Global warming potential; ODP: Ozon depletion potential; IRP: Ionization radiation potential; OFPhh: Ozone formation potential, human health; PMFP: Particulate matter formation potential; OFPte: Ozone formation potential, terrestrial ecosystem; TAP: Terrestrial acidification potential; FEP: Freshwater eutrophication potential; MEP: Marine eutrophication potential; TEP: Terrestrial ecotoxicity; FAEP: Freshwater ecotoxicity potential; MAEP: Marine ecotoxicity potential; HTPcar: Human toxicity potential (carcinogenic); HTPncar: Human toxicity potential, noncarcinogenic; LU: Land use; ADPe: Mineral depletion potential; ADPff: Fossil depletion potential; WD: Water depletion.

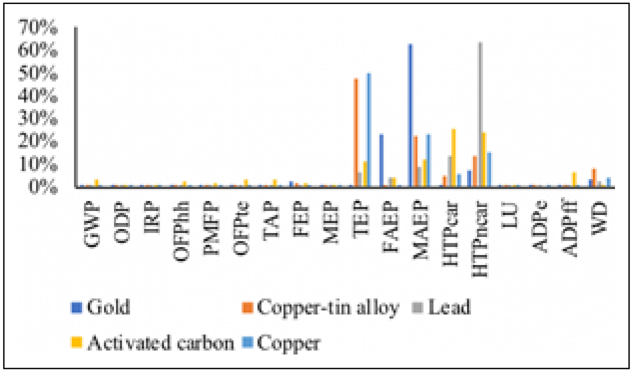

Figure 3. ReCiPe normalization results of upcycling applications.

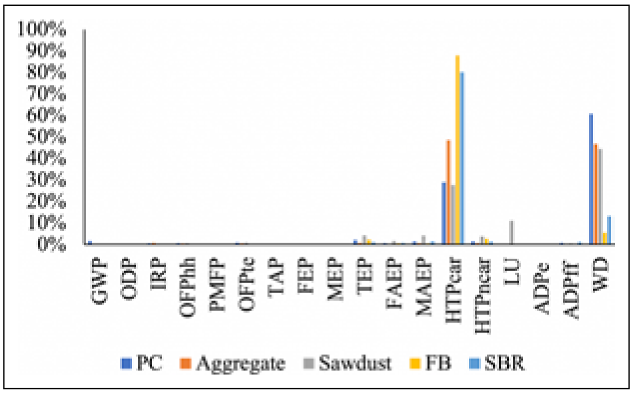

Figure 5. ReCiPe normalization results of recycling applications.

ADPe was found as the major impact category whereas FAEP and MAEP were determined as important categories for ReCiPe (Table 11, Level I). Then all three were selected for Level II. For recycling, ADPe and MAEP are the important impact categories for CML, those for ReCiPe were HTPcar and WD. Since MAEP has already been in Level II, only HTPcar was selected for Level II. So, ADPe, total ecotoxicity, and HTP (sum of HTPcar and HTPncar) were determined for Level III. The impact categories at the Level III were selected for the environmental criteria of the MCDM study and their characterization values were used in decision matrixes with the values/scores of technical and economic criteria for upcycling and recycling applications (Table 12 and 13, respectively).

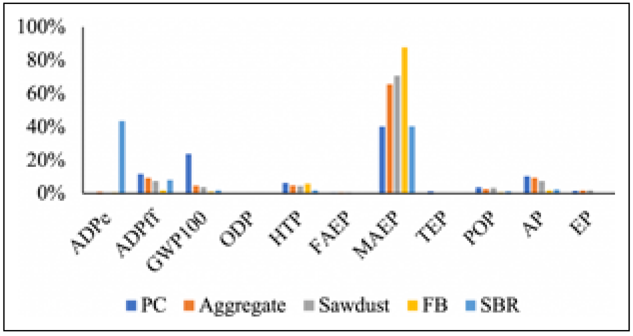

Figure 4. CML normalization results of recycling applications.

The weighting values of criteria obtained from Entropy method are given in Table 14. For both cases the c1 (ADPe) criterion was found to be the most important criterion. This situation resulted from the wide range of distribution in ADP values of upcycling and recycling applications.

TOPSIS results and general ranking of the alternatives are presented in Table 15 and Table 16. In these tables, Si^+, Si^- and Ci shows the distances from the ideal solution, nadir ideal solutions and relative closeness to the ideal solution, respectively. Table 15 shows that the gold recovery is the most important upcycling application with the highest Ci value (0.9845). Although the second upcycling application was the production of copper-tin alloy, it was observed that the Ci value (Ci: 0.1154) was quite low compared to the gold recovery. The Ci values of other upcycling applications are not remarkable (<0.1) compared to the values of gold recovery and copper-tin alloy recovery.

According to Table 16, recycling applications were prioritized as SBR>FB>PC>aggregate>sawdust. The highest Ci value is SBR (Ci: 0.7361), while other Ci values are closer to each other. There is no remarkable difference between PC and aggregate.

CONCLUSION

In this study, upcycling and recycling applications of waste PCBs were examined by using S-LCA and MCDM. S-LCA was applied by using material replacement data to have

Table 11. Impact category determination table for MCDM

Applications	Level I		Level II	Level III
	Major impact categories			
	CML	ReCiPe		
Upcycling	ADPe (96%)	FAEP (23%)	ADPe	ADPe
		MAEP (63%)	FAEP	^{1}Total
			MAEP	
Recycling	ADPe (13%)	HTPcar (76%)	HTPncar	Ecotoxicity
	MAEP (71%)	WD (14%)		^{2}HTP

1: The sum of terrestrial ecotoxicity, freshwater ecotoxicity and marine ecotoxicity; 2: The sum of human toxicity (carcinogenic) and human toxicity (non-carcinogenic).

Table 12. The decision matrix for upcycling applications

CN	Unit/Score	Upcycling applications[a]				
		U1	**U2**	**U3**	**U4**	**U5**
c1	kg Sb ed.	-5.81E+01	-2.05E-03	-6.81E-03	-9.97E-07	-2.02E-03
c2	kg 1,4-DCB	-1.05E+05	-1.16E+03	-3.50E+01	-3.82E+00	-5.37E+03
c3	kg 1,4-DCB	-1.11E+05	-4.75E+01	-4.80E+01	-1.15E+00	-2.33E+02
c4[b]	score	3	6	7	2	4
c5[c]	score	7	3	4	7	4
c6[d]	score	6	3	8	8	7
c7	$/ton	0.35	0.58	0.39	1.29	0.59
c8[e]	score	7	3	4	5	6
c9	$/ton	58,500	50,000	2,400	1,600	11,200

a: U1: Gold U2: Copper-tin alloy U3: Lead U4: Activated carbon U5: Copper; b: U1: Chemical + leaching=3, U2: Physical process +Thermal process =6, U3: Physical process =7, U4: Physical process + pyrolysis =2, U5: Chemical=4; c: Score value is defined to average operation times U1: 13h, U2: 1.5h, U3: 4h, U4: 12h, U5: 4.5h; d: U1: Higher than 95% gold dissolution. U2: Higher than %8 bronze dissolution. U3: Higher than 98% lead recovery. U4: Activated carbon recovery that has %98 adsorption capacity. U5: 98% copper recovery; e: U1: Chemical consumption. U2: No chemical consumption. U3: Nitrogen consumption. U4: CO_2 consumption. U5: Mineral acid consumption.

Table 13. The decision matrix for recycling applications

CN	Unit/Score	Recycling applications[a]				
		R1	**R2**	**R3**	**R4**	**R5**
c1	kg Sb eq.	-1.19E-08	-4.54E-10	-7.28E-08	-1.87E-06	-6.88E-05
c2	kg 1.4-DCB	-1.21E+00	-1.35E-02	-6.32E+01	-3.71E+01	-2.29E+01
c3	kg 1.4-DCB	-1.00E+00	-1.13E-02	-4.87E+01	-1.27E+02	-1.91E+01
c4b	score	7	7	6	6	5
c5c	score	9	8	7	3	8
c6d	score	5	6	6	7	5
c7	$/ton	0.06	0.32	4.36	0.13	0.44
c8e	score	4	3	5	4	6
c9	$/ton	85	0.080	210	1000	1900

a: R1: Portland cement. R2: Aggregate. R3: Sawdust. R4: Fiber glass. R5: Styrene Butadiene Rubber; b: R1: Physical process=7. R2: Physical process =7. R3: Physical process +Thermal process =6. R4: Physical process +Thermal process =6. R5: Physical process + pyrolysis=5; c: Score value is defined to average operation times R1: Average operation time 180 days. R2: 28 days. R3: 14 hours. R4: 1h; R5: 2 days; d: R1: 5% waste PCB addition R2: 10–25% waste PCB addition. R3: 10–20% waste PCB addition. R4: Virgin fiber glass production. R5: 4% waste PCB addition; e: R1: Chemical consumption. R2: No chemical consumption. R3: KH550 consumption. R4: Carbon powder consumption. R5 SBR consumption.

Table 14. Weighting values (w_i) of criteria for upcycling and recycling applications

CN	Upcycling applications	Recycling applications
c1	**0.295**	**0.333**
c2	0.249	0.123
c3	0.292	0.164
c4	0.017	0.002
c5	0.010	0.012
c6	0.009	0.002
c7	0.023	0.209
c8	0.008	0.006
c9	0.099	0.149

a rapid answer for environmental aspects. By using the MCDM, upcycling, and recycling applications were prioritized from an environmental, technical, and economic point of view. As a result, it is concluded that gold recovery and SBR production would be the primary focus applications for PCBs management in the circular economy concept.

This work has taken into account environmental, technical and economic aspects but can be extended to include other aspects such as social and applicability. Thus, more effective waste management will be ensured in terms of the circular economy. Additionally, this study was realized for only waste PCB, but it can be easily applied to other waste types as well. In conclusion, it is thought that the sequential application of S-LCA and MCDM provides a preliminary study that is useful in establishing a policy for waste management.

Table 15. TOPSIS results for upcycling applications

Applications	Si^{+}	Si^{-}	Ci	Ranking
U1	0.00770	0.4888	0.9845	1
U2	0.4819	0.0628	0.1154	2
U3	0.4883	0.0157	0.0311	4
U4	0.4888	0.0032	0.0066	5
U5	0.4802	0.0208	0.0415	3

U1: Gold; U2: Copper-tin alloy; U3: Lead; U4: Activated carbon; U5: Copper.

Table 16. TOPSIS results for recycling applications

Applications	Si^{+}	Si^{-}	Ci	Ranking
R1	0.3989	0.2041	0.3384	3
R2	0.4020	0.1916	0.3227	4
R3	0.4179	0.1178	0.2200	5
R4	0.3326	0.2679	0.4462	2
R5	0.1455	0.4057	0.7361	1

R1: Portland cement; R2: Aggregate; R3: Sawdust; R4: Fiberglass; R5: Styrene butadiene rubber.

Acknowledgements

This study was supported by Eskişehir Technical University Scientific Research Projects Commission under the grant number 20ADP093.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

REFERENCES

[1] W. Zhao, J. Xu, W. Fei, Z. Liu, W. He, and G. Li, “The reuse of electronic components from waste printed circuit boards: A critical review,” Environmental Science: Advances, Vol. 2, pp. 196–214, 2023. [CrossRef]

[2] J. Van Yken, K. Y. Cheng, N. J. Boxall, A. N. Nikoloski, N. Moheimani, M. Valix, M., V. Sahajwalla, and A. H. Kaksonen, “Potential of metals leaching from printed circuit boards with biological and chemical lixiviants,” Hydrometallurgy, Vol. 196, Article 105433, 2020. [CrossRef]

[3] Y. Zhu, B. Li, Y. Wei, S. Zhou, and H. Wang, “Recycling potential of waste printed circuit boards using pyrolysis: Status quo and perspectives,” Process Safety and Environmental Protection, Vol. 173, pp. 437–451, 2023. [CrossRef]

[4] J. Chen, J. He, L. Zhu, Q. Yao, Y. Sun, C. Guo, and B. Yang, “Efficient recovery of valuable metals from waste printed circuit boards via ultrasound-enhanced flotation,” Process Safety and Environmental Protection, Vol. 169, pp. 869–878, 2023. [CrossRef]

[5] L. Ali, H. A. Mousa, M. Al-Harahsheh, S. Al-Zuhair, B. Abu-Jdayil, M. Al-Marzouqi, and M. Altarawneh, “Removal of bromine from the non-metallic fraction in printed circuit board via its co-pyrolysis with alümina,” Waste Management, Vol. 137, pp. 283–293, 2022. [CrossRef]

[6] M. Y. Khalid, Z. U. Arif, W. Ahmed, and H. Arshad, “Recent trends in recycling and reusing techniques of different plastic polymers and their composite materials,” Sustainable Materials and Technologies, Vol. 31, pp. e00382, 2022. [CrossRef]

[7] H. Jung, G. Shin, H. Kwak, L. T. Hao, J. Jegal, H. J. Kim, and D. X. Oh, “Review of polymer technologies for improving the recycling and upcycling efficiency of plastic waste,” Chemosphere, Vol. Article 138089, 2023. [CrossRef]

[8] K. M. Wyss, B. Deng, and J. M. Tour, “Upcycling and urban mining for nanomaterial synthesis,” Nano Today, Vol. 49, Article 101781, 2023. [CrossRef]

[9] S. Yi, H. Lee, J. Lee, and W. Kim, “Upcycling strategies for waste electronic and electrical equipment based on material flow analysis,” Environmental Engineering Research, Vol. 24(1), pp. 74–81, 2019. [CrossRef]

[10] L. H. Xavier, M. Ottoni, and L.P.P. Abreu, “A comprehensive review of urban mining and the value recovery from e-waste materials,” Resources, Conservation and Recycling, Vol. 190, Article 106840, 2023. [CrossRef]

[11] G. Martinez-Ballesteros, J. L.Valenzuela-Garcia, A. Gomez-Alvarez, M. A.Encinas-Romero, F. A. Mejia-Zamudio, and A. D. J. Rosas-Durazo, “Base metals extraction from printed circuit boards by pressure acid leaching,” Minerals, Vol. 13(1), Article 98, 2023. [CrossRef]

[12] Z. Günkaya, A. Özdemir, A. Özkan, and M. Banar, “Environmental performance of electricity generation based on resources: a life cycle assessment case study in Turkey,” Sustainability, Vol. 8(11), Article 1097, 2016. [CrossRef]

[13] M. Rezaee, R. Saneie, A. Mohammadzadeh, H. Abdollahi, M. Kordloo, A. Rezaee, and E. Vahidi, “Eco-friendly recovery of base and precious metals from waste printed circuit boards by step-wise glycine leaching: Process optimization, kinetics modeling, and comparative life cycle assessment,” Journal of Cleaner Production, Vol. 389, Article 136016, 2023. [CrossRef]

[14] V. Kouloumpis, and X. Yan, “Life cycle assessment of a novel metal recovery method from co-processing of coal mine waste and low-grade printed circuit boards,” Journal of Environmental Management, Vol. 314, Article 115074, 2022. [CrossRef]

[15] P. Pokhrel, S. L. Lin, and C. T. Tsai, "Environmental and economic performance analysis of recycling waste printed circuit boards using life cycle assessment," Journal of Environmental Management, Vol. 276, Article 111276, 2020. [CrossRef]

[16] M. Ghodrat, M. A. Rhamdhani, G. Brooks, M. Rashidi, and B. Samali, "A thermodynamic-based life cycle assessment of precious metal recycling out of waste printed circuit board through secondary copper smelting," Environmental Development, Vol. 24, pp. 36–49, 2017. [CrossRef]

[17] A. Mardani, A. Jusoh, K. Nor, Z. Khalifah, N. Zakwan, and A. Valipour, "Multiple criteria decision-making techniques and their applications–a review of the literature from 2000 to 2014," Economic research-Ekonomska istraživanja, Vol. 28(1), pp. 516–571, 2015. [CrossRef]

[18] Y. Xu, L. Zhang, C. H. Yeh, and Y. Liu, "Evaluating WEEE recycling innovation strategies with interacting sustainability-related criteria," Journal of Cleaner Production, Vol. 190, pp. 618–629, 2018. [CrossRef]

[19] A. Khoshand, K. Rahimi, M. Ehteshami, and S. Gharaei, "Fuzzy AHP approach for prioritizing electronic waste management options: a case study of Tehran, Iran," Environmental Science and Pollution Research, Vol. 26, pp. 9649–9660, 2019. [CrossRef]

[20] S. Yousefzadeh, K. Yaghmaeian, A. H. Mahvi, S. Nasseri, N. Alavi, and Nabizadeh, "Comparative analysis of hydrometallurgical methods for the recovery of Cu from circuit boards: optimization using response surface and selection of the best technique by two-step fuzzy AHP-TOPSIS method," Journal of Cleaner Production, Vol. 249, Article 119401, 2020. [CrossRef]

[21] A. Fetanat, M. Tayebi, and G. Shafipour, "Management of waste electrical and electronic equipment based on circular economy strategies: navigating a sustainability transition toward waste management sector," Clean Technologies and Environmental Policy, Vol. 23, pp. 343–369, 2021. [CrossRef]

[22] M. Sharma, S. Joshi, and K. Govindan, "Issues and solutions of electronic waste urban mining for circular economy transition: An Indian context," Journal of Environmental Management, Vol. 290, Article 112373, 2021. [CrossRef]

[23] S. M. Grimes, and D. Maguire, "Assessment of priorities in critical material recovery from waste electrical and electronic equipment," Resources Policy, Vol. 68, Article 101658, 2020. [CrossRef]

[24] H. L. Le, E. Yamasue, H. Okumura, and K. N. Ishihara, "MEMRECS—a sustainable view for metal recycling from waste printed circuit boards," Journal of Environmental Protection, Vol. 4(8), pp. 803–810, 2013.

[25] ISO 14040, "Environmental management – life cycle assessment – principles and framework," 2006. https://www.iso.org/standard/37456.html Accessed on May 04, 2023.

[26] ISO 14044, "Environmental management — life cycle assessment — requirements and guidelines," 2006. https://www.en-standard.eu/iso-14044-2006-amd-1-2017-environmental-management-life-cycle-assessment-requirements-and-guidelines-amendment-1/ Accessed on May 04, 2023.

[27] M. D. Rao, K. K. Singh, C. A. Morrison, and J. B. Love, "Recycling copper and gold from e-waste by a two-stage leaching and solvent extraction process," Separation and Purification Technology, Vol. 263, 2021. [CrossRef]

[28] A. Shokri, F. Pahlevani, K. Levick, I. Cole, and V. Sahajwalla, "Synthesis of copper-tin nanoparticles from old computer printed circuit boards," Journal of Cleaner Production, Vol. 142(4), pp. 2586–2592, 2017. [CrossRef]

[29] L. Zhan, X. Xiang, B. Xie, and J. Sun, "A novel method of preparing highly dispersed spherical lead nanoparticles from solders of waste printed circuit boards," Chemical Engineering Journal, Vol. 303, pp. 261–267, 2016. [CrossRef]

[30] R. R. Rajagopal, L. S. Aravinda, R. Rajarao, B. R. Bhat, and V. Sahajwalla, "Activated carbon derived from non-metallic printed circuit board waste for supercapacitor application," Electrochimica Acta, Vol. 211, pp. 488–498, 2016. [CrossRef]

[31] F. P. C. Silvas, M. M. J. Correa, M. P. K. Caldas, V. T. Moraes, D. C. R. Espinosa, and J. A. S. Tenorio, "Printed circuit board recycling: Physical processing and copper extraction by selective leaching," Waste Management, Vol. 46, pp. 503–510, 2015. [CrossRef]

[32] G. Sua-iam, and B.Chatveera, "Effect of printed circuit board dust on the workability and mechanical properties of self-compacting concrete: A preliminary study," Case Studies in Construction Materials, Vol. 16, Article e00862, 2022. [CrossRef]

[33] S. Ganesh, P. Danish, and K. A. Bhat, "Utilization of waste printed circuit board powder in concrete over conventional concrete," Materials Today Proceedings, Vol. 42(2), pp. 745–749, 2021. [CrossRef]

[34] S. Tian, H. He, P. Yu, L. Zhou, Y. Luo, and D. Jia, "Sustainable utilization of waste printed circuit boards powders in HDPE-wood composites: Synergistic effects of multicomponents on structure and properties," Journal of Cleaner Production, Vol. 164, pp. 840–847, 2017. [CrossRef]

[35] Z. Sun, Z. Shen, S. Ma, and X. Zhang, "Sound absorption application of fiberglass recycled from waste printed circuit boards," Materials and Structures, Vol. 48, pp. 387–392, 2013. [CrossRef]

[36] F. Yang, S. Sun, S. Zhong, S. Li, Y. Wang, and J. Wu, "Performance of the heavy fraction of pyrolysis oil derived from waste printed circuit boards in modifying asphalt," Journal of Environmental Management, Vol. 126, pp. 1–6, 2013. [CrossRef]

[37] E. Ruiz, "AU, Undefined, ecoinvent database version 3.7.1," https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-7-1/ Accessed on May 04, 2023.

[38] R. Hischier, "Bronze production, GLO, Undefined, ecoinvent database version 3.7.1," https://www.eurasiasymposium.com/EWMS_2022/files/Hall2_2022/Session-1/119_Gunkaya.pdfAccessed on May 04, 2023.

[39] R. Dones, "Primary lead production from concentrate, GLO, Undefined, ecoinvent database version 3.7.1," https://www.eurasiasymposium.com/EWMS_2022/files/Hall2_2022/Session-1/119_Gunkaya.pdf Accessed on May 04, 2023.

[40] I. Muñoz Ortiz, "Activated carbon production, granular from hard coal, GLO, Undefined, ecoinvent database version 3.7.1," https://www.eurasiasymposium.com/EWMS_2022/files/Hall2_2022/Session-1/119_Gunkaya.pdf Accessed on May 04, 2023.

[41] R. Emilia "Moreno, copper production, cathode, solvent extraction and electrowinning process, GLO, Undefined, ecoinvent database version 3.7.1," https://www.eurasiasymposium.com/EWMS_2022/files/Hall2_2022/Session-1/119_Gunkaya.pdf-Accessed on May 04, 2023.

[42] G. Doka, "Cement production, Portland, GLO, Undefined, ecoinvent database version 3.7.1," https://ecoinvent.org/wp-content/uploads/2021/01/change-report_v3-7-1_20201217.pdf Accessed on May 04, 2023.

[43] D. Kellenberger, "Gravel and sand quarry operation, GLO, Undefined, ecoinvent database version 3.7.1," https://www.eurasiasymposium.com/EWMS_2022/files/Hall2_2022/Session-1/119_Gunkaya.pdf Accessed on May 04, 2023.

[44] G. Wernet, "Suction, sawdust, GLO, Undefined, ecoinvent database version 3.7.1," https://www.eurasiasymposium.com/EWMS_2022/files/Hall2_2022/Session-1/119_Gunkaya.pdf Accessed on May 04, 2023.

[45] D. Kellenberger, "Glass fibre production GLO, Undefined, ecoinvent database version 3.7.1," https://www.eurasiasymposium.com/EWMS_2022/files/Hall2_2022/Session-1/119_Gunkaya.pdf Accessed on May 04, 2023.

[46] R. Hischier, "Synthetic rubber production, RER, Undefined, ecoinvent database version 3.7.1," https://ecoinvent.org/wp-content/uploads/2021/01/change-report_v3-7-1_20201217.pdfAccessed on May 04, 2023.

[47] H. Çalışkan, B. Kurşuncu, C. Kurbanoğlu, and Ş. Y.Güven, "Material selection for the tool holder working under hard milling conditions using different multi criteria decision making methods," Materials & Design, Vol. 45, pp. 473–479, 2013. [CrossRef]

[48] J. Yuan, X. Li, C. Xu, and Y. Liu, "Investment risk assessment of coal-fired power plants in countries along the Belt and Road initiative based on ANP-Entropy-TODIM method," Energy Vol. 176, pp. 623–640, 2019. [CrossRef]

[49] Y. Zhu, D. Tian, and F. Yan, "Effectiveness of entropy weight method in decision-making," Mathematical Problems in Engineering, Vol. 2020, pp. 1–5, 2020. [CrossRef]

[50] R. Kumar, S. Singh, P. S. Bilga, J. Singh, S. Singh, M. L. Scutaru, and C. I. Pruncu, "Revealing the benefits of entropy weights method for multi-objective optimization in machining operations: A critical review," Journal of Materials Research and Technology, Vol. 10, pp. 1471–1492, 2021. [CrossRef]

[51] C. H. Chen, "A novel multi-criteria decision-making model for building material supplier selection based on entropy-AHP weighted TOPSIS," Entropy, Vol. 22(2), Article 259, 2020. [CrossRef]

[52] M. Tamasila, G. Prostean, and L. Ivascu, "Evaluating and prioritizing municipal solid waste management-related factors in Romania using fuzzy AHP and TOPSIS," Journal of Intelligent & Fuzzy Systems, Vol. 38(5), pp. 6111–6127, 2020. [CrossRef]

[53] Y. Çelikbilek, and F. Tüysüz, "An in-depth review of theory of the TOPSIS method: An experimental analysis," Journal of Management Analytics, Vol. 7(2), pp. 281-300, 2020. [CrossRef]

[54] M.M. Salih, B.B. Zaidan, A.A. Zaidan, and M.A. Ahmed, "Survey on fuzzy TOPSIS state-of-the-art between 2007 and 2017," Computers & Operations Research, Vol. 104, pp. 207–227, 2019. [CrossRef]

[55] S. Chakraborty, "TOPSIS and Modified TOPSIS: A comparative analysis," Decision Analytics Journal, Vol. 2, Article 100021, 2022. [CrossRef]