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Life Cycle Assessment and Optimization-Based Decision Analysis of Construction Waste Recycling for a LEED-Certified University Building

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Abstract: The current waste management literature lacks a comprehensive LCA of the recycling of construction materials that considers both process and supply chain-related impacts as a whole. Furthermore, an optimization-based decision support framework has not been also addressed in any work, which provides a quantifiable understanding about the potential savings and implications associated with recycling of construction materials from a life cycle perspective. The aim of this research is to present a multi-criteria optimization model, which is developed to propose economically-sound and environmentally-benign construction waste management strategies for a LEED-certified university building. First, an economic input-output-based hybrid life cycle assessment model is built to quantify the total environmental impacts of various waste management options: recycling, conventional landfilling and incineration. After quantifying the net environmental pressures associated with these waste treatment alternatives, a compromise programming model is utilized to determine the optimal recycling strategy considering environmental and economic impacts, simultaneously. The analysis results show that recycling of ferrous and non-ferrous metals significantly contributed to reductions in the total carbon footprint of waste management. On the other hand, recycling of asphalt and concrete increased the overall carbon footprint due to high fuel consumption and emissions during the crushing process. Based on the multi-criteria optimization results, 100% recycling of ferrous and non-ferrous metals, cardboard, plastic and glass is suggested to maximize the environmental and economic savings, simultaneously. We believe that the results of this research will facilitate better decision making in treating construction and debris waste for LEED-certified green buildings by combining the results of environmental LCA with multi-objective optimization modeling.

Keywords: multi-criteria decision analysis; economic input-output analysis; life cycle assessment; construction waste management; LEED

1. Introduction

Residential and commercial buildings generate a significant amount of construction and debris (C&D) waste in the United States. The estimated total amount of building-related C&D materials is approximately 170 million tons [1]. Based on the U.S. Environmental Protection Agency's (EPA) waste report, 39% of these wastes are residential and 61% are from commercial buildings [1]. Recycling or appropriate treatment of these C&D wastes not only reduces the amount of waste land-filled or incinerated, but additionally minimizes the environmental impacts associated with producing new materials from virgin resources. In this context, one of the barriers for effective policy making towards shifting to a more sustainable C&D waste management is that C&D generation statistics are not rigorously collected [2]. Even though the statistics vary significantly, a recent report indicates that recycling could create credible benefits as a sustainable solution [2]. For instance, according to the same report, in 2012, the estimated magnitude of GHG emissions offset corresponded to taking 4.7 million passenger cars off the road for an entire year. The green building movement has adopted several strategies to reduce C&D waste. Among the green building initiatives, the LEED (Leadership in Energy and Environmental Design) rating system, which was established by the U.S. Green Building Council (USGBC), has gained wide acceptance and has been adopted by several federal and state agencies for evaluating their building designs. LEED green building certification systems employ a simplified checklist that is mainly used in the design process [3]. To obtain LEED certification, a building must first satisfy certain prerequisites and then obtain points for credits related to sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality and design process. In general, LEED can be applied to new constructions, major renovations, existing buildings, commercial interiors, core and shell, schools, retail, healthcare, homes and neighborhood development [4]. LEED has two main construction waste material diversion credits, which are as follows [3]:

- Credit 2.1 (one point): recycle and/or salvage at least 50 percent of construction, demolition and land-clearing waste.
- Credit 2.2 (one point): recycle and/or salvage an additional 25 percent (75 percent total) of construction, demolition and land-clearing waste.

The credits are proposed to divert construction, renovation and demolition debris from landfill areas and redirect recyclable materials back to the manufacturing process. To accomplish this goal, it is necessary to develop a detailed waste management plan for recycling of various construction waste materials, such as cardboard, metal, brick, mineral fiber panel, concrete, asphalt, plastic, clean wood, glass, gypsum wallboard, carpet and insulation materials. However, setting a goal, such as "50 percent or 75 percent of construction waste must be recycled" without defining the possible economic and environmental impacts associated with recycling of each C&D waste material may lead to a misrepresented understanding of the comprehensive impact that recycling of that nature may cause. Therefore, recycling goals should be supported by robust decision making models considering environmental and economic impacts, simultaneously [5].

Studying the construction materials from a life cycle point of view is critical for an overall understanding about the sustainability impacts of processes associated with the entire life cycle of buildings. In fact, the literature is abundant with works that focus on the process life cycle of construction materials based on case studies. Several construction materials are analyzed from a life cycle perspective to quantify the environmental impacts; for example, wood and concrete [6], wood and alternative materials [7], generic *vs.* product specific comparisons [8], socio-economic aspects of life cycle impacts [9] and the case of multiple life cycles [10–13]; for recent comprehensive reviews, see [14].

Novelty and Organization of the Research

Even though a significant amount of work related to LCA-based sustainability assessment of construction materials and buildings has been done, the current literature lacks a comprehensive LCA of the recycling of construction materials that considers both process and supply chain-related impacts as a whole. Additionally, a decision support framework has not been also addressed in any work, which provides a quantifiable understanding about the potential savings and implications associated with recycling of such construction materials from the life cycle perspective. The goal of this research is to develop a comprehensive framework that aids in quantifying and minimizing the environmental impact of C&D waste, while maximizing the economic value added to the solid waste industry. To realize this goal, the following tasks were undertaken: (1) assess the net environmental impacts of C&D waste management strategies using the proposed hybrid LCA model; (2) optimize C&D waste recycling strategies using a multi-criteria optimization model considering all direct and indirect environmental and economic impacts of C&D waste management alternatives; and (3) optimize the sustainable waste recycling strategies by taking LEED requirements into consideration. Hence, this research aims at integrating the solid waste requirements of the LEED green building rating system in order to devise the most environmentally-friendly C&D waste treatment strategies. For a general research framework, please see Figure 1.

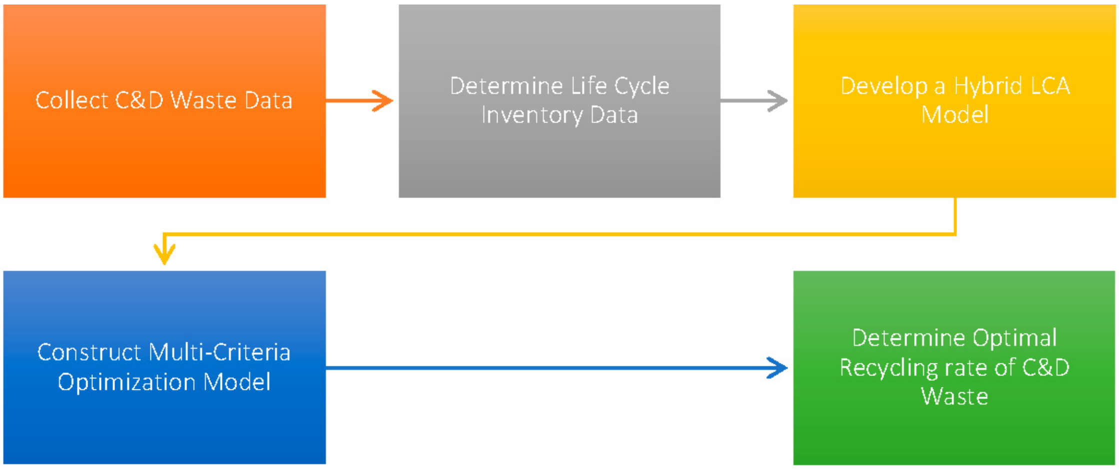

Figure 1. General research framework. C&D, construction and debris.

The rest of the paper is organized as follows: First, the case study is explained. Then, the proposed methodology that consists of hybrid LCA and optimization models is presented. Next, the LCA results of the certified green building and the results of the optimization model are presented. Finally, the conclusion and the future work are pointed out.

2. Case Study

In this paper, the LEED-certified Physical Science Building at the University of Central Florida was chosen as a case study for this research. In this analysis, the amount of C&D waste and its composition data were gathered from the LEED waste documentation, which is publicly available through the University of Central Florida (UCF) Office of Sustainability for the Physical Science Building [15]. The percentage of the waste composition of C&D materials of the building is included, such as asphalt, concrete, wood, non-ferrous and ferrous metals, cardboard, plastic, glass and cardboard. Total waste composition shows that concrete and asphalt have the largest share (over 60% of the total) among the C&D waste materials. The composition of all other building waste materials is presented in Figure 2, which shows the % shares of C&D waste of different materials related to the case study. Although the total composition of these waste materials is important to know, the life cycle impacts related to treatment of these wastes are critical. Hence, the net greenhouse gas (GHG) emissions, energy consumption and water withdrawal associated with recycling, land filling and incineration of C&D materials were quantified using the economic input-output (EIO)-based hybrid LCA methodology. Later, an optimization model is developed to optimize the construction waste recycling strategies.

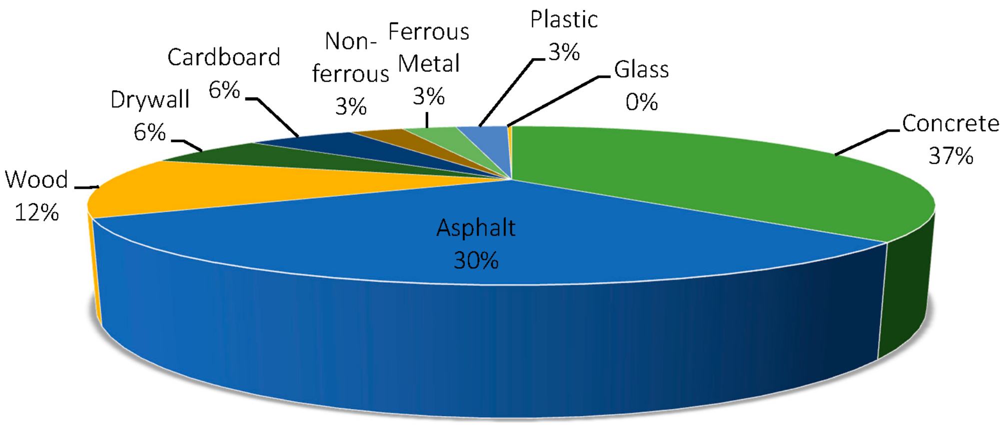

Figure 2. Percentage distribution of C&D wastes for the LEED-certified university building.

3. Methodology

Several important life cycle phases, including production of building materials from virgin and recycled resources, transportation, material recovery, incineration and conventional land filling, were analyzed for nine C&D waste materials, namely: asphalt, concrete, wood, non-ferrous and ferrous metals, cardboard, plastic, glass and cardboard. For the recycling, collection and transportation of wastes, material recovery process and producing new products from recycled materials were holistically investigated under the scope of this research. For the incineration, transportation of waste to the incineration facility, processing of waste and energy recovery from combustible waste are analyzed. In addition, the environmental impacts related to a conventional land filling process are quantified for the transportation of C&D to landfill and land filling of each C&D waste material, respectively.

3.1. Hybrid LCA Model

The proposed hybrid LCA model consists of process-based LCA (P-LCA) and economic input-output LCA (EIO-LCA). P-LCA is a commonly-used method to analyze the life cycle impacts of solid waste management systems. This LCA approach provides a detailed view of the processes and impacts involved in the management of waste. The EIO-LCA model, augmented with sector-level water use, energy consumption and GHG emissions vectors, has been used in this LCA study. In general, EIO analysis tackles the sector-level interdependencies and represents sectoral direct requirements, which are represented by the matrix A [16,17]. This matrix includes the dollar value of inputs required from other sectors to produce one dollar of output. The total output of a sector in this economic model with a final demand of f can be written as [18,19]:

$$\mathrm{x} = (I - \mathrm{A})^{-1} \times f \tag{1}$$

where x is the total output vector, I represents the diagonal identity matrix and f refers to the final demand vector representing the change in the final demand of the desired sector. After the EIO model has been established, the total environmental impacts can be calculated by multiplying the economic output of each industrial sector by the environmental impacts associated with per dollar of output. A vector of environmental outputs can be expressed as [20]:

$$R_i = E_i \times \mathrm{X} = E_i \times (I - \mathrm{A})^{-1} \times f \tag{2}$$

where R_i is the total environmental output vector for the environmental impact category of i and E_i represents a diagonal matrix, which consists primarily of the environmental impacts per dollar of output for each industrial sector. In this research, a hybrid EIO-LCA model is built to consider the environmental impacts associated with different waste management scenarios. This LCA model quantifies the total environmental burdens associated with the waste management system, which is presented in the following equation [20]:

$$K_i = E_i \times (\mathrm{I}-\mathrm{A})^{-1} \times f + Q_i \times e_i \tag{3}$$

where K_i denotes the total environmental impact defined as the summation of environmental burdens associated with the production of resource inputs (by tracing all supply chains) and the direct environmental impacts related to waste treatment processes. Q_i is the total input requirement for a process, and e_i is the unit environmental impact factor associated with the consumption of Q_i. For example, the production of reinforced steel, which is widely used in residential and commercial buildings, has high GHG emissions. During its production process, electricity is consumed as an energy source for steel manufacturing. In our hybrid LCA model, to quantify the direct and indirect GHG emissions considering the whole supply chain of electricity production, we used Equation (2). In addition, Q_i represents the amount of electricity used in the steel production process, and e_i represents the emission factor related to electricity generation. In this way, Equation (3) presents the total carbon emission related to the indirect supply chains of electricity production ($E_i \times (\mathrm{I}-\mathrm{A})^{-1} \times f$) and onsite electricity production processes ($\mathrm{Q}_i \times e_i$).

3.2. Multi-Criteria Optimization Model

After quantifying the total environmental impacts of different waste management strategies, the next challenge is selecting the best recycling strategy considering environmental and economic benefits, simultaneously. As mentioned earlier, several environmental impact categories, such as energy consumption, GHG emissions and water withdrawals, are quantified using a hybrid LCA model. In addition, the developed LCA model quantified the direct and indirect economic value added associated with the recycling of the analyzed C&D materials. At this point, a multi-criteria optimization model will be critical for finding a feasible alternative that yields the most preferred amount of recycling for each building waste material. Hence, a compromise programming model was developed. This approach is widely used for optimally solving multi-objective linear, non-linear or integer programming problems [21–24]. The compromise programming model measures the distance based on the L_a metric. The L_a metric defines the distance between two points, such as $Z_k^*(X)$ and Z_k *(X)*. As can been seen from Equation (4), compromise programming uses a distance-based function in order to minimize the difference between ideal and compromise solutions. The formulation of the $\mathrm{L_a}$ metric is presented as follows:

$$L_a = \mathrm{Min}(\sum \pi_{\mathrm{k}}{}^{\mathrm{a}}(\mathrm{Z}_{\mathrm{k}}^*(\mathrm{X}) - \mathrm{Z}_{\mathrm{k}}(\mathrm{X}))^{\mathrm{a}})^{\frac{1}{\mathrm{a}}} \tag{4}$$

Due to each objective function having different units, normalization is needed before the optimization analysis is performed. The values after normalization will be confined to a given range, such as zero to one. The normalization function *Z* is presented in Equation (5):

$$\mathrm{Z} = \frac{\mathrm{Z}_{\mathrm{k}}^*(\mathrm{X}) - \mathrm{Z}_{\mathrm{k}}(\mathrm{X})}{\mathrm{Z}_{\mathrm{k}}^*(\mathrm{X})} \tag{5}$$

After completing the normalization procedure, the distance-based compromise programming formulation can be written as [25]:

$$\mathrm{MinL_a} = \mathrm{Min}(\sum \pi_{\mathrm{k}}{}^{\mathrm{a}}(\frac{\mathrm{Z}_{\mathrm{k}}^*(\mathrm{X}) - \mathrm{Z}_{\mathrm{k}}(\mathrm{X})}{\mathrm{Z}_{\mathrm{k}}^*(\mathrm{X})})^{\mathrm{a}})^{\frac{1}{\mathrm{a}}} \tag{6}$$

Subject to:

$$\sum_{k=1}^{p} \pi_k{}^a = 1 \tag{7}$$

$$1 \leqslant a \leqslant \infty \tag{8}$$

In this formulation, Z_k^* represents the ideal solution for objective k. The parameter p represents the total number of objectives, and $\pi_k{}^a$ refers to the corresponding weight associated with each objective. Since we give an equal importance for our economic and environmental objectives, $\pi_k{}^a$ is assumed to be equal for each objective function. In general, three points of the compromise set are calculated for decision analysis, such as a = 1, 2 and ∞. After presenting the theoretical background of the compromise programming, this model has been used for selecting the best recycling strategy. As mentioned earlier, we have the following four primary objectives: maximizing economic value added, maximizing GHG savings, maximizing the net reductions in energy and water consumption. Based on these objectives, the following equations are solved using a multi-objective optimization approach, which is presented as follows:

Notation:

Index:

i: Material index

Parameters:

C_i: economic value added per ton recycled waste for material i

GHG_i: GHG emission savings per ton recycled waste for material i

W_i: water savings per ton recycled waste for material i

E_i: energy savings per ton recycled waste for material i

Q_i: total amount of waste generated by the LEED-certified building for material i

$LEED_{rf}$: recycling factor

Decision variable:

X_i: optimal amount of recycled waste allocated for material i

Objective function:

$$Max\ Z_1(X_i) = \sum_{\mathrm{i}=1}^{\mathrm{M}} (\mathrm{C_i} \times \mathrm{X_i}) \tag{9}$$

$$Max\ Z_2(X_i) = \sum_{\mathrm{i}=1}^{\mathrm{M}} (\mathrm{GHG_i} \times \mathrm{X_i}) \tag{10}$$

$$Max\ Z_3(X_i) = \sum_{\mathrm{i}=1}^{\mathrm{M}} (\mathrm{W_i} \times \mathrm{X_i}) \tag{11}$$

$$Max\ Z_4(X_i) = \sum_{\mathrm{i}=1}^{\mathrm{M}} (\mathrm{E_i} \times \mathrm{X_i}) \tag{12}$$

Subject to:

$$\sum_{i=1}^{M} X_i \leqslant LEED_{rf} \times \sum_{i=1}^{M} Q_i \tag{13}$$

$$X_i \leqslant Q_i\ for\ i = 1, 2, \ldots, M \tag{14}$$

$$\forall X_i \geqslant 0 \tag{15}$$

The first objective is to maximize the total economic value added (Equation (10)). The second objective maximizes the GHG emission-based savings (Equation (10)). The water savings are addressed by the third objective, as shown in Equation (11). The energy savings objective function is also represented in Equation (12). The total of the optimal waste for each material *(i)* is less than or equal to the total recycled waste multiplied by the LEED recycling factor ($LEED_{rf}$) (see Equation (13)). Subsequently, the decision variable (X_i) must be less than or equal to the recycled waste (Q_i), as shown in Equation (14). Finally, all decision variables are greater than or equal to zero (see Equation (15)).

Since our goal is to select the best combination of C&D materials for 50% recycling of overall construction waste, the total waste amount multiplied by 0.5, which is known as the $LEED_{rf}$, is used. Due to being one of the most robust optimization software in the applied optimization field, the LINGO© software package is used for solving the multi-objective optimization model [26]. Since we have four objective functions (Z_1, Z_2, Z_3 and Z_4) and three compromise programming functions (a = 1, a = 2 and a = ∞), the LINGO© program has been run to solve each mathematical model. By using the mathematical optimization model, the optimal recycling amount of each construction material has been calculated for the overall 50% recycling goal for single and multiple objectives.

3.3. Data Collection

In this paper, several sources have been used to collect the life cycle inventory data for different C&D waste management alternatives. First, the process data for producing each building material from virgin resources and recycled C&D waste are gathered from Christensen [27]. This detailed data included all electricity, fuel and other resource inputs, as well as atmospheric GHG emissions associated with producing building materials from recycled or virgin materials. Additionally, electricity, fuel consumption and GHG emissions data for the material recovery process were compiled from the LCA study of Denison [28]. The waste reduction model (WARM), which was developed by the U.S. EPA, is utilized for quantifying the emissions related to incineration and landfilling of each C&D waste [29]. The energy production efficiency and electricity generation associated with incineration of cardboard, paper, plastic and wood waste are obtained from the Waste Analysis Software Tool for Environmental Decisions (WASTED) model developed by Diaz and Warith [30].

For transportation of C&D materials from the building construction site to both the material recovery facility and final disposal area, a 50-km transportation distance is assumed for each transfer process. Diesel fuel consumption and emission factors data are also provided by the National Renewable Energy Laboratory (NREL) life cycle inventory database for a diesel-powered single-unit truck [31]. After quantifying the life cycle inventory data for each waste management alternative, the producer prices of each energy and material input are obtained, and the Carnegie Mellon's EIO-LCA software was used for calculating direct plus indirect environmental impacts related to C&D waste management [32].

4. Results

4.1. LCA Results

In this part, environmental impacts analysis results are presented in terms of energy, GHG and water savings.

4.1.1. Energy Savings

The amount of fossil fuel consumption has been quantified in terms of terajoules (TJ) for recycling, landfilling and incineration of per ton building-related C&D waste. Results indicated that recycling of non-ferrous metals and plastics resulted in considerable reductions for the energy consumption among the alternative waste management approaches (see Table 1). This is due to the recycling of these materials reducing the production-related fuel and electricity input requirements. Among C&D materials, recycling of non-ferrous metals and plastics showed the highest potential to reduce the total energy footprint.

On the other hand, recycling of some C&D wastes, such as wood, drywall and cardboard, did not have a significant impact on minimizing the net energy consumption compared to other C&D materials. Although concrete and asphalt have the highest percentage contributions to the total waste amount, their recycling did not significantly reduce the net energy footprint due to high energy consumption during the recycling process. Additionally, landfilling and incineration did not have significant impacts on the overall energy footprint compared to the recycling of waste materials. Therefore, it is likely to conclude that a high recycling of metals and plastics, which accounts for almost 90% of the total energy savings of the nine construction materials, will be critical for reducing the net energy footprint of the C&D management systems.

Table 1. Energy savings of construction materials (TJ).

Material	Recycling	% Share	Landfilling	% Share	Incineration	% Share
Cardboard	0.271	3.6%	−0.004	5.6%	0.000	27.2%
Non-ferrous	5.720	75.5%	−0.002	2.8%	N/A	N/A
Ferrous Metal	0.156	2.1%	−0.002	2.8%	N/A	N/A
Concrete	0.241	3.2%	−0.024	37.0%	N/A	N/A
Plastic	0.978	12.9%	−0.002	2.7%	0.000	13.2%
Wood	0.093	1.2%	−0.008	12.3%	0.000	59.6%
Glass	0.010	0.1%	0.000	0.2%	N/A	N/A
Drywall	0.084	1.1%	−0.004	6.1%	N/A	N/A
Asphalt	0.027	0.4%	−0.020	30.3%	N/A	N/A

4.1.2. GHG Emission Savings

In addition to energy consumption, the current study quantified the amount of GHG emissions and savings related to C&D waste recycling. We utilize the definition of carbon footprint as the total emissions of carbon dioxide or GHGs expressed in terms of CO_2 equivalents related to recycling, landfilling and incineration of per ton C&D waste. Based on the analysis results, recycling of ferrous and non-ferrous metals are found to have significant benefits for reducing total GHG emissions with a total percent share of 79.3% (see Table 2). This is because recycling of these metals reduced the amount of electricity and fuel inputs, which are highly utilized for the production of metal products. Additionally, on-site emissions are decreased when using recycled metals instead of virgin resources. Recycling of other C&D materials, such as paper, glass and cardboard, also contribute to reductions in the net GHG emissions.

Table 2. GHG emission savings of construction materials (Mt CO_2-eqv.).

Material	Recycling	% Share	Landfilling	% Share	Incineration	% Share
Cardboard	9.430	7%	−2.714	6%	-26.718	18%
Non-ferrous	38.142	30%	−1.370	3%	N/A	N/A
Ferrous Metal	61.732	49%	−1.370	3%	N/A	N/A
Concrete	−23.800	-	−17.918	37%	N/A	N/A
Plastic	15.733	12%	−1.318	3%	−32.250	22%
Wood	−7.910	-	−5.955	12%	−90.400	61%
Glass	0.436	0%	−0.108	0%	N/A	N/A
Drywall	0.562	0%	−2.963	6%	N/A	N/A
Asphalt	−8.930	-	−14.663	30%	N/A	N/A

On the contrary, recycling of C&D wastes, such as wood, drywall and asphalt, did not have a significant impact on GHG savings when compared to other C&D materials. Moreover, recycling of asphalt and concrete is not found to be an environmentally-friendly option due to increasing GHG emissions. This is because recycling of these materials requires high fuel consumption during crushing and emitted on-site GHG emissions in this process. When incineration was more closely analyzed, wood, plastic and cardboard resulted in additional GHG emissions. For this reason, combustion of these materials is not found to be an environmentally-friendly waste treatment option due to increased GHG emissions. Therefore, recycling has a positive impact on reduced energy consumption, and a high recycling of metal and plastic materials will have a key importance for decreasing the net carbon footprint of the LEED construction management strategies.

4.1.3. Water Savings

Water footprint analysis results are also presented for recycling, landfilling and incineration of per ton C&D waste. Recycling of non-ferrous metals and asphalt is found to be beneficial due to reductions in overall water consumption (see Table 3). This is because recycling of these materials reduced water consumption for the direct and indirect processes required for the production of these materials.

Table 3. Water savings of construction materials (kgal).

Material	Recycling	% Share	Landfilling	% Share	Incineration	% Share
Cardboard	0.201	0.2%	−1.102	5.6%	−0.048	27.3%
Non-ferrous	5.707	5.2%	−0.556	2.8%	N/A	N/A
Ferrous Metal	0.130	0.1%	−0.556	2.8%	N/A	N/A
Concrete	−0.211	-	−7.276	37.0%	N/A	N/A
Plastic	0.945	0.9%	−0.535	2.7%	−0.023	12.9%
Wood	−0.058	-	−2.418	12.3%	−0.106	59.8%
Glass	0.007	0.0%	−0.044	0.2%	N/A	N/A
Drywall	0.009	0.0%	−1.203	6.1%	N/A	N/A
Asphalt	101.988	93.6%	−5.954	30.3%	N/A	N/A

Among these C&D materials, asphalt showed the highest potential (94% of total share) for reducing the overall water footprint. This is due to recycling of asphalt producing a large amount of natural aggregate, which requires a large amount of water during its mining process. On the other hand, recycling of C&D wastes, such as wood, drywall, concrete and cardboard, did not show a significant contribution to water footprint savings. When compared to recycling, landfilling did not help the environmental sustainability, due to increasing water consumption.

It is important to note that landfilling of concrete and asphalt showed a higher water footprint value compared to other materials. This is because the waste composition of concrete and asphalt wastes was found to be the highest among C&D materials, and disposal of these materials through landfilling required a higher amount of water. In conclusion, a high recycling of metals, glass, plastic and paper should be encouraged by policy makers to diminish the net water footprint of the building-related construction wastes.

4.2. Optimization Results

Figure 3 presents the optimal recycling percentage of construction wastes with respect to each single objective. Mathematical optimization results show that 100% of cardboard, ferrous and non-ferrous metals, plastic and glass wastes should be recycled for maximizing economic and environmental benefits. For GHG gas reductions and water footprint savings, recycling of concrete waste, which accounts for 37% of total waste, is not found to be a feasible option. However, recycling a small portion of concrete makes a positive contribution to net economic savings and energy minimization. In addition, 100% recycling of asphalt waste is found to be a feasible policy when economic and GHG savings are under consideration. For economic savings, 100% recycling of ferrous and non-ferrous metals, asphalt, plastic and glass is suggested, whereas recycling of drywall is not found to be an economically feasible recycling strategy. On the other hand, approximately 100% of produced drywall should be recycled to maximize energy and GHG emissions savings, as well (see Figure 3).

After generating the output of this single objective optimization, a compromise programming model is used to determine the optimal set of recycling amounts when considering the maximization of all objectives, simultaneously. For this model, three points of the compromise set, such as a = 1, 2 and ∞, are calculated for decision analysis, and the percentage recycling rates are presented in Figure 4 for each waste material. Multi-criteria optimization results revealed that recycling of wood and concrete is not found to be a feasible solution when all objectives are aimed to be maximized. However, 100% recycling ferrous and non-ferrous metals, plastic, glass and cardboard will be a sound policy from economic and environmental perspectives. The recycling of a small portion of wood is suggested for a compromise solution in which *a* is infinity. However, this recycling rate is found to be negligible when compared to the recycling rates of other construction materials. According to optimization results, recycling of over 90% of drywall is suggested for the three points in the set. Consequently, by using the results of the LCA model in conjunction with the multi-objective optimization model, the decision makers will have a better understanding of optimum recycling rates of each building waste material (see Figure 4).

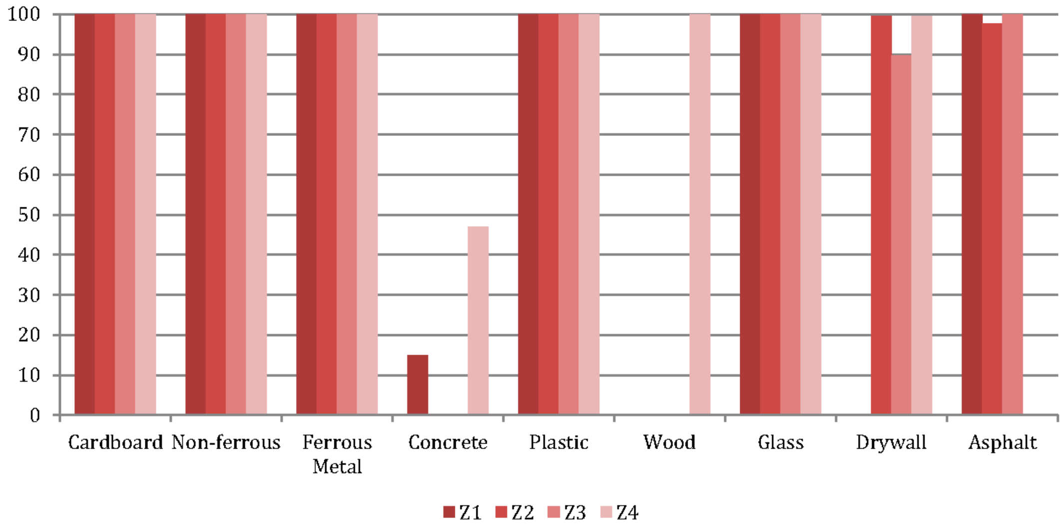

Figure 3. Optimal recycling percentages of C&D wastes for single objectives.

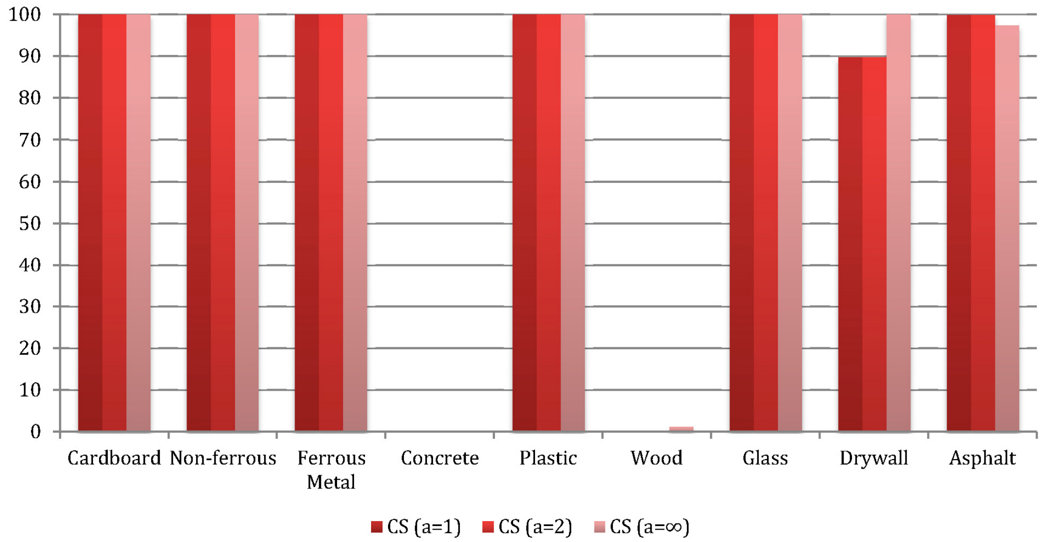

Figure 4. Optimal recycling percentages of C&D wastes for compromise solutions (CS).

5. Conclusions, Limitations and Future Work

The overarching goal of this research was to offer a decision making methodology for recycling of building materials, specifically for LEED-certified green buildings. This study is the first attempt to combine the EIO-based LCA model with multi-objective decisions analysis for construction waste management options. First, the EIO-based hybrid LCA model was used for quantifying the environmental impacts of building materials associated with different waste management scenarios. Second, a multi-criteria optimization model was developed to propose sustainable waste management strategies considering both environmental and economic impacts all together. Our analysis shows that recycling of asphalt and concrete increased the net carbon footprints due to high fuel consumption and emissions during the recycling process. Moreover, recycling of these materials has a minimum impact on the net energy footprint reductions. On the contrary, ferrous and non-ferrous metals are critical for reducing the net carbon footprint of waste management systems. In addition to that, 100% recycling of metals, plastic, glass and cardboard will be an economically- and environmentally-sound policy based on multi-objective optimization results. Even though the case study focuses on a LEED-certified university building, the proposed approach can be robustly integrated for other types of buildings as long as comprehensive C&D waste data are readily available.

It is critical to note that this work presents an integrated decision making framework combining optimization and LCA methods. Our results are based on recycling of 50% of total C&D debris for a selected LEED-certified university building in the United States. Based on assumptions made and the collected data, recycling of concrete is not found to be a feasible option when environmental and economic impacts are considered simultaneously. In other words, recycling of other C&D materials, such as ferrous and nonferrous metals, plastic and glass, is found to be a better strategy, and policy makers should give priority to these materials for recycling. On the other hand, our results still showed that recycling of concrete has a positive contribution to the economy and environment in terms of cost and energy savings. Keeping in mind that among different types of C&D wastes, the composition of concrete waste is found to be higher than 80% of the volume of C&D waste in many countries, such as Australia and Japan, to minimize the concrete waste generated from construction activities, recycling of concrete waste is one of the best methods, and many studies propose that recycling concrete as aggregate for new concrete production can provide a cost-effective method for the construction industry and help save the environment [33,34].

It is certain that the net environmental impacts of C&D waste management are not limited to the findings presented in this study. The application domain of the proposed approach can be extended to other types of buildings, which is a horizontal research extension. Additionally, the vertical depth of the methodology can be further extended by adding different weight scenarios for economic *vs.* environmental impact domains for policy making. Ecological impacts due to toxic releases, hazardous waste generation and ground water pollution can also be considered for analyzing the environmental impacts of different waste treatment options. Additionally, a multi-criteria decision making model is used to select the most appropriate building-related waste materials to maximize environmental and economic savings. However, the social impacts of C&D waste recycling are still critical and can be considered for a more comprehensive sustainability analysis. Therefore, we plan to develop a multi-criteria-based decision making model to consider all economic, social and environmental impacts of waste recycling strategies for the future. In this way, it is possible to have an optimized solution for C&D recycling by considering the triple-bottom-line sustainability impacts. In addition, as a future research direction, further analyzing alternative buildings from different universities worldwide could provide a more comprehensive framework that can be used for sensitivity analysis purposes. Consequently, this research provides an important decision making model, which offers vital guidance for policy makers when developing environmentally- and economically-sound waste management policies.

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