

Article

Environmental Assessment of Alternative Strategies for the Management of Construction and Demolition Waste: A Life Cycle Approach

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Abstract: The management of solid waste is currently seen as one of the most important concerns that national authorities, particularly in south Europe, must address. In recent years, emphasis has begun to be paid to Construction and Demolition Waste (CDW) being the largest waste stream in the European Union that is produced by renovation and repair work on buildings, roads, bridges, and other constructions made of bulky materials such as asphalt, bricks, wood, and plastic. Many EU countries responded quickly as a result of the large amounts of such waste and the presence of hazardous substances in their composition. This study illustrates the anticipated outcomes of several CDW management strategies other than final disposal, such as recycling, reuse, and incineration, for a public-school building in Greece. In order to assess how well the chosen schemes performed in terms of various environmental criteria, the SimaPro software suite and the Ecoinvent v.3 Life Cycle Inventory database were used. In order to enhance the quality of the outcomes, inventory data from earlier studies were also employed as input data for the Life Cycle Assessment tool.

Keywords: Construction and Demolition Waste; Environmental Impact Assessment; Life Cycle Inventory; Life Cycle Assessment

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1. Introduction

Global high-speed urbanization entails the increased demand for building developments, energy, food, fiber, feed, and transportation. Therefore, waste generation as a result of urbanization is outpacing the rate of population growth itself [1–7]. The construction industry is well known for its negative environmental implications, which are related with both raw material production and extraction, as well as project execution [1,2,8–10]. Some of the sector's most significant impacts are associated with the development of Construction Waste (CW), which, according to Sols-Guzmán et al. (2009) [11], has become increasingly substantial due to the accelerated growth of cities [12].

It should be highlighted that the construction industry engages multibillion euro activities throughout the European Union (EU) which ends up in 0.66 t waste per capita annually on average among EU Member states. Thus, Construction and Demolition Waste (CDW) constitutes the largest waste stream in EU, representing 25–30% of the total waste generated [13]. Due to the adverse environmental impacts and the high levels of waste production, CDW management has become a priority in the sustainable development agenda [14]. Worldwide, the relevant legislations and policies follow the well-known waste management prioritization of the 3Rs or 4Rs principles, i.e., 'reduce', 'reuse', 'recycle', and 'recover' [15,16]. To this end, the European Commission also provides guidance

to achieve resource efficiency in the construction sector including circularity as a billowing opportunity [13]. The proposed waste reuse strategy is based on the 70% CDW recovery rate goal by 2020 set by the EU Waste Framework Directive (2008/98/EC) [17] which is also driven by the new Circular Economy Action Plan [18].

Although the goal was averagely overachieved with 89% recovery rate among EU-28, practices such as backfilling and low-grade recovery, are still followed undermining the effort of a genuine circular transformation of the economy. As reported by Saez and Osmani, the key barriers in the CDW recovery include inefficient regulatory issues, poor end-of-life logistics, dubious CDW data inventory, and low market acceptance for CDW recycled materials [19]. Low reuse of CDW is also discussed by several researchers. For instance, it was observed that only 10% of the CDW generated is reused as raw materials in Hanoi, Vietnam exposing feasibility and legislative issues, while in China almost 80% is discarded to landfills and reuse accounts only for 3% [20,21]. At the same time, the recovery rate ranges from 10 to 90% among Member States, e.g., Germany 34%, Spain 37.9%, France 47.5%, and United Kingdom 89.9% [14,16], although these high recovery rates might be misleading due to limited information provided on whether the recovered materials are further used in high-grade or low-grade applications [22].

The cost of removing hazardous materials implies another hurdle in CDW recovery, and the implementation of end-of-waste criteria in order to simplify extended legislation related to hazardous waste is important [23]. More specifically, Diotti et al. (2020) [24] analyzed the CDW and recycled aggregates' contaminants in a leaching test exposing the most important chemical compounds limiting the recovery of these materials and invoking the need for a selective demolition. The importance of immediate separation of hazardous and non-hazardous materials of CDW is also highlighted by Weil et al. (2006) [25].

To fully exploit the recoverability of CDW, it is necessary to establish marketplaces for these secondary materials, standardize their quality, and increase price competition of recycled CDW materials. Recovered metal and glass have already gained access to markets in contrast to ceramics bricks and concrete which have a rising opportunity to do so [26]. Demolition wood used for energy recovery in Combined Heat and Power (CHP) Plants is already regulated in the EU in terms of exhaust specifications by the Waste Incineration Directive and constitutes an advantageous solution considering that higher level of contaminants can be released and contains low sensitivity in quantitative downturns. Iacovidou et al. (2016) [27] analytically presented the potential of reusability rates of CDW components, while Clarence Ginga et al. (2020) [28] carried out extensive research on CDW component reuse and recycling globally.

To date, there are countries with significant achievements in the field of CDW recovery, such as Denmark, the Netherlands, and Belgium [15,29,30]. Based on their example, optimal CDW management practices would dictate audit of CDW components, selective demolition/dismantle process, separation of hazardous and non-hazardous materials, classification of the non-hazardous materials as suggested also by the EU Construction and Demolition Waste Management Protocol [31]. It is worth noting that there are numerous projects around EU member states that have a high potential for replication and success in achieving the WFD recovery target as well as improving sustainable CDW management techniques [30].

Nevertheless, the Greek reality differs from the European. Materials such as wires, glass, and door/window frames are frequently reused. In addition that, the materials recovered are mostly used as aggregates for rural road paving [32]. Some volumes end up in landfills, however the majority are still disposed of in uncontrolled sites [8,33]. This, in combination with the lack of a centralized reporting system, as well as an authorized network for collecting and utilizing the materials contained in created CDW, results in one of the EU28's lowest recovery and recycling rate [8,33]. The lack of trustworthy statistics on CDW generation, as well as the absence of monitoring procedures, make it difficult to fully assess national performance [32,34]. Until recently, the activities taken have been fragmented and rely on the individual willingness and initiative of those responsible for

building or demolition. Currently, the existing CDW treatment facilities in Greece primarily treat the mineral component of CDW, while metals, plastics, and glass are transported to other recycling facilities that handle each specialized material fraction [35]. A more recent study for the promotion of improved techniques in CDW in Greece highlighted the introduction of untreated CDW landfill disposal taxation since 2014 and the increase of reuse/recycling to 50% in 2019 [36].

The environmental assessment of CDW management systems is a usual practice applied in recent years in order to support the decision-making process and alignment with the national and global regulatory frameworks [37]. To this end, research and data analysis led to the development of several indicators for the assessment of the efficiency and sustainability of CDW management, thus, pointing out the critical factors to be improved, emphasizing in legislation gaps [38,39]. Zorpas (2020) [40] expounded a useful methodology for policy-making regarding material reuse and recycle. In this context, Life Cycle Assessment (LCA) is increasingly applied as a useful tool for the investigation of the best practices and alternative scenarios for CDW management as well as the evaluation of their environmental behavior [41–43].

In general, LCA studies on CDW have been performed to examine the environmental impacts of buildings' end-of-life [44–49], to assess the environmental impacts of recycling processes [8,9,33,50], and to analyze the environmental performance of C&DW management systems [15,49–55]. In addition, several LCA studies have provided useful data and guidelines towards greater sustainability in the CDW life cycle. For instance, Butera et al. showed that CDW reuse for road construction purposes is a more preferable technique than landfilling, while issuing a warning on the environmentally optimal distance to be covered for the transportation of CDWs, setting the limit at 40 km [56]. In order to deploy realistic alternative practices that could also cover future tendencies and trends, recent advances in the research of CDW recycling should be included. Nedeljkovic et al. conducted an extended review on fine Recycled Concrete Aggregates (fRCA) properties and their use in concrete mix [10].

The overall aim of this study is to assess the environmental benefits and burdens associated to different CDW management practices in Greek public buildings. More specifically, seven different scenarios will be developed and examined, taking into account current end-of-life practices as well as a relatively technologically advanced scenario containing various identified best practices of recycle, recovery, and reuse of waste materials. Finally, their environmental impact will be assessed and compared using the SimaPro software [57]. As a case study, a typical school building will be used to evaluate the selected waste management schemes in the seven different scenarios [58].

2. Materials and Methods

2.1. Methodology

The aim of this study is to evaluate multiple waste management schemes for CDW, including final disposal as analyzed in the Inventory Analysis section. The evaluation of the selected schemes was conducted the use of Life Cycle Assessment methodology utilizing the SimaPro 7 [59] software as a supporting tool to carry out the assessment. In addition, inventory data from previous research were used as input data for the LCA modeling to improve the quality of the results. For this reason, a public-school building in Greece was selected, as case study, for testing the proposed practices of CDW management schemes application.

In general, LCA is conducted in four main phases, namely (i) Goal and Scope Definition, (ii) Life Cycle Inventory (LCI), (iii) Life Cycle Impact Assessment (LCIA), and (iv) visualization of the results. Concerning the "Goal and Scope Definition" phase, this includes the determination of the overall objectives and the system boundaries of the pilot study, as well as the selection of the sources of data used for the analysis. On the other hand, during the LCI (Phase 2), a detailed compilation of all the environmental inputs

(material and energy) and outputs (air, water, and solid emissions) takes place at each stage of the life cycle. Moreover, in Phase 3, the environmental burdens identified in Phase 2 are analyzed in terms of their importance and effects during each of the selected waste management schemes.

The main framework of an LCIA method considers both mandatory elements (classification and characterization) that convert LCI results into indicators for each impact category and optional elements (normalization and weighting) using numerical factors based on value-choices. In this context, in total, 11 indicators, also mentioned in ISO 14040-1 standard, were considered during the LCA process as presented in Table 1.

Table 1. Environmental indicators in the CML method.

Indicators	Description
AD—Abiotic Depletion	Indicator of the use of nonrenewable sources for energy production
ADF—Abiotic Depletion (fossil fuels)	Indicator of fossil fuel extraction
GWP—Global Warming Potential	Indicator relevant to the GH effect according to IPCC
ODP—Ozone Depletion Potential	Indicator relevant to the stratospheric ozone depletion phenomenon
HT—Human Toxicity	Indicator of consequences of toxic substances
FWAE—Fresh Water Aquatic Ecotox	Indicator of products' ecotoxic impacts on fresh water
MAE—Marine Aquatic Ecotoxicity	Indicator of toxic substances impact on the marine ecosystem
TE—Terrestrial Ecotoxicity	Indicator of toxic substances' impacts on terrestrial ecosystems
PO—Photochemical Oxidation	Indicator of photo-smog creation
AP—Acidification Potential	Indicator relevant to the acid rain phenomenon
EP—Eutrophication Potential	Indicator relevant to surface water eutrophication

2.2. Functional Unit and System Boundaries and Expansion

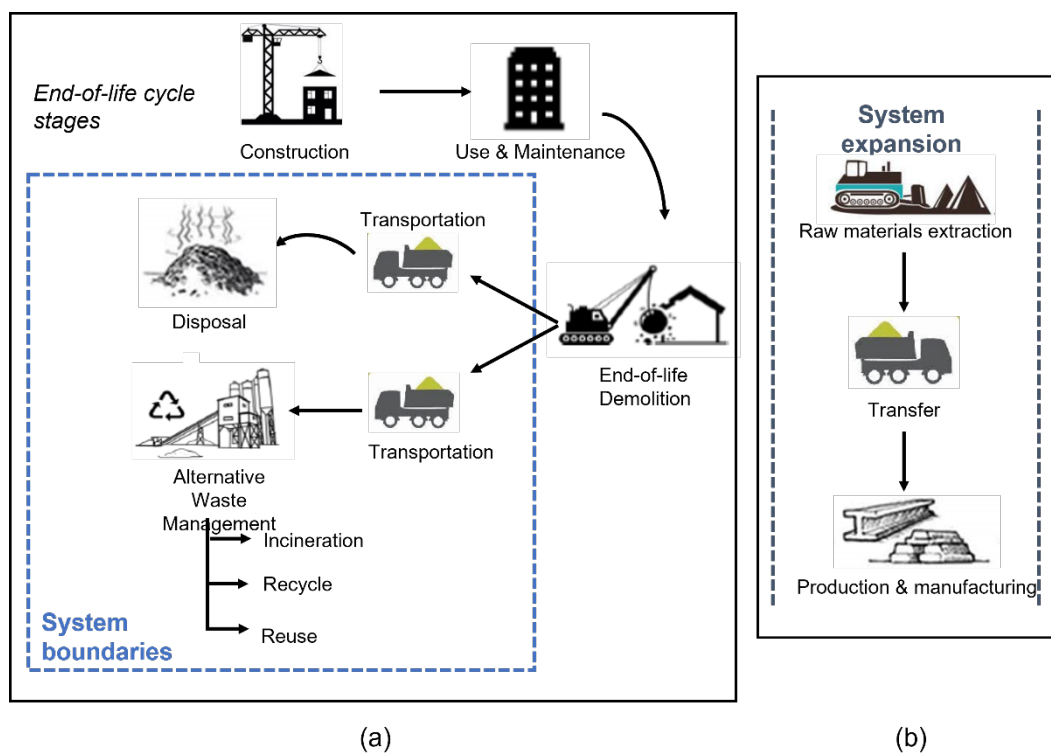
Greece currently has 15,446 schools, of which 4500 are over 45 years old [58]. More specifically, based on official data, only about 40% of the existing buildings are considered relatively new, since they were constructed after 1985 [60,61]. Consequently, the demolition of the existing school buildings and their replacement with new, environmentally friendly, and energy efficient ones will be an urgent need within the next years, also in alignment with the European and national frameworks and directives. In this context, the proposed CDW management practices were tested and evaluated using the LCA method in a public-school building in Greece. In particular, the selected high school building was constructed in 2016 in the municipality of Kassandra located in the peninsula of Halkidiki in northern Greece. The total building area of the 2-story building is 985 m².

The system boundaries of the case study under consideration are illustrated in Figure 1a. It is clearly depicted that only the last phase of the building's life cycle (end-of-life phase) has been included in the LCA model. In addition, the types of waste produced by the building demolition (system boundaries) include metals (steel, aluminum, copper, and zinc), inert waste (tiles, concrete, bricks, ceramic materials, stones, clinker), wood, plaster, plastic (PVC), glass, and insulation materials and they are presented in Table 2.

Table 2. CDW quantities produced by school building demolition in the Municipality of Kassandra.

Material	EWC Code	Quantity	Material	EWC Code	Quantity
1. Concrete	17 01 01	1374.72 m ³	11. Iron and steel (pipes)	17 04 05	3.02 t
2. Bricks	17 01 02	181.90 t	12. Reinforcing steel	17 04 05	215.47 t
3. Ceramic tiles	17 01 03	14.82 t	13. Insulation materials	17 06 04	2.74 t
4. Sanitary ware	17 01 03	1.41 t	14. Cables	17 04 11	3381.00 m
5. Marbles	17 01 03	75.92 t	15. Cement mortar	17 01 07	3.80 t
6. Wood	17 02 01		<i>Other material</i>		
7. Glass	17 02 02	972.70 m ²	Windows frame	17 04 02	48.30 m ²
8. Plastic (pipes)	17 02 03	0.43 t	Steel	17 04 05	238.79 t
9. Aluminum (cladding)	17 04 02	660.00 m ²	Doors	17 02 01	137.00 m ²
10. Iron and steel (boiler)	17 04 05	0.31 t	Cement plaster	17 01 07	130.91 m ³

Furthermore, the system expansion is illustrated in Figure 1b showing the extension of the system boundaries by adding the following processes: (a) Raw materials mining, (b) materials transfer, and (c) production and manufacturing processes replacing procedures such as reuse, recycling, and incineration. In this light, the environmental burdens of the production processes were excluded from the LCA model [62].

**Figure 1.** CDW management methods, system boundaries (a) and expansion (b).

2.3. Inventory Analysis

The evaluation of the different CDW management schemes was conducted by using LCA method under seven scenarios of unique or parallel application of a variety of the above schemes/practices. The proposed practices included the strategies of reuse, recycling, energy recovery, and final disposal in landfills which would be adopted by the construction industry (i.e., constructors, engineers, public authorities) [63].

All strategies have already been implemented in real life case studies and were evaluated in terms of the environmental, economic, and social scope. In addition, in all scenarios, the process of demolishing the building (either for traditional demolition or for

selective demolition) is excluded, while the transportation and treatment process of each of the waste streams is included in the system boundaries. Furthermore, in all scenarios examined, it was assumed that the transportation is being held with a 16-32tn lorry, EURO 5, diesel technology according to Ecoinvent v.3 Life Cycle Inventory database for road transportations.

Moreover, in the case study, the assumption that the distance covered by empty lorries are also included in the calculations is made. More specifically, the distance to the sanitary landfill is considered 40 km, to the sorting plant 20 km, to the recycling plant 50 km, and to the incineration facility 70 km, while in the case of waste reuse, there is no need for waste transferring. The types of the produced waste are presented in Table 2.

The LCA study was conducted using the CML 2001 method for the necessary calculations of the environmental impacts of all scenarios. The selected scenarios of CDW management schemes are presented in detail as follows.

Scenario 1 (S₁): In this scenario, the school building is demolished without any sorting of the different inert materials. All types of the produced waste are transferred directly to the sanitary landfill for final disposal.

Scenario 2 (S₂): The CDW is managed by using three separate schemes, waste sorting, landfilling, and recycling. All waste fractions are transferred to a sorting plant (Sorting plant with crusher: 3.7 kWh/ton), while waste fractions No 1–8 and 13–15 are delivered to the sanitary landfill and No 9–12 to the recycling plant.

Scenario 3 (S₃): The school building is also demolished without prior materials sorting and all waste fractions are delivered to a sorting plant. After sorting, glass, insulation materials, and cables are disposed of in the landfill, aluminum and reinforcing steel are recycled, wood and plastic pipes are burned in an incinerator for energy production, and cement mortar and waste No 1–15 are reused for clinker production in a unit at a 100 km distance. Energy produced by incineration is recovered in electricity and thermal power (in the study area, no incineration plant exists. Thus, it is assumed that a plant is located 70 km away from the school building).

Scenario 4 (S₄): In this scenario, on-site waste sorting takes place (selective deconstruction—all non-hazardous and hazardous components are removed before demolition of the building structures). All waste fractions, except for metals and glass which are recycled, go to sanitary landfill.

Scenario 5 (S₅): On-site waste sorting. Inert waste (No 1–5 and 15) is recovered in road engineering. Aluminum, glass, and insulation materials are recycled. Wood waste is used as fuel for district heating (in the study area, no combustion plant exists, thus, wood waste is assumed to be transferred in a plant 230 km away) and the rest of non-dangerous waste are delivered to a sanitary landfill.

Scenario 6 (S₆): The difference between this scenario and Scenario 5 is that inert waste is transferred to a cement plant 100 km away from the school building and used to produce new concrete blocks as raw material. The making of concrete blocks with recycled aggregates requires the addition of natural aggregates and increasing of the cement content in relation to standard concrete block composition, in order to have the same technical characteristics as those of usual concrete blocks.

Scenario 7 (S₇): This scenario is almost the same as Scenario 6, but with the difference that wood waste is transferred to a cement plant with other inert waste for clinker production and not to a burning plant for energy recovery.

3. Results and Discussion

The evaluation of the selected CDW management schemes within the seven proposed scenarios revealed their environmental impact considering the eleven environmental indicators introduced by CML method (Table 1). The results of this analysis are presented in Figure 2, while Table 3 shows the detailed information for each indicator.

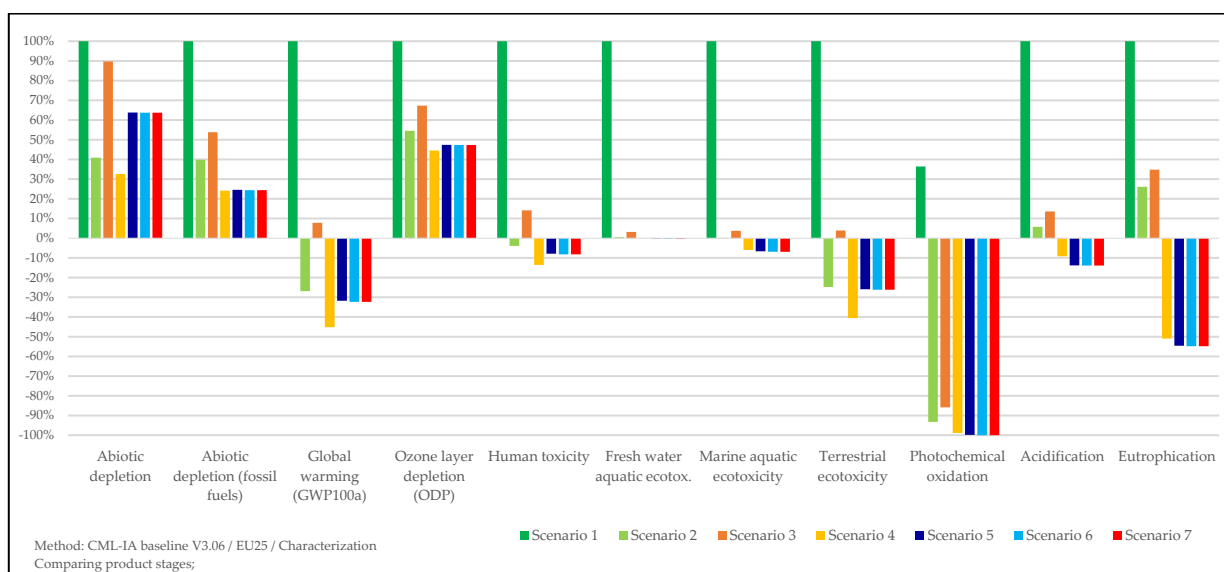


Figure 2. Environmental impact of CDW management schemes within selected scenarios.

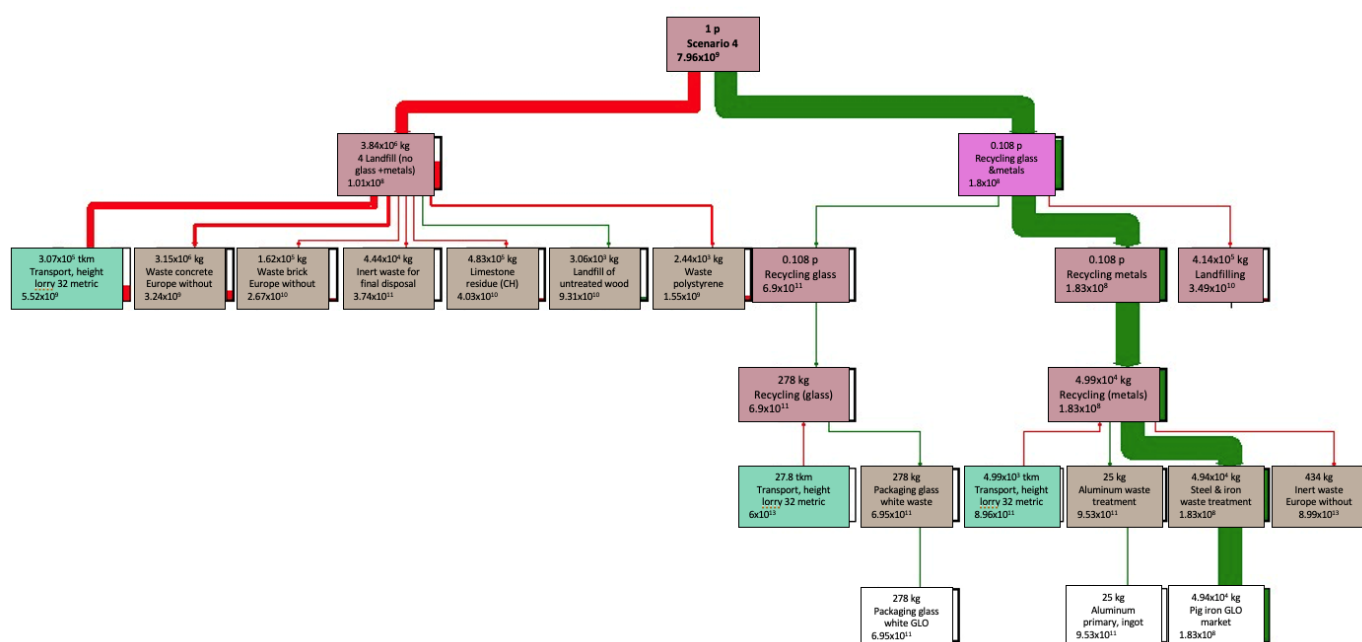
Based on the above results, it can be assumed that Scenario 1 is the worst among the others showing severe environmental impact regarding all the selected indicators. When compared to alternative management systems, the high level of environmental burdens in all impact categories is related to the lack of reuse and disposal of all waste generated in landfills. Thus, uncontrolled landfilling is considered the most undesirable CDW management scheme. In general, all scenarios seem to have significant environmental impact in terms of the abiotic depletion and ozone layer depletion. In particular, the ADF category reflects the impact of diesel consumption. To this end, and mainly due to the transportation included in all scenarios, the results are comparable for all cases. Similarly, ODP is highly affected by the transport distance considered for the different scenarios. Furthermore, Scenario 3 which includes all schemes, landfilling, recycling, reuse, and incineration, has an impact on all indicators except for the indicator of photochemical oxidation. More specifically, landfilling contributes the most to FWAE and MAE, while incineration affects ADF. Moreover, this scenario makes clear how CDW transportation has a significant impact on the environmental benefits of recycling.

On the other hand, no other scenarios (2, 4, 5, 6, 7) have an impact concerning global warming, human toxicity, marine aquatic ecotoxicity, acidification, eutrophication, and especially photochemical oxidation. It is expected that recovering recyclable aggregates will enable a reduction in most of the examined environmental impact categories. In addition, according to Figure 2, Scenario 4, which includes only CDW landfilling, and recycling appear to show the lowest impact in almost all the selected environmental indicators. Scenario 4 has an impact on abiotic depletion and ozone layer depletion and no environmental impact in terms of the rest of the indicators. This is due to the limited waste transport to only few waste management facilities (e.g., to the landfill and glass and metal recycling facility), as well as the absence of incineration or other energy intensive processes, such as the combustion of wood waste streams as a fuel.

Table 3. Evaluation of CDW management schemes' scenarios on their environmental impact.

Impact Category	S1	S2	S3	S4	S5	S6	S7
AD (kg Sb eq)	1.17	0.479	1.05	0.382	0.749	0.747	0.747
ADF (MJ)	1.54×10^6	6.14×10^5	8.28×10^5	3.72×10^5	3.77×10^5	3.76×10^5	3.76×10^5
GWP (kg CO ₂ eq)	8.85×10^6	2.38×10^{-4}	6.95×10^3	4×10^{-4}	2.81×10^{-4}	2.86×10^{-4}	2.86×10^{-4}
ODP (kg CFC-11 eq)	0.0207	0.0113	0.0139	0.0092	0.0098	0.0098	0.0098
HT (kg 1,4-DB eq)	1.01×10^5	3.9×10^{-3}	1.43×10^4	1.37×10^{-4}	7.95×10^{-3}	8.28×10^{-3}	8.28×10^3
FWAE (kg 1,4-DB eq)	2.05×10^6	9.73×10^3	6.49×10^4	1.96×10^{-3}	2.77×10^{-3}	7.05×10^{-3}	7.05×10^{-3}
MAE (kg 1,4-DB eq)	6.45×10^8	1.26×10^6	2.41×10^7	3.88×10^{-7}	4.28×10^{-7}	4.43×10^{-7}	4.43×10^{-7}
TE (kg 1,4-DB eq)	186	-46.2	7.24	-75.53	-48.36	-48.76	-48.76
PO (kg C ₂ H ₄ eq)	15.55	-39.83	-36.67	-42.22	-42.64	-42.70	-42.70
AP (kg SO ₂ eq)	491.82	28.42	67.00	-44.92	-67.77	-68.41	-68.41
EP (kg PO ₄ eq)	119.30	31.13	41.53	-60.72	-65.10	-65.38	-65.39

The above conclusion is also indicated by the 'Network process' which represents the visualization of environmental impacts for specific indicators of SimaPro software as shown in Figure 3. It should be noted that red lines indicate the environmental burdens, while green lines depict the environmental benefits.

**Figure 3.** Environmental impact of Scenario 4 regarding the global warming indicator.

According to the findings of the provided LCA analysis, recycling is critical for mitigating the effects of the CDW management system. Although steel and aluminum account for only approximately 5 percent of the CDW composition, they play a significant role in the overall environmental performance of the management system. Furthermore, the avoided impacts from the recycle of glass and plastic must not be overlooked as well, even though they are lesser than those from steel. Moreover, due to the massive amounts of waste transported and the long distances traveled, transportation is one of the most significant steps in CDW management, as it has been observed in the analysis. To this end, the scenarios that present the best performance are Scenario 4 and Scenario 7, since they provide either minimum transport or great rates of recycling. Table 4 presents the optimal scenarios that need to be adopted per impact category.

Table 4. Best and worst scenarios per impact category.

Impact Categories	Best Performance Scenario	Worst Performance Scenario
Abiotic depletion	Scenario 4	Scenario 1
Abiotic depletion (fossil fuels)	Scenario 4	Scenario 1
Global warming (GWP100a)	Scenario 4	Scenario 1
Ozone layer depletion (ODP)	Scenario 4	Scenario 1
Human toxicity	Scenario 4	Scenario 1
Fresh water aquatic ecotoxicity	Scenario 7	Scenario 1
Marine aquatic ecotoxicity	Scenario 7	Scenario 1
Terrestrial ecotoxicity	Scenario 4	Scenario 1
Photochemical oxidation	Scenario 7	Scenario 1
Acidification	Scenario 7	Scenario 1
Eutrophication	Scenario 7	Scenario 1

4. Conclusions

CDW management is a very important environmental issue for regional and local waste management authorities. This is indicated also by the EU directives that promote new schemes for managing this waste fraction. This study evaluated CDW management schemes other than final disposal—recycling, reuse, incineration—concerning their environmental impact on several selected indicators. LCA provided evaluation data that helped in ranking the available methods.

The evaluation results revealed that deconstruction/selective demolition is a good practice required to achieve sustainable CDW management, along with the use of environmentally friendly building materials; the replacement of hazardous substances and materials; the development of construction materials' secondary market; and the adoption of stricter legislation framework. In addition, the recycling of metals and glass has a positive impact in terms of environmental impact and lead to an optimized waste management scheme. However, the higher the recycling rates, the greater the impact of transportation. In fact, the significance of transportation distances between the CDW production site to the MRF, where recycling aggregates are generated, rises with the expansion in selective collection. As a result, higher waste streams handled at the sorting plant result in greater impacts from the transportation of potentially recyclable items. Thus, an effective method for collecting CDW and distributing aggregates is required.

A waste management strategy is not effective without a good sorting of different types of waste. For CDW, recovery of aggregates for road engineering is a better solution than the use of these aggregates to produce concrete blocks. The poor technical characteristics of recycled aggregates that are involved in the making of concrete blocks are not environmentally and economically efficient in comparison to concrete blocks produced with natural aggregates. The results of this study can be considered as a roadmap for regional and local authorities in implementing good CDW management while refreshing their building stock.

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