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Quantification of carbon emission of construction waste by using streamlined LCA: a case study of Shenzhen, China

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Abstract Currently, the majority of the construction waste (CW) has been collected without classification and simply disposed in China. To quantify the environmental impacts and provide reasonable policy recommendations, this paper conducted an assessment for the life cycle carbon emissions (CEs) for CW based on a streamlined life cycle assessment method. Three typical CW management approaches in Shenzhen City were selected to perform the case study and comparative analysis. The results show that scenario I with low recycling rate generates the largest CEs amount by 542.56 kg for 1 ton CW, followed by scenarios II and scenario III that generate 538.61 and 483.85 kg, respectively. In addition, the results show the material embody impact is the largest contributor to CEs for CW examined, accounting for 78 % of the total amount in the overall life cycle. Analysis results also show that wood, steel and concrete wastes are the top three contributors within nine materials, with proportions of 25, 23 and 13 %, respectively. Therefore, the most effective way to decrease the CEs of CW is minimizing the generation of CW, since the CEs of the majority of waste are not sensitive to alteration of treatment methods or recycling rate.

Keywords Construction waste · Waste management · Carbon emission · Streamlined LCA

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Introduction

During the construction activities, some materials failed to be formed to the building components but generated the construction waste (CW) owning to various reasons, which include but not limited to improper procurement and planning, inefficient material handling, residues of raw materials and unexpected changes of building design [1, 2]. According to China resources comprehensive utilization annual report 2014, more than 1 billion tons of construction and demolition wastes (C&D waste) were generated in China in 2013, and a quarter of them were CW [3]. However, only 10 % of CW was recycled, while the majority remained to be simply landfilled or just dumped [4], despite CW having been proved to be a kind of high potential recovery resource since 80 % of them can be recycled [5]. Moreover, CW has created negative impacts on environment (water and soil pollution, air pollution, climate change and adverse effects on flora and fauna), economy (loss of primary resources, international reputation, effect on tourism and fuel consumption in transportation) and public health and social life (health hazards, use of public space, proliferation of pests and impact on working safety) [6]. In addition, when new landfill construction has been confronted by opposition and pressure from social strains, episodic events of illegal waste dumping around the area of industrial estates have arisen [7]. Worldwide, particularly in many developing countries, the huge amount of CW has imposed a lot of pressure on landfills and triggered people's concerns about environmental issues [8].

Since the 1980s, researchers have paid attention to finding effective measures and strategies to solve CW-related problems. One of the most widely known measures is the "CW management hierarchy", which refers to reduction, reuse, recycling and disposal [9]. Yet, this order of priorities does not ensure the minimization of environmental impacts of waste management systems or the optimal combination possible [10]. To address this issue, some applications of the life cycle assessment (LCA) methodology to C&D waste management have been reported in the literature [11, 12, 13, 14]. However, there is constraint in the wide application of the approach, due to shortage and weak representation of basic data [15]. Thus, a so-called streamlined life cycle assessment (SLCA) method is proposed, which is designed to achieve the full functionalities of LCA with lower costs of data collection and analysis and still reliable analytical results [16, 17, 18].

This study aims to be based on a sensible, credible, and flexible methodology—streamlined LCA—that maps the intrinsic attributes of CW to greenhouse gas (GHG) emissions by assessment of its carbon emissions (CEs). It aims to reveal opportunities to reduce the carbon impact of CW by identifying the key drivers of GHG impacts, as well as to examine the difference by comparing several scenarios. The assessment considers emissions across the overall life cycle of CW. Existing information drawn from the most relevant available data sources is leveraged to create the best possible preliminary estimate. Statistical simulations are then performed to quantify the uncertainty and evaluate our confidence in the GHG “hotspots”. Because it is helpful to build the methodology around waste that has been extensively studied, CW was initially targeted for demonstration.

Methodology

Streamlined LCA application

This study is mainly based on the SLCA methodology which is frequently employed in the research by Olivetti and Duan [17, 18]. The merits of the SLCA model include data management, process analysis and results expression, as well as considering the uncertainty and sensitivity analysis. The application of the model with high efficiency and low analysis cost could make researchers break away from the dependence on professional software. There are three core steps involved in the SLCA, each described in detail below:

- First, identifying and aggregating sources of data by reviewing academic literature concerning LCA of related or similar studies, commercial life cycle inventory (LCI) databases, existing industry analyses of components or products of interest, and some limited primary data collection processes. These data were carefully examined and comparably evaluated, with the aim of creating the best possible preliminary estimate through the use of existing data.
- Second, Monte Carlo statistical simulations were performed to capture the uncertainty and sensitivity using Crystal Ball software. 1000 trials for each parameter were drawn for each run. After each run of 1000 trials, the average, standard deviation, and the range encompassing 95 % of observed CEs were recorded and analyzed. The objectives of this step were to measure, prioritize, and potentially minimize uncertainty in the footprint result. Understanding uncertainty helps to improve confidence in composition comparisons as well as any decisions that might be made based on the footprint.
- Last, a contribution analysis was also undertaken to sort the impacts of components within a product or materials. The goal of the contribution analysis was to determine the set of interest (SOI), which is the subset of components or materials that make up the majority of the environmental impact of the study object. The SOI was helpful in characterizing the object’s overall impact. In addition, the SOI allowed us to identify which activities contribute most to the variance of the result, leading to an understanding of which activities could be targeted for further evaluation to lower the overall uncertainty in the result.

Goal and scope

The main goal of this study is to assess the environmental impacts of CW. The environmental impacts associated with the life cycle of these waste materials are considered as CEs (equivalent emissions-CO_2, eqv CO_2). Characterization factors included the GHGs CH_4, N_2O and carbon dioxide (CO_2), and global warming potentials of 1.25 and 298 were used to convert CO_2, CH_4 and N_2O emissions into CO_2 equivalents (CO_2 eq), respectively. The functional unit is defined as the total waste of 1000 kg t^{-1} of generated waste corresponding from the process of carrying out construction work. Three main processes of CW’s life cycle such as material embody impact, transportation, and end of life were analyzed for nine different CW materials: iron, steel, aluminum, copper, concrete, concrete block, brick, mortar, and wood. Particularly, the materials embody impact including the CEs generated during the process from the extraction of raw materials to the formation of construction materials. The impacts of transportation stage considered the emissions from the transportation of construction materials from the material production factories to the construction sites. Additionally, the end-of-life stage considered four treatment approaches, which can be determined including recycling, inert material landfill, sanitary landfill, and incineration. Figure 1 presents the processes considered in the life cycle of CW.

The City of Shenzhen in China has been taken as a study case. Three scenarios including low, advance, and ideal, representing the different recovery efficiency of waste management in Shenzhen have been considered. Table 1 describes the classification and composition of CW and the scenarios under this study.

Low efficient recovery scenario (scenario I)

The majority of CW remains to be simply landfilled, or just to be illegally dumped. Only 10 % of them were recycled in the past in Shenzhen as well as currently in many cities of China [4]. Under this scenario, the recycling rate is quite low, and the inert waste is mainly landfill and wood is incinerated. As a consequence, the treatment of CW would create negative impacts on environment.

Advance efficient recovery scenario (scenario II)

In current CW management practices in Shenzhen, the disposal of CW is not by a single way, but by an integrated model that considers the types of waste. Normally, these high economic value waste-like metals were sorted out and the others collected, respectively, after being generated, while the rest of the CW would be transported to integrated treatment plants or landfills, or incineration plants. The integrated waste treatment plants are usually located near the landfills. Particularly, 40 % of concrete, 30 % of brick and block and 20 % of mortar can be recycled into concrete aggregate or water-permeable brick. 96 % of metal waste is recycled (it is assumed to be 100 % in the calculation of this study); wood waste is incinerated (without energy recovery) and the remaining part is dumped or landfilled.

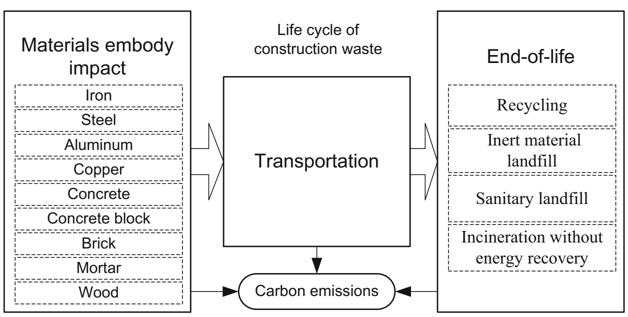


Fig. 1 Processes considered in the life cycle of construction waste

Ideal efficient recovery scenario (scenario III)

According to related literature, the recycling rate of CW had reached 50 % by 2005 in many European countries and in some countries reached 70–80 %, such as Denmark and the Netherlands [19]. Similarly, the rate reached 85 % in Japan by 2000 and also more than 50 % in Australia [20]. It is necessary to promote the recycling rate because it is the most effective way to solve problems of CW after generation. On considering this positive situation, an assumption is put forward in scenario III, which assumes that the recycling rate could be improved to be as high as possible.

Streamlined LCA model

Material embody impact

The material embody impacts are expressed as the CEs related to each activity, e.g., CO_2 emitted for every ton of materials, which is expressed as embodied materials impact

Table 1 Waste treatment scenarios and treatment methods

	Low (scenario I)	Advance (scenario II)	Ideal (scenario III)
Iron	80 % (R) and 20 % (SL)	100 % (R)	100 % (R)
Steel			
Aluminum			
Copper			
Concrete	100 % (IML)	40 % (R) and 60 % (IML)	
Concrete block		40 % (R) and 60 % (IML)	
Brick		30 % (R) and 70 % (IML)	
Mortar		20 % (R) and 80 % (IML)	
Wood	100 % (I)	100 % (I)	100 % (SL)
Overall recycling rate	8 %	34 %	72 %

Recycling methods: metal–melt recycling; concrete, mortar–concrete aggregate; brick–water permeable brick

R recycling (considering recovered materials would displace the raw materials), *IML* inert material landfill (landfill for inert waste like concrete, brick, mortar waste), *SL* sanitary landfill (landfill for non-inert waste like metal, wood waste), *I* incineration (incineration without energy recovery)

(E_i). CEs of material embody impact can be represented by (Eq. 1):

$$C_{\mathrm{Me-co_2}} = \sum_{i=1}^{9} W_i \times E_i, \quad (1)$$

where i refers to different types of waste (e.g., iron, steel, aluminum, copper, concrete, concrete block, brick, mortar and wood), $C_{\mathrm{Me-co_2}}$ refers to carbon emissions of material embody impact, W_i to weight of waste i, and E_i to carbon emissions for 1 ton of material i.

Transportation

In this study, only the China mainland has been taken into account to calculate the emission impact of the transportation phase (but only including the distribution of finished products, at the province and state level), using shipment data for focal products. The CEs (expressed as kg eqv CO_2/t km, C) correspond to transportation modes (by lorry and train, k). Since the waste transport distance from the site to the final treatment plant is immeasurable, it was therefore not taken into account. CEs of transportation stage can be represented by (Eq. 2).

$$C_{T-\mathrm{co_2}} = E_t \times \sum_{i=1}^{9} (W_i \times L_i^t) + E_l \times \sum_{i=1}^{9} (W_i \times L_i^l), \quad (2)$$

where i refers to different types of waste, $C_{T-\mathrm{co_2}}$ to carbon emissions of transportation stage, W_i to weight of waste i, L_i^k to transportation distance of waste i by the transportation mode k, E_k to carbon emissions per unit for different transportation modes.

End of life

The final stage is end of life, which was split into several scenarios in terms (i) of the CW management practices in China, including low efficient recovery scenario (scenario I), advanced efficient recovery scenario (scenario II), and ideal efficient recovery scenario (scenario III), which is noted as end of life (scenario I to scenario III). For different waste types, four treatment approaches can be determined including recycling, inert material landfill, sanitary landfill and incineration, in which deduction benefits should be considered when selecting recycling methods. The emission factor of i (expressed as kg eqv CO_2/t, E_{k_i}). Calculation of the CEs in end-of-life stages is expressed in Eq. 3:

$$C_{\mathrm{EL-co_2}} = \sum_{i=1}^{9} \left\{ W_i \times \sum_{k=1}^{4} (E_{k_i} \times P_{k_i}) \right\}, \quad (3)$$

where i refers to different types of waste, k to different treatment approaches, $C_{\mathrm{EL-co_2}}$ to carbon emissions of end-of-life stage, E_{k_i} to carbon emissions of material i with the treatment approach k, and P_{k_i} to the percentage of material i which is processed by the treatment method of k.

Inventory analysis

For the inventory analysis, the data introduced in this study were mainly come from three sources. For instance, the construction waste inventory was referenced from the Technical Code for Construction Waste Reduction (TCCWR, Shenzhen technical specifications, 2011). Besides, the transportation distances for different materials and wastes were referenced from the published data of the National Bureau of Statistics of the People's Republic of China (NBS, 2014). The Ecoinvent database was used to obtain the inventory data of the processes involved in the study. Table 2 shows the CW inventory; the data illustrate the average value of the amount of CW, including four building types such as residential, commercial, industry and public buildings in Shenzhen. The waste compositions are classified into four groups, namely metals, stone, wood and other construction wastes. As we can see, concrete was of the highest proportion when compared with other CW. In addition, metals, wood, mortar, and concrete brick were found to be in high quantities among the construction waste materials. Considering metals, steel has a considerable contribution to this kind of waste. After analyzing the waste compositions, it is important to understand the distance associated with the transportation of materials and wastes.

Table 2 Construction waste composition and transportation distance

Code	Metals	Weight (kg t^{-1})	Train (km)	Lorry (km)
0101	Iron	20.6	1124	100
0102	Steel	51.5	1124	100
0103	Aluminum	10.3	1124	100
0104	Copper	20.6	1124	100
Code	Stone	Weight (kg t^{-1})	Train (km)	Lorry (km)
0201	Concrete	526.0	0	100
0202	Concrete block	36.4	0	100
0203	Brick	15.6	0	100
0204	Mortar	42.0	0	100
Code	Wood	Weight (kg t^{-1})	Train (km)	Lorry (km)
0301	Wood	185.0	1131	100
Code	Others	Weight (kg t^{-1})	Train (km)	Lorry (km)
0401	Others	92.0		

Constrains and limitations

The reliability of the results and the conclusions of the LCA depend in large measure on the quality of the inventory data that is used.

Even though we conducted a selection of representative waste according to the data of TCCWR (Shenzhen technical specifications (2011), some of the compositions of construction wastes are challenging to identify and quantify, e.g., as plastic and foam wastes belong to other wastes. In addition, primary data on energy consumption during the manufacturing and assembly of the focal products are scarce. There is also incomplete information on details concerning transportation (collect waste to treatment plant), although this is not expected to contribute significantly to the life cycle emissions of CW.

In addition, there is uncertainty from the secondary data. There are sources of uncertainty in the commercial database, such as the emission factors and data obtained from the Ecoinvent database. This uncertainty may arise from measurement error, variation within processes, temporal discrepancies, and geographical distributions. There is also substantial uncertainty within data drawn from the literature due to differences in system boundary definition. However, such secondary data can be incorporated as proxies for primary data to simplify and streamline the evaluation process.

Because many of these data sources have been evaluated for uncertainty (distributions have been assigned), a Monte Carlo analysis is incorporated (with 1000 iterations) into the Product Attribute to Impact Algorithm (PAIA) methodology-based model to understand parameter uncertainty around the most sensitive aspects. The results are revealed either by mean value or percentile (5 and 95 %).

Results and discussion

Entire life cycle impact of 1 ton construction waste

The results of the CEs throughout the overall life cycle of 1 ton construction waste are specified in Fig. 2 and documented in Table 3. The material embody impact dominates the CEs of the life cycle, since there is a 95 % confidence

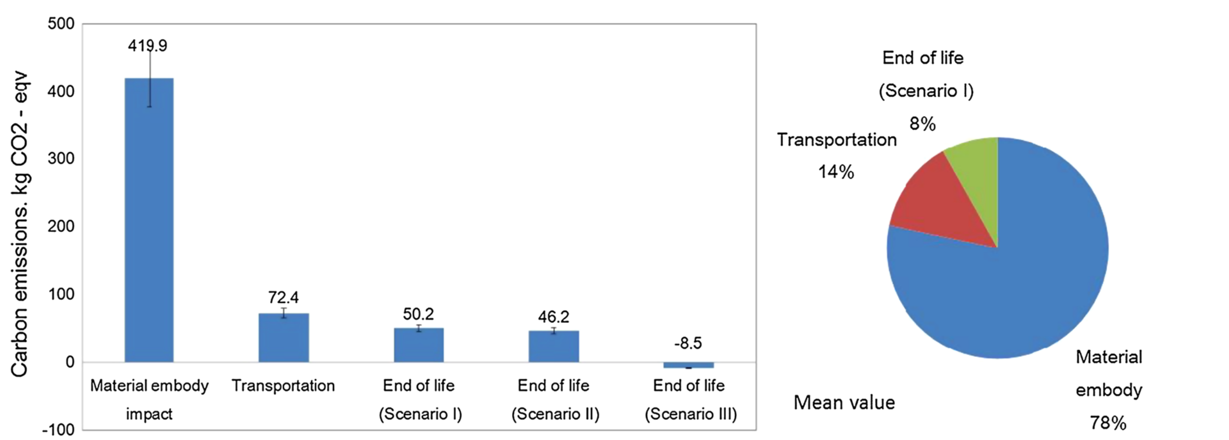


Fig. 2 Carbon emissions of life cycle stages of generated construction waste

Table 3 Entire life cycle impact for 1 ton construction waste and scenarios comprising results (measured by 1 t) (kg CO_2 eqv)

	Material embody impact	Transportation stage	End of life (scenario I)	End of life (scenario II)	End of life (scenario III)	Scenario I	Scenario II	Scenario III
Iron	30.93	4.78	−1.92	−2.43	−2.43	33.79	33.28	33.28
Steel	116.04	11.90	−2.24	−2.87	−2.87	125.70	125.07	125.07
Aluminum	64.65	2.39	−0.45	−0.57	−0.57	66.59	66.47	66.47
Copper	49.08	4.79	−0.9	−1.15	−1.15	52.97	52.72	52.72
Concrete	63.60	4.70	2.62	0.43	−2.87	70.92	68.73	65.43
Concrete block	18.19	0.33	0.18	0.05	−0.14	18.70	18.57	18.38
Brick	12.78	0.14	0.08	0.04	−0.05	13.00	12.96	12.87
Mortar	24.72	0.38	0.21	0.13	−0.16	25.31	25.23	24.94
Wood	39.95	43.02	52.61	52.61	1.72	135.58	135.58	84.69
Total	419.94	72.43	50.19	46.24	−8.50	542.56	538.61	483.85

level that the material embody impact exceeds 78 % of the total impact when considering scenario I in the end-of-life stage, while the transportation stage and end of life combined are responsible for around 14 and 8 % of total life cycle CEs. Since the recycled products could reduce the demand for raw materials during construction activity and benefit the environment, it would result in negative numbers in the CEs of end-of-life stage when considering scenario III. If considering scenario III in the calculation, the proportion of material embody impact would be more significant. Thus, minimizing the generation of CW is the most effective way in reducing CEs of CW due to the dominative contribution of material embody impact.

The last three columns in Table 3 are the accumulated value of life cycle CEs for three different scenarios. The CEs of scenario II is 538.61 kg per ton which is 11 % higher than scenario III (483.86 kg). However, the difference between scenario I and scenario II is not significant, despite that the treatment and disposal methods of CW are quite different. This is mainly because wood contributes the most CEs of the overall life cycle impacts, and safe landfill generates less CEs than incineration without energy recovery. Therefore, to minimize the CEs of CW, we should not focus on the treatment and disposal of metals and blocks, but aim at the wood waste.

Figure 3 shows the life cycle CEs of CW under the current CW management in Shenzhen (scenario II). The results indicate that the metal wastes contributed the largest. Iron, steel, aluminum and copper are considered to account for 51 % of CEs. Wood waste accounts for a quarter of the total CEs. Besides the block material waste, including concrete, mortar, concrete block, and brick share 24 % of total CEs. In general, wood, steel, and concrete wastes are the top three contributors, with proportions of 25, 23, and 13 %, respectively. The demonstrated results can be used as a baseline for CEs calculations. Any changes to product or process can be compared to this baseline to gauge the effectiveness of carbon mitigation projects.

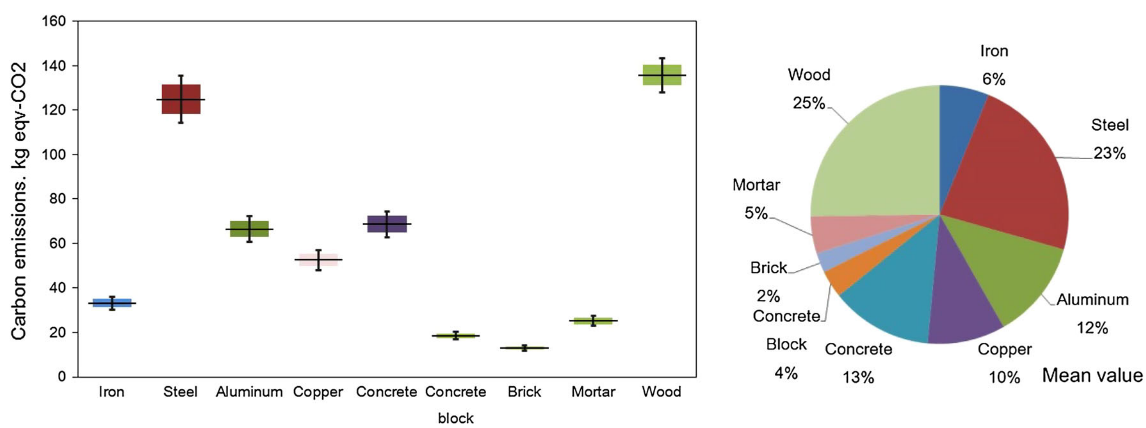
Contribution and sensitivity analysis

The goal of the methodology for contribution analysis developed is to determine the set of interest (SOI), or the list of components most important to resolve to fully characterize the impact. The findings show that five of the components (wood, steel concrete, aluminum and copper) account for move than 80 % of the total impact with a confidence of 95 %; and additionally there is a confidence level of 95 % in the assertion that the wood and steel contribute more than 40 % of the total impact, as shown in Fig. 4.

Figure 5 shows the sensitivity analysis results (contribution to variance, for material embody impact, transportation and end-of-life phases). The contribution to variance reveals that the end of life (*E*) of the production of steel recycling is the activity that most contributes to the overall result, with a contribution to variance of 33 %, followed by the end-of-life of iron and copper. The transportation of the materials (*T*) also contributes a lot to the variance. By focusing on reducing the uncertainty within these most significant items, the overall uncertainty in the overall life cycle of CW will be reduced most effectively.

Comparison analysis

Because of the CEs of material embody impact and transportation stage are the same, this study only compares the difference of the CEs of end-of-life. As shown in Fig. 6, the CEs of metals (i.e., iron, steel, aluminum and



Note: Error bars denote combined uncertainties (5% percentile & 95% percentile) from Monte Carlo simulations.

Fig. 3 Life cycle carbon emissions of construction waste divided by components (scenario II). *Error bars* denote combined uncertainties (5 percentile and 95 percentile) from Monte Carlo simulations

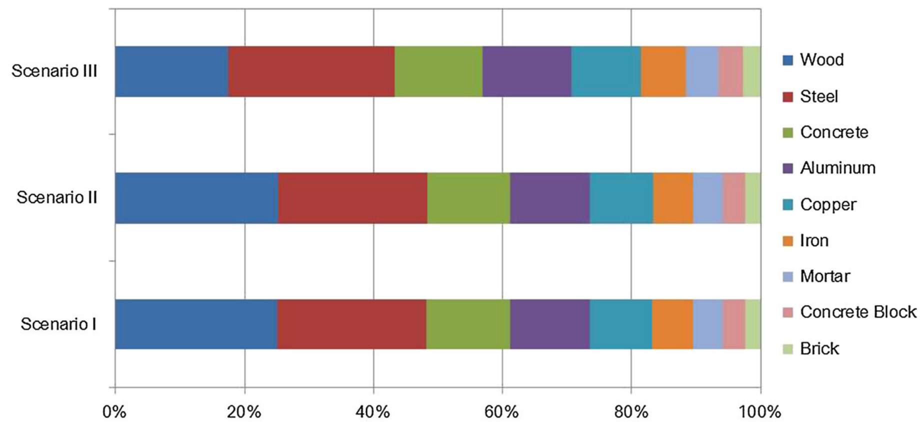


Fig. 4 Contribution to carbon emissions of construction waste

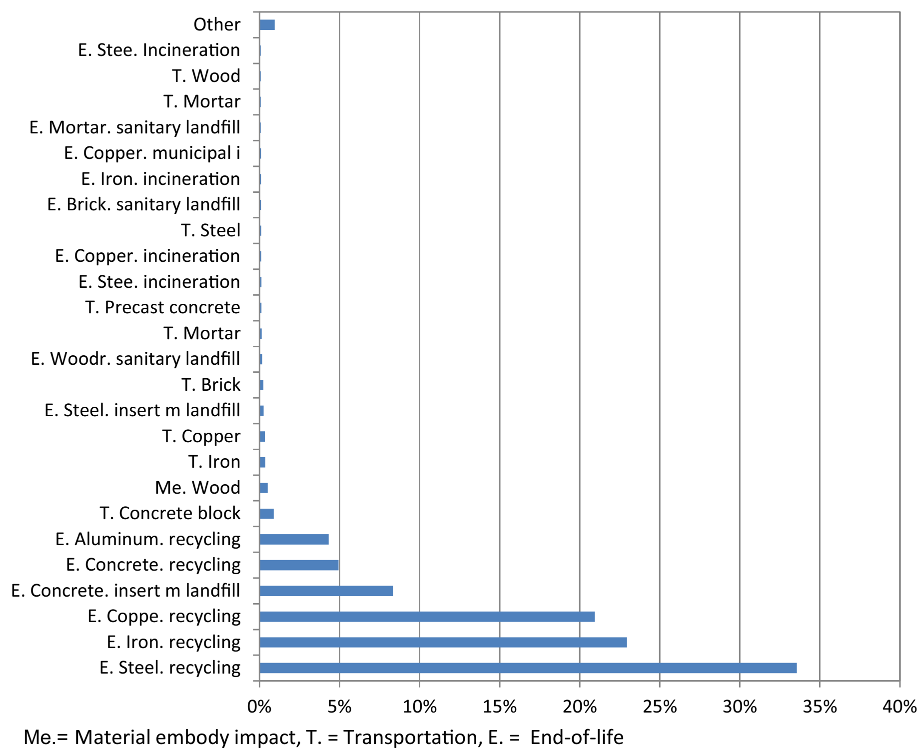


Fig. 5 Contribution to variance in construction waste (overall life cycle)

copper) showed a negative value, since their recycling reduced the CEs of the overall life cycle. Scenario II and scenario III show the same level, because they are under the same treatment methods and recycling rate. With the rise in recycling rate, the deduction of CEs of metals accordingly increased. For concrete waste, the CEs in three scenarios are significantly different. As in end of life (scenario I) with 100 % landfill, the CE is 2.6 kg and in end of life (scenario II) the CE is 0.4 kg with 40 % of concrete recycled and 60 % disposed in an inert landfill. In end of life (scenario III) the CEs are −2.9 kg with 100 % recycling, which implies that environmental deductible benefits were acquired. So, the higher the recycling rate of concrete waste achieved, the more environmental deductible benefits are obtained. Finally, for concrete block, brick, and mortar waste, the CE is very few; thus, there is no need for a particular strategy for classifying and recycling of these types of wastes. If there are no other non-inert wastes mixed, they can be simply transported into inert landfills for disposal.

For the wood waste, as the incineration method was adopted in end-of-life (scenario I and scenario II), both emission values were equal, up to 52.6 kg. When switching to sanitary landfill in end-of-life (scenario III), the CEs decrease to 1.7 kg. Consequently, when considering the environmental impact indicator of CEs only, sanitary landfill is a much better way to dispose the wood waste rather than incineration.

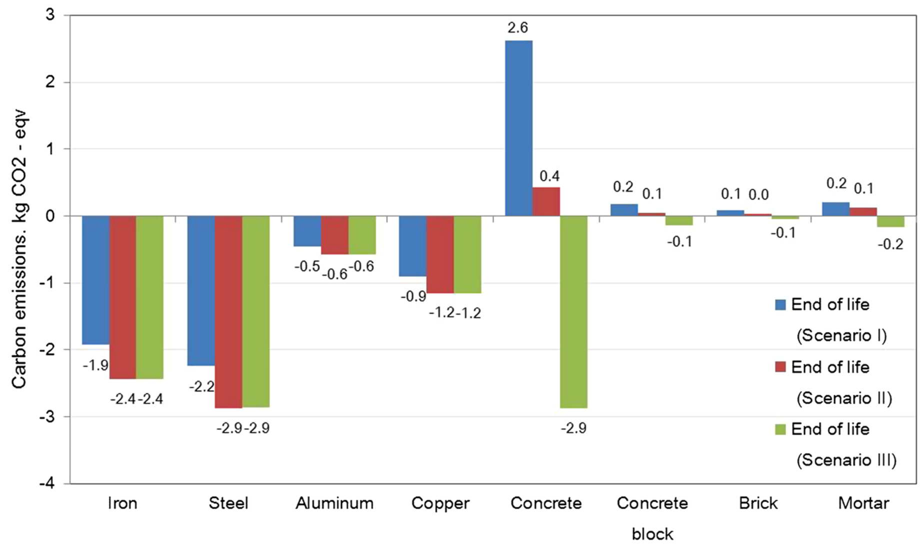


Fig. 6 Comparisons of waste disposal scenarios (wood excluded)

Conclusions

This study presents a model based on the SLCA method to quantitatively streamline environmental assessment by identifying the high-impact activities within the life cycle of CW. The model was applied on a case study regarding three scenarios analysis basis to the life cycle activities of CW in Shenzhen, China, which were then specified. The results indicate that CW management should be focused on minimization management, since the deductible benefits of CEs brought about are not enough to offset the CEs in material embody impact and transportation stage regardless of the disposal measures taken. For all kinds of wastes, metals wastes, including iron, steel, aluminum and copper, account for more than a half of the CEs. Therefore, the minimization of metal waste generation can benefit CEs reduction of CW to a large extent.

If the generation of CW is inevitable, it is quite necessary to take appropriate disposal methods for different kinds of wastes. Improper methods may produce an extremely negative impact on emissions. Moreover, if we consider the environmental deductible benefits from consumption reduction for raw materials the CEs of waste recycling are less than that of landfill. In other words, when looks at the single indicator of CEs, recycling becomes superior to other disposal methods. Accordingly, recycling of waste is an effective measure to reduce CEs after waste generation.

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