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Rehabilitation of Public Spaces with Construction Excavation Waste (E-CDW): A Case Study of Costanera San Miguel-Lima-Peru

Milagros Defilippi[1,3], José Antonio Herrera[2], Patty Condor[3], Joaquín Mantilla[3], Cesar Eyzaguirre[3], Alexis Dueñas[4]

[1] Faculty of Architecture and Urbanism, Universidad Nacional Federico Villarreal, Peru
[2] Faculty of Science and Engineering, Pontificia Universidad Católica del Perú, Peru
[3] Asociación de Estudios Ecológicos e Investigación Civil Sostenible (ADEICS), Peru
[4] Grupo PELCAN- Pontificia Universidad Católica del Perú, Peru

***Corresponding author:** tdefilippi@unfv.edu.pe

Lima is the most important city in Peru, as it is home to about a third of the country's total population (around 10 million people), and concentrates more than half of the national GDP. Considering various sources, Lima concentrates 60% of the activity in the construction and real estate sector, with buildings averaging 10.5 floors in height, which can extend in certain districts up to 20 floors. A multi-stage methodology was developed, comprising three stages. In the first stage, based on the data collected by the Association of Ecological Studies and Sustainable Civil Research (ADEICs) institution, the excavation construction and demolition waste (E-CDW) generation trends were modelled and the annual E-CDW generation rate was predicted using ARIMA models, Holt-Winters and Neural Networks. In the second stage, life cycle assessment (LCA) was used to estimate the environmental impacts related to ten impact categories, including global warming. Finally, using the hedonic price model, the economic value of the E-CDW waste was estimated. The reuse of excavation material is an alternative for the recovery of public spaces. It is the case of the waterfront of the district of San Miguel, where a total of more than five million m^3 of waste have been reused since 2017 to 2023. This waste has been collected from more than 1400 construction sites, comprising 30% of the total works in the city. This waste is composed of approximately 90% rocky material and 8% fine material, and its reuse has made it possible to generate 30 hectares of new land and recover 60 hectares of public space. The experience demonstrated the positive impact associated with the reuse of excavation material in the recovery of public areas in the city of Lima, with an economic value of 1089 million dollars of the urban land recovered and generated.

Keywords: reuse of excavation material, construction waste management, recovery of public spaces.

Introduction

The city of Lima is one of the most important cities in the country, home to approximate ten million people and contributes at least 50% of the national GDP (IMP, 2020). The city has experienced significant, unplanned growth due to demographic pressures from migration since the 1950. Thus, the growth pattern known as the context–process, which urban planners use to describe the evolution of cities throughout the twentieth century, is characterized as the sprawl or oil slick model, exhibiting an extensive, horizontal development pattern (Muñiz et al., 2006). This expansion is driven by dominant demographic pressures, including housing demand, the concentration of economic activities, and urban phenomena such as densification and urban renewal (Sierra Club, 1999; Valle et al., 2020).

The processes of urbanization, urban renewal, and densification in Peru, particularly in coastal cities such as Lima and its districts, have shaped a pattern of construction that has been analyzed from the perspective of urban stocks, according to which the predominant materials are brick masonry and reinforced concrete (Cucchi et al., 2024), among others. These materials will also be predominant in the generation of construction and demolition waste.

Three stages are described in the urban renewal process (Self, 1961). The first is dominated by horizontal or surface growth, that is, the extension of the city according to the main or collector road axes. The second considers changes in land use, displacing rural activities extending the area of urban land. Finally, the processes of renovation and densification will have consequences in terms of growth patterns, and in the modification of the functionality of neighborhoods and districts. Elsewhere, in new building constructions, materials such as concrete and steel can be found dominating instead of brick (INEI, 2017).

In addition, densification and urban renewal activities produce waste arising from both construction and demolition processes (Guignot et al, 2015). According to several scholars, the third category should also be ackonwledged based on its source – excavation waste (Pinzon Galvis and Cortes Montealegre, 2019). Furthermore, they can be classified in two types of excavation construction and demolition waste (E-CDW). The first is the waste mixed with foundation elements (concrete, footings, steel, mainly construction iron, etc.), which will be called E-CDW type 1, requiring a prior segregation process to revalue the non-stone waste and arrange for its subsequent confinement. The second is a clean substrate, composed of rock, gravel, fine and coarse clay, among others, referred to in this work as E-CDW type 2, and can be disposed of and reused without any further limitation beyond its characterization and verification.

The scientific literature identifies three lines of research (Chica et al., 2023). The first highlights that CDW, both construction and demolition, should be treated and managed to include them in the revaluation chain (Bassani et al., 2019). The second indicates that this waste should be confined in special landfills. The third states that they should be used in processes of reuse of public spaces and service infrastructures, inspired by the circular economy (Al-Malack et al., 2016). In this regard, this research provides insight into the trends in excavation waste generation in the construction sector in the city of Lima, with the aim of estimating urban stocks, which must be managed by the specialized landfills that the city requires, within a sustainable waste management framework, from the perspective of the circular economy. On the other hand, it provides results on the estimated environmental impacts of excavation waste reuse, covering impact categories such as climate change, as well as others including ecotoxicity and acidification, to mention a few. Finally, it estimates the economic impact of reusing excavation material in the generation of urban soil.

Methods

The project area covers 50 100 m^2 in the coastal strip of San Miguel district (*Table 1*). The adjacent coastal profile served as the main focus of the research. To incorporate the environmental impact analysis, it was necessary to establish a functional unit based on the volume of reused construction excavation waste (E-CDW, in m^3). In addition, the recovered area (in m^2) was considered as a substitute parameter, both of which were evaluated from a life cycle perspective.

Table 1. *Units of analysis and research variables*

Component	Variable	Acronym for variables	Value	Source
Structural	Average distance to the nearest police station in km	*(dis_c)*	1.35	Google Earth
	Monthly recovered area in m^2	*(a_recupera)*	24 668.25	ADEICS
Socio-economic	Average monthly income of households in the district in soles	*(ing_prom)*	2815.78[a]	INEI
	Perception of insecurity in the district in percentages (%)	*(p_insegurid)*	30.2	
Environmental	Air quality (nitrogen dioxide) in μg/m^3	*(NO_2_concen)*	160μm^3b	ADEICSe
	Air quality (particulate matter) in μg/m^3	*($PM_{2.5}$_concen)*	28.5c	ADEICSe

Note: *a: Exchange rate S/ 3.80 per US dollar; b: 0.80 below the established Environmental Quality Standard (EQS) (200 μg/m^3); c: 0.57 below their respective EQS (50 μg/m^3); d: Monthly drone flights and. Monthly environmental monitoring. Source: ADEICS (2025) (Association of Ecological Studies and Sustainable Civil Research) – administrative records.*

Goals and scope

The main objective was to determine the technical, environmental and economic viability of the reuse of E-CDW for the recovery of public spaces on the San Miguel waterfront. The specific objectives were as follows: a) to estimate the generation, in the medium time, of the volumes of E-CDW, in the urban context, for the generation of public space (case of the San Miguel waterfront); b) to evaluate the environmental impacts derived from the reuse of CDW in public spaces, through the perspective of life cycle assessment (LCA); and c) to measure the social perception of the reuse of CDW in the urban context, through the economic valuation of the recovered and generated area.

Trends in E-CDW generation with time series

The E-CDW generation data constitute temporal variations of the analyzed variables. Once the time series is selected, the respective analysis is considered, with the decomposition technique, which yields three components. The first is related to the trend, the second is seasonal or refers to the presence of repetitive cycles, and finally, the third refers to the stationary component, which reflects the stochastic characteristics of the behavior of the variables over time (Liu Sun and Covarrubias López, 2023).

The level of variation in the rate of generation of E-CDW with respect to time could be possibly influenced by the availability of means and resources from previous periods, especially in the case of non-renewable materials and other resources, or even some renewable ones. This would imply that there may not be a “non-contemporary” or delayed relationship between Y or E-CDW and X or time (Gujarati and Porter, 2010).

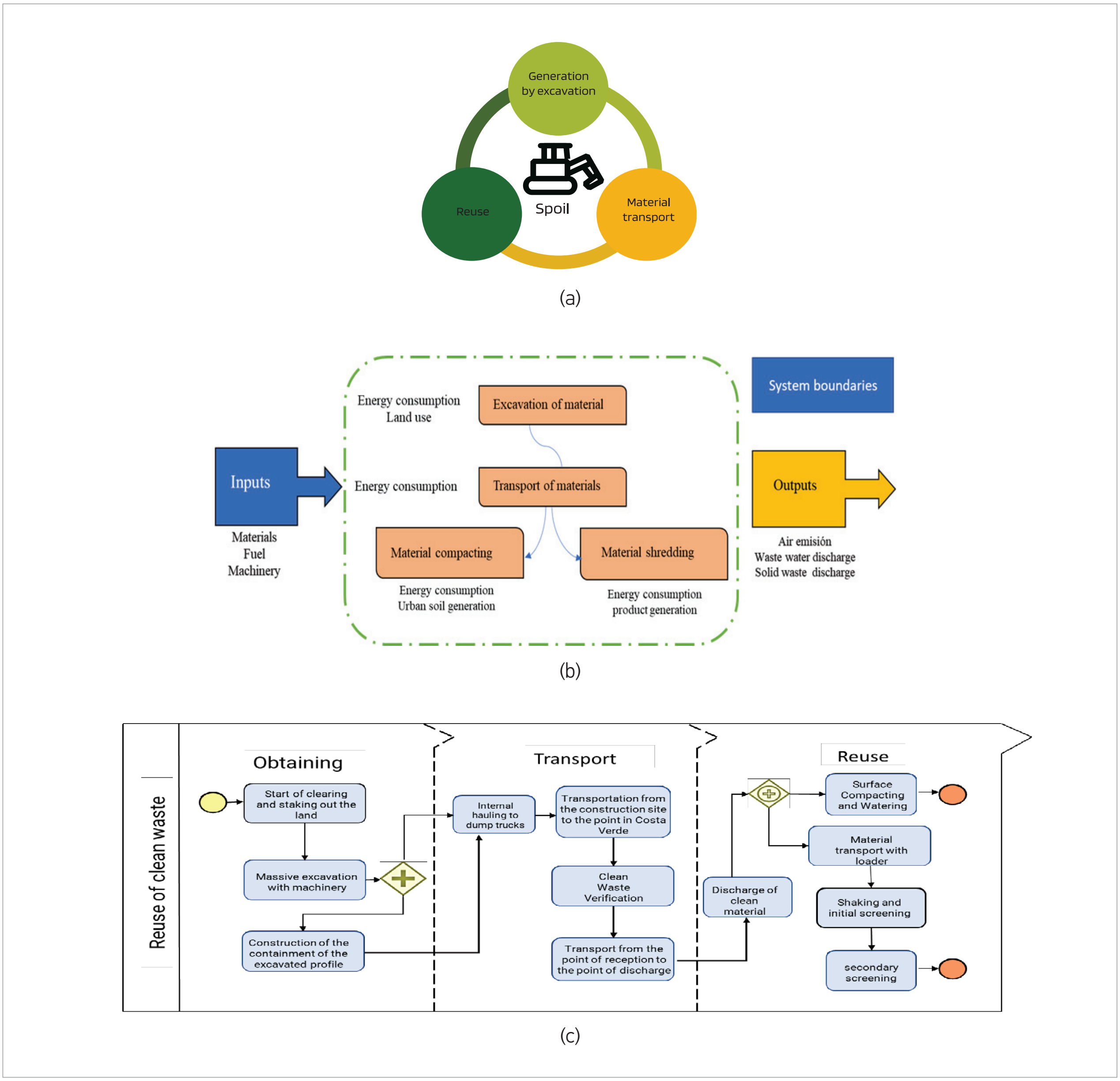
After decomposing, it is necessary to corroborate that the time series studied do not constitute spurious (meaningless) regressions. For this it will be necessary not only to verify the R^2 (coefficient of determination), or the t (time), which could indicate a high consistency of the proposed regressions, However, it is important to examine the R^2 value; when the coefficient of determination is very high and the Durbin–Watson statistic is very low, a spurious regression scenario may occur (Riddel, 2001). The stationarity test or “unit root test” is used.

Environmental impacts with LCA tools

The environmental impacts of excavation waste reuse were estimated using the LCA approach. The system evaluated for this purpose is detailed in *Fig. 1*. In the first case, the processes considered are excavation, transport of material and reuse in the formation of slopes for the generation of urban soil (*Fig. 1a*). The unit operations and system boundaries are shown in *Fig.1b* in detail at the thread level for each unit operation and addressed in the life cycle inventory (LCI) shown in *Fig. 1c*.

The life cycle inventory used in the study of the reuse of excavation material is shown in *Table 2*, according to which the excavation and reuse processes are the most intensive in the use of machinery and in the demand for fossil fuels.

Fig. 1. *Case study processes, unit operations, and system boundaries*



Note: a: Stages of the life cycle of the reuse of excavation material; b: Boundary of the reuse system for the case studied; c: unit operations identified in the E-CDW reuse process.

Table 2. *Life cycle inventory for case study (E-CDW reuse)*

Process	Unit Operation	Unit	Quantity
Excavation	Clearing and staking out		
	SKID/ Skid-steer loader	1 unit	$3.33 \cdot 10^{-5}$
	Diesel	lt	0.06
	Plaster	kg	0.01
	Stakes	kg	0.00
	Massive excavation		
	Excavator	2 units	$2.66 \cdot 10^{-7}$
	Diesel	lt	0.07
	Backhoe	1 unit	$1.33 \cdot 10^{-5}$
	Retaining walls		
	Concrete	m^3	$1.86 \cdot 10^{-2}$
	Steel	kg	1.54
	Wood	kg	2.80
Transport	Cartage		
	Skid	1 unit	$3.33 \cdot 10^{-5}$
	Diesel	lt	0.04
	Front loader	1 unit	$2.66 \cdot 10^{-5}$
	Diesel	lt	0.11
	Water	lt	$4.55 \cdot 10^{-1}$
	Transport to the disposal point		
	Tipper route	km	$2.83 \cdot 10^{1}$
	Plastic	kg	0.15
	Internal transport		
	Front loader	2 units	$2.83 \cdot 10^{-6}$
	Diesel	lt	0.11
	Tipper route	km	1.80
Reusability	Extend and compacted		
	Grader	2 units	$3.04 \cdot 10^{-7}$
	Diesel	lt	0.12
	Plate compactor	2 units	$3.04 \cdot 10^{-7}$
	Diesel	lt	0.22
	Water	lt	$1.60 \cdot 10^{1}$
	Screening and crushing		
	Sieve	1 unit	$2.02 \cdot 10^{-6}$
	Conveyor[1]	1 unit	$2.02 \cdot 10^{-6}$
	Shredder	1 unit	$2.02 \cdot 10^{-6}$
	Generator Set	1 unit	$2.02 \cdot 10^{-6}$
	Diesel	lt	$7.95 \cdot 10^{-1}$
	Crushing 4"		
	Conveyor belt	M	$1.01 \cdot 10^{-5}$
	Shredder	1 unit	$1.01 \cdot 10^{-5}$
	Diesel	lt	1.33

Note: *1: The element has an extension of 12 m.*

The impact categories considered in the case study are shown in *Table 3*, which made it possible to achieve the specific objective of characterizing and estimating the environmental impacts associated with the case study (Jang et al., 2022; Song et al., 2020; Mikosch et al., 2022). The modeling of the environmental impacts was done by the Ecoinvent database (v.3.10) embedded in environmental software (SimaPro) v. 9.6.

Table 3. *Impact categories analyzed in the reuse of E-CDW*

Impact Category	Description	Source
Climate change	Oriented to the increase in temperature near the earth's surface due to the increase in GHG emissions from anthropic activities. Indicator: Air warming potential Unit: kg CO_{2eq} for a 100-year horizon	ISO (2018)
Formation of fine particulate matter	Refers to solid particles and liquid droplets suspended in the air that cause serious health problems. Indicator: Mechanical particle concentrations (2.5 microns) in the air kg $PM_{2.5eq}$ in particles of chemicals, dust or metals	EAE (2013)
Acidification	Understood as the loss of the neutralizing capacity of soil and water (decrease in pH level). Indicator: Acidification potential Unit: SO_{2eq} kg	ISO (2006)
Ozone depletion	Referring to the negative effect on the ability of the ozonosphere to protect the surface from solar ultraviolet radiation, mainly focused on chloro-fluorine-carbon compounds (aerosols and refrigerants). Indicator: Ozone depletion potential Unit: kg CFC-11eq	EAE (2013)

Impact Category	Description	Source
Resource depletion	Related to the use of natural resources for the manufacture of various products. Indicators: - Fossil depletion (surplus energy for fossil fuel) - Water depletion (water consumption in the life cycle of the inventory used) Unit: kg oileq per m^3 of water	
Human toxicity	Related to the harmful effect of toxic substances emitted into the environment that affect the health of the human population (absorbed from the air or food). Indicator: - Carcinogenic human toxicity - Non-carcinogenic toxicity. Unit: kg 1.4-DCB	
Ecotoxicity	Referring to the negative consequences of chemical substances on an ecosystem. Indicator: - Potential for marine ecotoxicity - Freshwater ecotoxicity potential - Land-based ecotoxicity potential Unit: kg 1.4-DCB	ISO (2006)
Eutrophication	Related to nutrient enrichment by algae in the aquatic environment due to water pollution either by elements in the air or in rivers. Indicator: - Potential for eutrophication in freshwater - Potential for marine eutrophication Unit: - kg P_{eq} (freshwater) - kg N_{eq} (seawater)	Recipe (2013)

Economic valuation of environmental externalities

Hedonic prices are economic valuation tools that are applied, from real estate development to the valuation of environmental goods and services (Izquierdo and de los Llanos, 2004). Bover and Izquierdo (2003) use the dummy variable technique for the calculation of hedonic price indexes, which in this case consists of measuring the change of a given product, allowing the constant term in hedonic regression to change over time, and which under a linear formulation would have the following expression:

$$P_{it} = \beta_t + \sum_{k=1}^{n} a_k C_{ikt} + e_{it} \quad (1)$$

where P_{it} is the i-th observation of the price of the urban area recovered in period t, c_{ikt} is the level of the k-th characteristic, a_k is the implicit price of the characteristic k, and e_{it} is a perturbation term.

For the estimation of b_t, dummy variables of time D_st are defined, so that $b_t = \sum b_s D_{st}$, where $D_{st} = 1$ when s = t and or in the other cases. Note that the estimated b_t coefficients reflect price changes between periods that are not due to changes in characteristics. In the literature (Izquierdo and de los Llanos, 2004), b_t coefficients have been estimated using a variable number of t periods. A_t one extreme is the possibility of estimating using the entire sample period with constant a_k coefficients. On the other hand, it can be estimated by pairs of adjacent years, with a potential failure problem of sufficient observations in a single period, and then concatenated between periods 1 and 2. In this way, it is used in the constants b_1 and b_2 in the following equations:

$$P_{i1} = b_1 + \sum a_{12k} C_{ik1} + e_{i1} \quad (2)$$

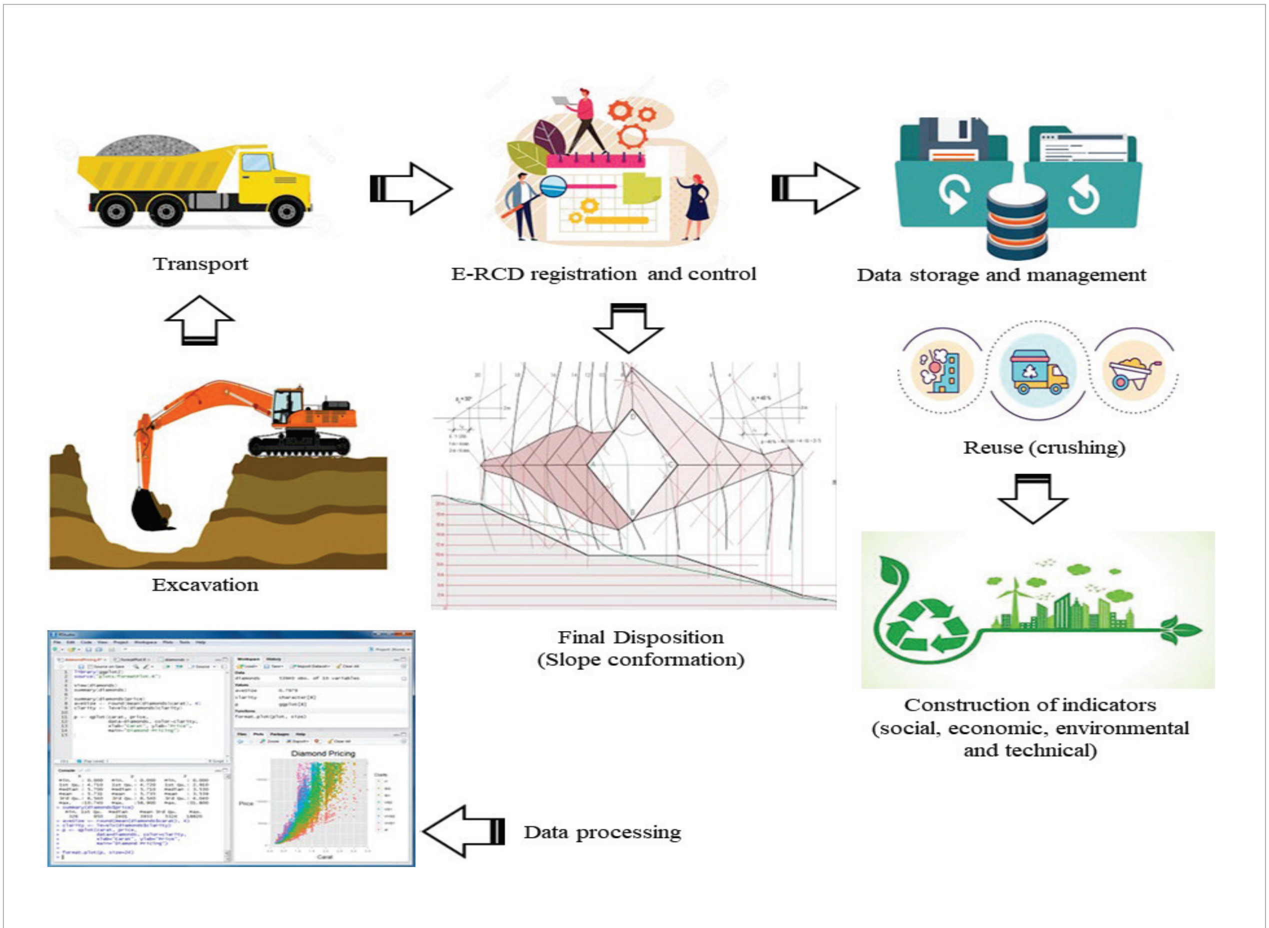
$$P_{i2} = b_2 + \sum a_{12k} C_{ik2} + e_{i2} \quad (3)$$

Data and sources

The data sources used are the following: 1) project database (ADEICs), containing data related to the management of the final disposal of E-CDW (excavation material) related to the company that transports the waste, point of origin (work), volume transported, frequency, type of vehicle, license plate of the vehicle; 2) certificate of final disposition, i.e., a document that serves as a passport, outlining the volume, distance of travel and details of the work; 3) questionnaire, an instrument that contains six closed questions regarding the opinion of the previous and current state of the Costanera San Miguel, four assessment questions on the operation of the recovered public space, and five questions on the opinion on the use of construction and demolition waste; 4) satellite images, corresponding to the months of January, July and December of the years 2017–2022 from Landsat8 to determine the changes in the morphology and configuration of the area.

The data processing stage of this research is given in *Fig. 2*. The first stage, as shown in *Fig. 2*, expresses the direct relationship with the obtaining of technical data, at the level of CDW materials, resources, machinery, waste generation, as well as the description of the final disposal process. The second stage (see *Fig. 2*) makes it possible to organize the information around the main processes or unit operations, and thus prepare environmental inventories, as well as to identify the characteristics of each of the areas of study.

Fig. 2. *Procedure for data processing to estimate the effects of E-CDW reuse*

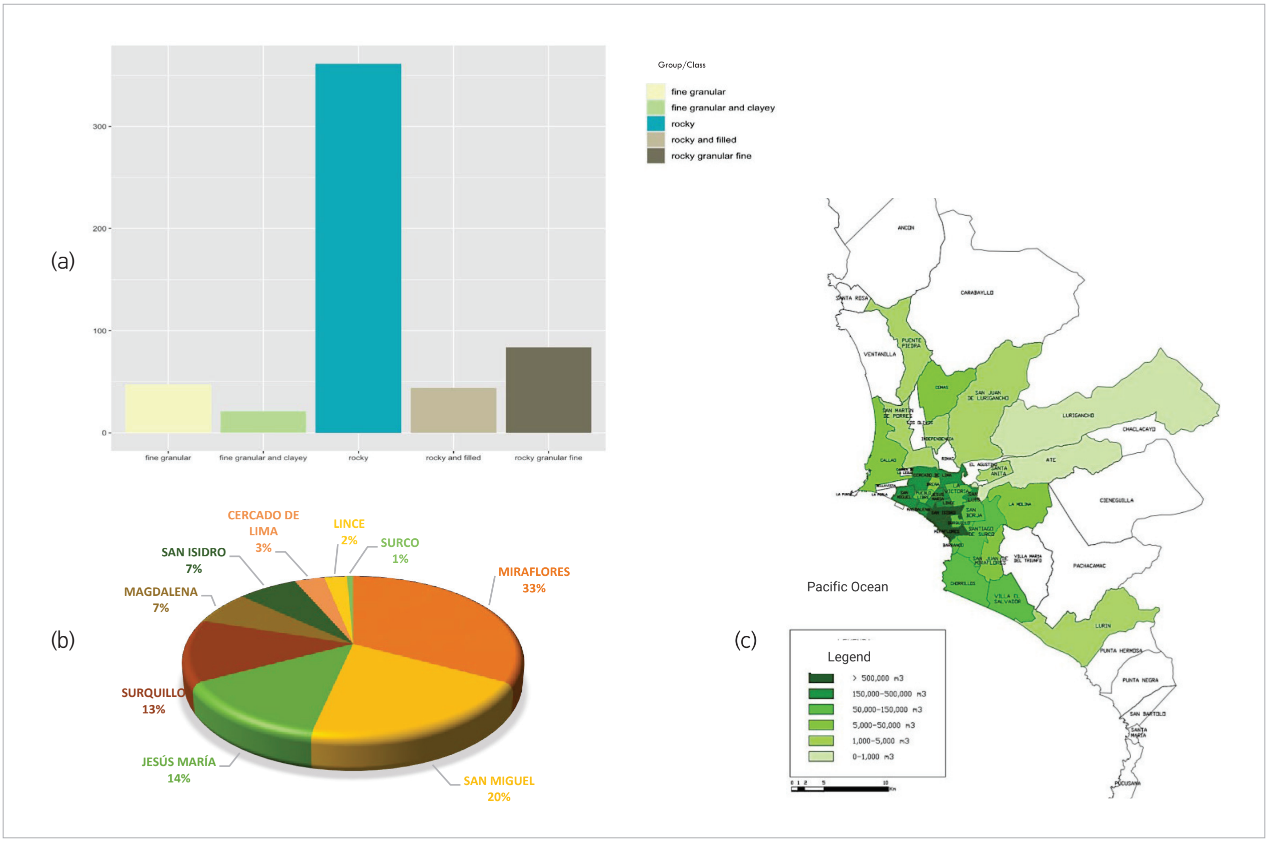


Note: The computer processing of the data collected was performed using SimaPro software, with the Ecoinvent, Econometric View and RStudio databases.

Results

E-CDWs vary due to their geographical location and soil type (*Fig. 3a*). Differences in the excavation material are also observed. The biggest part (65%) of the material comes from rocky soils, followed by 18% from rocky soil but with a fine granular and clayey bottom on alluvial gravel. The fine granular clayey material on alluvial gravel fine, sand, with aeolian sand and fillings accounts for 8.4%, as well as rocky soil and fillings account for 7.7%. Fine and clay material on alluvial gravel accounts for 3.7%. The excavation material (E-CDW) consists of two components: rocky material (8%) and fine clay (92%).

Fig. 3. *Number of cubic meters by soil type*



Note: a: Composition of the excavation material according to its nature and gravimeter type; b: Origin of the excavation material according to districts; c: Map of the city of Lima and the districts included in the case study.

To evaluate the distance, the geographical origin of the E-CDW was evaluated, having established that the cluster was made up of the Miraflores, San Isidro and Surquillo districts, representing 53% of the material received, followed by the cluster of San Miguel, Magdalena and Jesús María, which contributed with 41% of the reused material (see *Fig. 3b*). Finally, there were two additional clusters, one consisting of Cercado-Lima and Lince (5%) and another made up of Surco and others (1%).

The origin of the E-CDW material matters environmentally as its transportation requires fossil fuels, increasing the carbon footprint. *Fig. 3c* shows the location and distances to the final disposal point, a relevant data for modeling the impacts related to the climate change category. The maximum reuse levels of E-CDW from the "CSM-project" were recorded in 2018 with 2.2 million cubic meters (m^3), followed by 2017 and 2019, with 1.88 and 1.77 million m^3, respectively. This places the average reuse of E-CDW at 1.62 million m^3 per year.

The level of reuse for the year 2020 is not consistent because it corresponds to the period of the pandemic and, therefore, reflects an atypical behavior. Then, the volume exceeded one million cubic meters.

Table 4 shows the behavior of the different models applied, of which there are non-independent residuals in the case of the seasonal naive method with a *P* value of $1.12{\cdot}10^{-6}$ and the linear regression model with a *P* value of $2.62{\cdot}10^{-5}$. In other cases, the waste is distributed independently, which is desirable. Therefore, the best predictive models are Holt-Winters, ARIMA and neural networks (NNAR).

Table 4. *Comparative predictive capacity of designed models of the volumes of E-CDW used in the recovery of the public area in the CSM project (2018–2022)*

Method	Statistics (Q*)	gL	*P* value	Sig.
Seasonal naive method	50.186	12	$1.12{\cdot}10^{-6}$	***a
Linear regression model	42.619	12	$2.62{\cdot}10^{-5}$	***a
Holt-Winters Method	0.383	12	1.00	b
ARIMA (2,0,1) with non-zero mean	8.789	9	0.46	b
NNAR (2,1,2)	16.668	12	0.16	b

Note: *Significance codes: at 0.001 (***). The acronym NNAR stands for neural networks. A means that waste is distributed non-independently, and B means that waste is distributed independently (ideal)*

The carbon footprint is an important aspect to evaluate the reuse of E-CDW, with the use of the IPCC 100-year methodology. It was estimated that for each m^3 of excavation material, emissions are 20.8 kg CO_{2eq} during excavation, 8.83 kg CO_{2eq} during transportation, and the lowest emissions occur during reuse (–0.708 kg CO_{2eq}), as can be seen from *Fig. 4a*. Material reuse reduces CO_2 emissions by nearly 20%, generating 26.5 kg of CO_{2eq} per m^3 (*Fig. 4b*), compared with scenarios without reuse. Likewise, the estimated potential reduction in the reuse in this case is equivalent to just over 10 000 tons of CO_{2eq} considering a reduction of 5.65 kg per m^3.

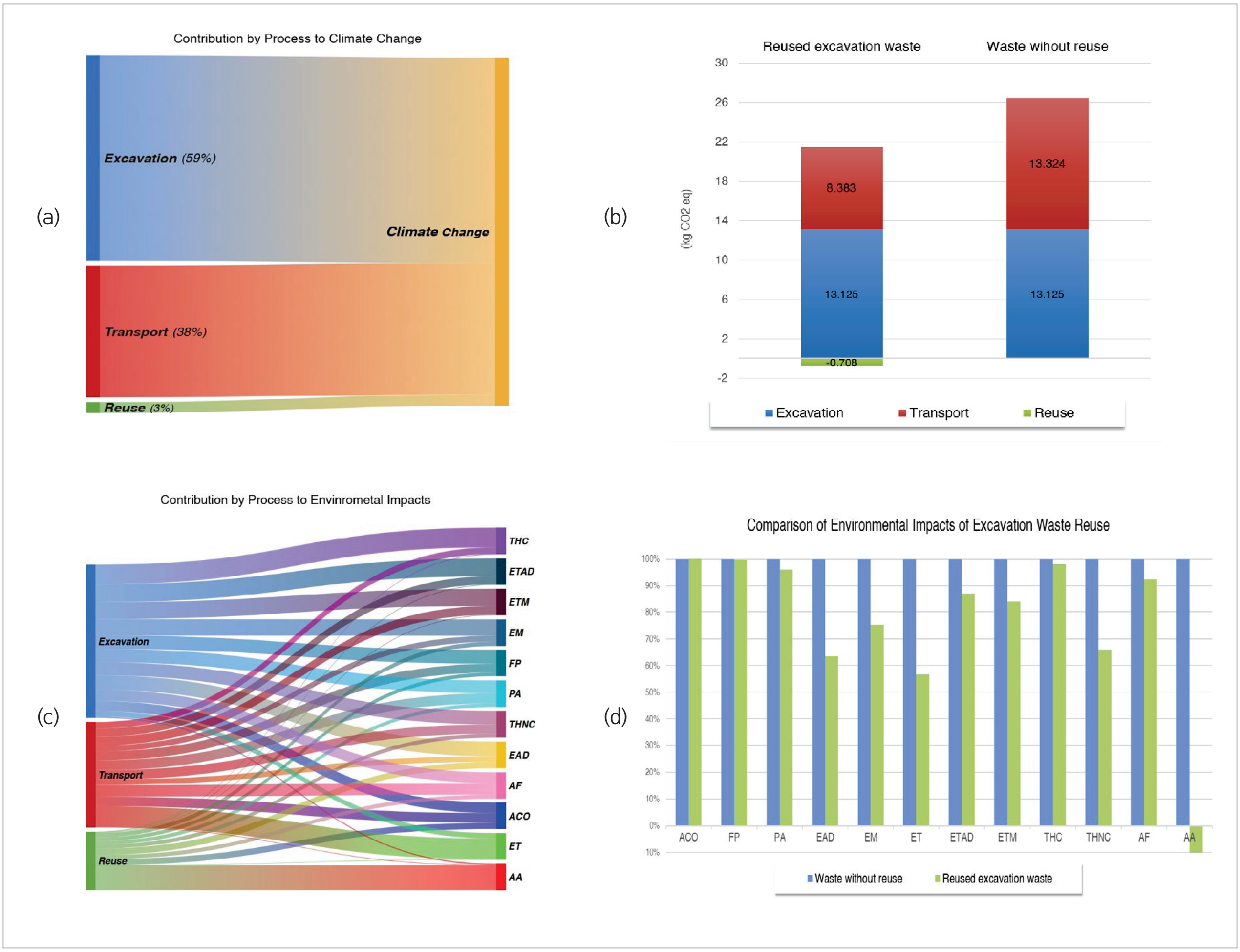
Fig. 4c shows the results of the environmental impact generated by various categories of impacts, using the ReCiPe v.20213 methodology. The excavation process is closely linked to human carcinogenic toxicity, marine eutrophication, freshwater eutrophication, and ecotoxicity in both fresh and marine waters. Meanwhile, transport has greater relevance for the category of terrestrial ecotoxicity, fossil depletion, ozone layer depletion and particulate formation. The reuse process in the category of water depletion is very important, also followed by freshwater eutrophication, marine eutrophication and non-carcinogenic human toxicity, while it has been a contributor to the categories of ozone depletion, particulate formation, fossil depletion and acidification potential.

It should be noted that in the category of water scarcity, a negative value is obtained, which indicates that, by avoiding virgin aggregate use in the formation of the new slope, water extractions to moisten the slope, roads, irrigation of the material as a preventive measure to mitigate the generation of particulate matter are being avoided. *Fig. 4d* shows the comparative results for different categories of impacts, according to the ReCiPe v.2023 methodology, in which it is observed that in the categories of ozone depletion (ACO) and particulate matter formation (FP) there are no differences between the scenario with and without reuse of E-CDW. The greatest differences are seen in the categories of freshwater eutrophication (EAD), marine eutrophication (ME), and terrestrial ecotoxicity (ET).

It is observed that the urban land price variable (Prec) has a negative and significant correlation with the area (a_recovered), perception insecurity (Per_insec) and NO_2 concentration (NO_2_concen) and a positive and significant correlation with income (Inc_mean). Even though there is a negative correlation with distance (dist_c), as indicated by empirical evidence, this correlation is not significant because of the P value greater than 0.05. In the case of the concentration of particulate matter (PM2.5_concen), the correlation found is positive, but not significant.

The results (see *Table 5*) correspond to the models Theta, Lambda y Left-hand-side-only. In the Theta model, it was obtained that the parameters take positive values y as suggested by economic theory. However, only the parameter λ is significant at 5% with a *P* value = 0.03. In all variables, the predicted effect is fulfilled.

Fig. 4. *Environmental impacts associated with the reuse of E-CDW in the climate change category in CO_{2eq} and other impact categories with ReCiPe v.2013*



Note: (a) Sankey diagram at the level of unit operations (life cycle) of the E-CDW reuse process; (b) Carbon footprint in Kg CO_{2eq} according to scenarios; (c) sankey diagram for various impact categories according to the ReCiPe method; (d) environmental footprint of the reuse process according to scenarios with the ReCiPe method. The acronyms used in the graph: THC: human-carcinogenic toxicity; MS: marine eutrophication; ETAD: freshwater ecotoxicity; ETM: marine ecotoxicity; AF: fossil fuel depletion; EAD: freshwater eutrophication; THNC: non-carcinogenic human toxicity; ACO: ozone layer depletion; FP: particulate matter formation; PA: terrestrial acidification potential; ET: terrestrial ecotoxicity; AA: water scarcity.

From the regression of the Lambda model, the parameter was estimated to have a positive value, λ = 1.49, and is statistically significant at the 1% level (*P* value = 0.01). The significant variables are *Inc_mean* and *a_recovered* with a significance of 1% and 5%, respectively. From the regression of the Left-hand-side-only model, it was obtained that the parameter takes the positive value θ = 0.09, although it is not significant at 5% (P value = 0.91). The significant variables are *Inc_mean*, a_recovered and *Per_inse* with a significance level of 1%, 5% and 10%, respectively.

As shown in *Table 5*, the mean of the dependent variable is closer to the mean of the predicted value, which implies that the Theta model approximates the real value of the price of the recovered m^2 more adequately, than the other models. Similarly, the results for residuals show that the Theta model has the smallest difference between the observed value and the predicted value. Finally, based on the results presented by the three models estimated, based on the Box-Cox regressions, the Theta model better estimates the impact of the variables on the price of the m^2 recovered from the

Table 5. *Summary of econometric estimates for the models evaluated*

Functional/variable forms	OLS	THETA MODEL θ = 1.05 (0.778) λ = 12.90* (5.89)	LAMBDA MODEL λ = 1.49*** (0.57)	LEFT-HAND-SIDE-ONLY MODEL θ = 0.10 (0.83)
Constant	1978.57 (1239.10)	−2660941	−35353.69	12.02
Structural and neighborhood characteristics				
a_ recovered (area)	−0.018* (0.01)	$-7.42{\cdot}10^{-56}$	−0.01 **	$-8.87{\cdot}10^{-6}$ **
dis_c (distance)	1.46 (90.49)	0.00	465.47	−0.00
Characteristics attributable to socioeconomic factors				
Inc_mean (income)	1.16 *** (0.20)	$6.55{\cdot}10^{-42}$ ***	1.54 ***	0.00 ***
Per_insec (insecurity perception)	−1567.05 (1066.57)	$-3.44{\cdot}10^{7}$ *	−172294.1	−0.94 *
Environmental characteristics				
NO_2_concen (gases concentration)	−488.63 (370.26)	−1004.93 *	−28909.92	−0.25
$PM_{2.5}$_concen (particulate matter concentration)	215.44 (276.82)	369.78	11596.73	0.12
Observations (cases)	55	55	55	55
R^2	71.59	-	-	-
Adj R – squared	68.04			
LR Chi2 (7)	-	70.23	60.78	61.20

Note: *Level of significance *** P < 0.01, **P < 0.05, *P < 0.1. Standard errors are shown in parentheses.*

properties located on Costa Verde belonging to the District of San Miguel. With this, it is evident that there is a socioeconomic assessment, since a significant impact of social variables such as the perception of insecurity and environmental variables that allow a maximization of social well-being was found.

Discussion

Trends in the generation of E-CDW

The reuse of excavation material is an alternative for the recovery of public spaces, as has been in the case of the boardwalk in the district of San Miguel, where more than 5 million m^3 of E-CDW were reused (2017–2023), a value higher than that reported in other sources (Suárez et al., 2018). It is important to have probabilistic tools to study the behavior of CDW generation volumes over time, especially excavation material (E-CDW) which has high reuse rates. The first is linked to the disposal of the E-CDW in new works, through filling, slope stabilization or road affirmation. The second refers to grinding and crushing to obtain aggregates for new construction projects.

In the literature, there are other methods for estimating CDW volumes, in general terms, such as the CDW indicator model (Jia et al., 2017). However, the models used in this research, such as the Holt-Winters, ARIMA (2,0,1) and NNAR neural network (2,1,2), have been corroborated to be the most efficient to estimate the trends in excavation waste generation (Box and Jenkins, 1976; Guavita, 2018). This is due to the very nature of waste emission patterns in the city, which are linked to fluctuations in the real estate market (Moreno Sarmiento, 2008). It is concluded that the assessed value of E-CDW is a good indicator to estimate the environmental impact of the construction industry in a city, and thus, design the final landfills, with disposal by confinement or disposal by reuse that must exist in a city with the characteristics of a metropolis such as Lima.

Reuse of E-CDW and climate change

The reduction in emissions, obtained in this research, is very similar to those reported by MINAM (Ministry of the Environment, Peru), which states that through changes in transport and storage, there was a decrease of 15 000 MT of CO_{2eq} (MINAM, 2022). Zhang et al. (2021) report that, in China, a reduction of more than 100 000 tons of CO_{2eq} was achieved through reuse practices.

The results obtained are congruent, in magnitude, with those referred to by Lachat et al. (2021), who estimated that between 18 kg and 45 kg of CO_{2eq} was produced per ton of reused concrete. In a similar range are the findings of Zhang et al. (2019) who indicate 16 kg and 50 kg of CO_{2eq}. A notable difference is reported by Gómez (2020), who points out between 1 kg and 6 kg of CO_{2eq} for the reuse of one ton of CDW. Paula Junior et al. (2020) estimates that per m^3 of concrete with recycled aggregates, 300 kg of CO_{2eq} is generated, and more than 50% of this contribution comes from the transportation of the aggregate. There are no similar references for excavation waste. The closest indicates that this process differs substantially due to the type of machinery and supplies used. Forsythe and Ding (2014) consider that 200 kg of CO_{2eq} are emitted for an activity level of 90 m^3 excavated, around 2.22 CO_{2eq} per m^3 excavated. In our case, the impact is 13.12 kg CO_{2eq}, six times higher. The differences stem from the process itself, which varies in machinery usage intensity.

As for the impact categories and the differences presented between both scenarios, they coincide in magnitude with what was reported by Lachat et al. (2021) regarding the potential for acidification and ozone depletion, with Guignot et al. (2015) for the depletion of fossil resources, as well as what was estimated for the eutrophication category (Zhang et al., 2021). Moreover, according to Suarez et al. (2021), the best scenarios, both in environmental and economic efficiency, are those where metal and other recyclable wastes, as well as rock and soil wastes, are 100% recycled, the latter aspect coinciding with the results reported by us, where reuse can reduce carbon footprint by 20% and generate positive externalities, as also reported by Dahlbo et al. (2015).

Economic impact and reuse of E-CDW

It has been shown that the reuse of E-CDW has a significant impact at the environmental level, reducing of CO_{2eq} emissions by approximately 20%, which corresponds to an avoided emission of 31 591 t CO_{2eq} per year, with an approximate value per carbon credit of 725 751 US dollars, which would be consistent with various sources reporting that the CDW reuse contributes to the fight against climate change (Pardo Rozo and Sanjines Tudela, 2014).

The economic valuation described refers to environmental aspects, and if there are prices imputed to other categories of impact such as ecotoxicity, eutrophication, depletion of natural resources (fossils) or water scarcity, a similar valuation could well be risked. The impacts of the reuse of E-CDW transcend the environmental sphere and enter urban economy, affecting the price of urban land close to green areas, friendly landscapes, increased security or restoration of degraded urban areas. In this sense, a different situation is required to assess these impacts, from a social and economic perspective (Shonkwiler and Reynolds, 1986).

However, the environmental impacts related to E-CDW are expressed as both positive and negative externalities, the former being demonstrated in the previous paragraph. Nevertheless, the negative externalities, which exceed the objective of this research, can be related to indirect construction costs like loss of materials, transportation costs, and E-CDW removal costs in uncontrolled landfills (Acosta, 2002). In these cases, the valuations by avoided costs and hedonic prices are efficient (Robayo et al., 2015). As it has been demonstrated in our case, such valuation methods can be used for the design of incentives and penalties in encouraging the reuse and recycling of E-CDW (Bernardo et al., 2016).

The hedonic price model used has proven to be useful to assess the social, economic, as well as environmental effects of the case study, i.e. the recovery of public spaces and generation of urban land from the reuse of E-CDW. Therefore, the estimated economic effect of 1089 million dollars for a recovered area of 60 ha and a generated area of 30 ha on Costanera of the district of San Miguel, is in alignment with the pioneering findings of Rosen (1974) and Palmquist (1989).

Conclusions

The first conclusion, related to the prediction of E-CDW generation, is an important issue when designing special landfills, given the enormous generation rates of this waste. In this sense, it is concluded that time series models are an important tool, which, in our case, have allowed us to explore the generation behavior of E-CDW in the context of a city like Lima. Thus, it was established that models such as Holt-Winters, ARIMA (2,0,1) and NNAR neural network (2,1,2) proved to be robust and efficient for the purpose of estimating the generated volumes of E-CDW.

The second and important conclusion is the estimation of the environmental impacts related to E-CDW reuse operations. It was found that reuse allows a reduction of CO_{2eq} emissions by 20%, which is substantial, considering that the E-CDW generation rate in Lima, bordering one million tons, would mean a reduction of 10 000 tons of CO_{2eq} emissions. Additionally, other impact categories, such as freshwater eutrophication (EAD), marine eutrophication (ME), and terrestrial ecotoxicity (ET), are positively affected by reuse.

The economic valuation of environmental externalities is a useful tool for designing public policies, within the framework of sustainable development and in the circular economy approach. In this sense, the findings obtained from the above research indicate that the hedonic pricing method has proven to be effective and sufficient to determine that the E-CDW waste; not only does it have positive environmental impacts, as mentioned above, but can also become an economic alternative by providing reclaimed and generated urban land. The estimated economic impact, in the case of Lima, exceeds one billion dollars.

Finally, with respect to the main purpose of the research, the reuse of E-CDW has proven to be technically feasible, since the operations and the technology involved do not imply a high complexity and are accessible to local operators of solid waste in Peru. On the other hand, it has proven to be viable not only from the environmental perspective, leading, for example, to a 20% reduction in the associated CO_{2eq} emissions, as well as improvement in other environmental factors such as the ecotoxicity of fresh and sea water. From an economic perspective, the reuse of E-CDW is viable by providing a scarce and tangible asset in the city – urban land.

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