STUDY OF THE ENVIRONMENTAL PERFORMANCE OF END-OF-LIFE TYRE RECYCLING THROUGH A SIMPLIFIED MATHEMATICAL APPROACH

by

Alfonso ARANDA USON**, *German FERREIRA, Ignacio ZABALZA BRIBIAN, and David ZAMBRANA VASQUEZ

CIRCE – Centre of Research for Energy Resources and Consumption,
University of Zaragoza, Zaragoza, Spain

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The end of life tyres (ELT) management generates CO_2-eq emissions due to the involved processes. Therefore, this research has been conducted with the aim of quantifying the environmental performance of an ELT management system, in terms of CO_2-eq emissions, which includes the recycling operation through the ELT treatment plant, the transport system and the secondary raw material derived from ELT processing; apart from other different ELT recovery methods. To this end, the environmental performance method based on life cycle assessment and complemented with the Clarke and Wright's saving algorithm has been developed in order to evaluate and optimise the location of the ELT treatment plants. To validate the proposed method, the Autonomous Community of Aragon in Spain is shown as a case study. Different ELT management scenarios have been analysed for the Aragon's ELT treatment plant and the optimisation of transportation of the baseline scenario is carried out by means of the Clarke and Wright algorithm. By applying the proposed methodology it has been identified that the current location of the Aragonese treatment plant has benefits in net CO_2-eq emissions for the different radii studied with a maximum of 200 km. On the other hand, The Clarke and Wright method has been applied in order to obtain the transportation optimisation of the total travelled distance from the 42 collection/sorting centres to the treatment plant. As a result, the travelled distance can be reduced about 15%.

Key words: *CO_2-eq emissions, end-of-life tyres, life cycle assessment, industrial ecology, emission mitigation*

Introduction

The end of life tyres (ELT) disposal represents a global environmental problem due to the high quantity of tyres generated every year; according to ETRMA about 3.4 million tonnes of used tyres (reusable/retreading and ELT) is generated yearly in Europe. Tyres are made of vulcanised rubber (*i. e.* cross-linked polymer chains) and various reinforcing materials such as textile and steel fibres. Co-polymer styrene-butadiene (SBR) or a blend of natural rubber and SBR as a base with the principal aggregated components such as carbon

* Corresponding author; e-mail: alaranda@unizar.es

black, extender oil, zinc oxide, stearic acid, and sulphur are the most commonly used rubber matrices for tyres [1].

In Europe, the basic concepts and definitions regarding waste management were established by the Waste Framework Directive 2008/98/EC [2], which also includes "waste hierarchy" as one of the waste management principles used in waste policy making across the Member States. Reducing or preventing the amount of waste is generally accepted as the main priority of this Waste Framework Directive. However, the next steps in the hierarchy: including the reuse of products, the recycling of materials, other recovery processes (*e. g.* energy recovery) and the disposal at landfills, are taken into account and applied by different waste management strategies in different countries.

According to Directive 75/442/EEC on waste, ELT are classified as non-hazardous waste [3] (code 160103 according to the European Waste Catalogue) and are therefore covered by three main directives: the directive concerning landfills (1999/31/EC) [4], the Directive concerning end-of-life vehicles (200/53/EC) [5], and the directive concerning incineration (2000/76/EC) [6]. These Directives have defined the main objectives in ELTs recycling operations, the technical specifications for ELT energy recovery in cement manufacturing and the reduction of ELT landfilling.

In Spain, all of these Directives are transposed into the law 10/1998 on waste [7] which also establishes the role of the Autonomous Community as the body responsible for the development of regional waste plans with the inclusion of specific targets for reduction, reuse, recycling, other recovery methods and disposal. Additionally, the National Waste Management Plan (2008-2015) references the main objectives of the ELT management till 2015 in order to accomplish the waste hierarchy [8]. In Aragon, the current planning instrument is the Waste Management Plan of Aragon (G. I. R. A., 2009-2015) which is clear in its prohibition of ELT landfilling, following the EU directives. Furthermore, G. I. R. A. does not consider incineration an ELT energy recovery treatment [9]. To reduce the environmental impact, enterprises have to consider a global vision of the whole process, "from the cradle to the grave", so that the consumed resources and the produced waste per unit of a product have to be known. To reach that, the life cycle assessment (LCA) methodology is used as an environmental management tool to deliver a higher degree of eco-efficiency [10]. The latter means that an eco-efficient production implies necessary the optimal materials and energy resources exploitation as well as the minimization of wastes and emissions.

Previous studies have studied different ELT treatment options from an environmental point of view [11-14]. Most of them are concerned with the general LCA of the main available treatments for scrap tyres, such as material recovery and waste-to-energy technologies in order to discover the best option [1, 15, 16]. Other studies have focused on combustion, gasification, pyrolysis and other technologies to recover energy from ELT and the emissions resulting from these technologies [14, 17-20]. On the other hand, the collection and transportation of the ELT is also an important process that has to be analysed and optimised. In literature there are some examples mainly taking into account three different points of view: minimising operational costs such as fuel consumption and vehicles involved, minimising environmental impacts and maximising social profits. While Dehghanian *et al.* [21] analysed all these issues jointly using LCA and methods Analytical hierarchy process (AHP), Tavares *et al.* [22] focused their research on the optimisation of waste collection routes for minimum fuel consumption using a 3-D GIS modelling because more than 70% of the total waste management budget is currently spent on fuel, and Anic-Vucinic *et al.* [23]

showed that a significant reduction of greenhouse gas emissions can be expected in Croatia by means of implementing their measures over the waste management system.

On the other hand, other authors have focused their research on the determination of the optimal vehicle routing for solid waste collection within a capacitated vehicle routing problem (CVRP), as a variant of vehicle routing problem (VRP) [24], distributed in exact algorithms [25] and a multitude of approximate algorithms as heuristic solutions methods [26], "Tabu search" [27] methods, genetic algorithms [7] and fuzzy logic methods [28] that have been applied to waste collection systems. Gamberini *et al*. [29] also applied an integrated approach to a case study in Italy in order to ensure that the collection of electrical and electronic goods is accomplished satisfying both technical and environmental performance measures using the LCA methodology. In addition, specific studies of several recycling technologies have been conducted [30-32].

However, no relevant studies have specifically focused on an evaluation method to quantify the environmental performance of any used ELT recovery method (energy and material), the treatment plant and the transport system integrated into a single system whose function is to recover the value of the ELT. Thus, the aim of this study is to present an evaluation methodology which is based on a simplified mathematical approach and connected to the LCA methodology for generating a tool to estimate the CO_2-eq emissions.

Methodology

The presented evaluation method estimates and allows for finding improvement for the environmental performance, in terms of the benefit in net CO_2-eq emissions, of an ELT recycling system applying a simplified mathematical approach which permits making a more complete environmental assessment by connecting mathematical models to the conventional LCA methodology. The ELT collection/sorting centres and the different locations of ELT recovery centres are considered to determine the transportation needs as well as the amounts of materials that can be collected from each centre and received by the nearby ELT recovery centres. The CO2-eq emissions emitted by the treatment plant and those avoided by the used ELTs recovery methods are included.

Equations (1)-(3) and tab. 1 summarise the evaluation method used in this research. Table 1 shows a matrix for a general geographic situation. This matrix represents the difference between the amount of CO_2-eq emissions emitted for a spatial distribution "*i*" that includes CO_2-eq emissions due to ELT transportation from the collecting/sorting centres to the treatment plant, the CO_2-eq emissions due to the operation of the treatment plant, and theCO_2-eq emissions due to the treated products transportation from this plant to the ELTs recovery facilities (E_{gi}); and the amount of CO_2-eq emissions avoided for a scenario "*j*" representing a set of considered ELT recovery methods (E_{aj}). The element of the matrix shown in tab. 1, β_{ij}, can be written as:

$$\beta_{ij} = E_{g_i} - E_{a_j} \tag{1}$$

$$E_{g_i} = \sum_{x=1}^{x=n} E_{g_x} = E_{g_1} + E_{g_2} + E_{g_3} + \ldots + E_{g_n} \tag{2}$$

$$E_{a_j} = \sum_{y=1}^{y=m} E_{a_y} = E_{a_1} + E_{a_2} + E_{a_3} + \ldots + E_{a_m} \tag{3}$$

where E_{gx} is the CO_2-eq emissions that have been produced by "*n*" subsystems for "*i*" spatial distribution and E_{ay} is the CO_2-eq emissions avoided by "*m*" ELT recovery methods considered for the "*j*" scenario. In this research seven spatial distribution (i = 7) have been studied considering, on the one hand, that the materials obtained from the treatment plant are distributed by 45%, 23% and 25% per tonnes for (E_{a1}) moulded objects production, (E_{a2}) synthetic turf and (E_{a3}) steel works (m = 3), respectively; and, on the other hand, CO_2-eq emissions due to (E_{g1}) ELT transportation from the collecting/sorting centres to the treatment plant, (E_{g2}) operation of the treatment plant, and the (E_{g3}) treated products transportation from this plant to the ELT recovery facilities (n = 3). This analysis has been carried out for two treatment plant locations (j = 2).

Table 1. Net CO_2-eq emissions – Matrix of the relationship between the ELTs spatial distribution and the ELTs recovery scenarios

ELT recovery scenario j↓	1	2	3	4	5	6	← ELT spatial distribution i
1	β_{11}	β_{12}	β_{13}	β_{14}	β_{15}	β_{16}	
2	β_{21}	β_{22}	β_{23}	β_{24}	β_{25}	β_{26}	
3	β_{31}	β_{32}	β_{33}	β_{34}	β_{35}	β_{36}	

The elements of the matrix β_{ij} can be positive or negative values. In this first case, the generated emissions are higher than the avoided emissions in each particular scenario. The second case, which involves a negative or zero value, occurs when the avoided emissions are higher than those generated or equal to them, respectively.

The LCA methodology has been used to rigorously determine CO_2-eq emissions. This methodology is useful for analysing the environmental impact caused by any type of process and product [33]. SETAC (Society of Environmental Toxicology and Chemistry: www.setac.org) defines the LCA as "an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying consumed energy and materials and waste released to the environment, and to evaluate and implement opportunities to affect environmental improvements". In other words, LCA studies cover the environmental aspects and the potential impacts throughout a product's life (*i. e.* cradle-to-grave) from raw material acquisition through production, use and disposal.

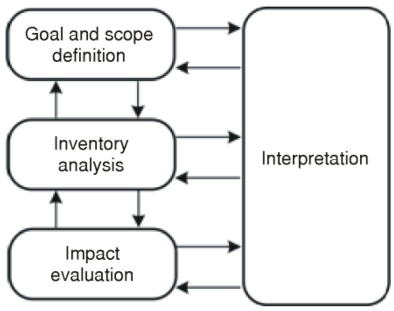

Figure 1. Principal phases of an LCA study [34]

The most up-to-date structure of the LCA was proposed by the ISO 14040:2006 guidelines [34] and divides the assessment procedure into four basic steps: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation. Figure 1 shows the principal phases of an LCA study where the dynamic character and the interrelation of the four phases can be seen.

ISO 14040:2006 prescribes clear definitions of the goal and the scope from the beginning of all LCA studies including the system boundary and the functional unit. After this phase, the inventory analysis is carried out by data collection inside the system boundary. In this study, the environmental impacts have been determined at the midpoint level (*e. g.* climate change). A midpoint impact category indicator is considered a result point in the cause-effect chain (environmental mechanism) of a particular impact category somewhere between the stressor (a set of conditions that may lead to an impact) and the impact category indicator at endpoint level (like damage to human health and damage to ecosystem quality) [26]. To this end, the CML 2001 impact assessment method [26] was used to quantify and com pare the potential environmental impacts of the life cycle inventory by using the software SimaPro v. 7.2 [35]. Also, the carbon footprint of the transport system was estimated through the CML baseline 2001 methodology, which summarises the greenhouse gas emissions in terms of CO_2-eq emissions.

As far as transportation is concerned, a simple approach that can be used to the VRP solving is the "savings" algorithm of Clarke *et al*. [36]. This savings algorithm is a heuristic algorithm and considers a depot *D* and *n* demand points. The basic savings concept expresses that initially the distance savings can be obtained by joining two routes, say (*x*) and (*y*) into one route, expressed by eq. (4). In this sense, the total distance travelled is reduced by the amount:

$$S_{(x',y')} = 2d\left(D,x'\right) + 2d\left(D,y'\right) - \left[d\left(D,x'\right) + d\left(x',y'\right) + d\left(D,y'\right)\right]$$
$$S_{(x',y')} = d\left(D,x'\right) + d\left(D,y'\right) - d(x,y) \tag{4}$$

where $S_{(x', y')}$is the distance savings results from combining points *x* and *y* into a single route for every pair (*x'*,*y'*) of demand points, and *d* represents the distance travelled from depot *D* to *x'* or *y'* or from *x* to *y*. Large values of $S_{(x', y')}$ indicate that is attractive to visit points *x* and *y* on the same route taking into account if the total demand on the resulting route does not exceed the vehicle capacity. Also, the routing is constrained by working hours, disposal site opening hours and other factors.

Goal and scope definition

Objective and functional unit

The main objective of this study is to determine the environmental performance of end-of-life tyre recycling by applying the proposed method which uses the LCA methodology as a tool to estimate the CO_2-eq emissions. In this study, the functional unit is 1 t of ELT from a collection/sorting centre.

Target area and quality data

Figure 2 shows the geographic location of the target area (Autonomous Community of Aragon) used

Figure. 2. Target area

to apply the method. The Autonomous Community of Aragon has a surface area of 47,719.2 km^2 and a population of approximately 1.3 M people. In this region, there is only one treatment plant situated in the city of Zaragoza, which has been selected as the case study. This plant receives ELTs from all the Aragonese municipalities that form the community. The local government follows a mandatory waste recycling program which establishes a collection system from authorised collection/sorting centres that store the ELTs before their transport to the aforementioned treatment plant. Approximately 42 collection/sorting centres are currently available distributed across the three provincial capitals of the Autonomous Community: Zaragoza (70%), Huesca (26%), and Teruel (4%) [9].

System description

The stages involved in the studied ELT recovery methods are shown in fig. 3. The environmental assessments of the selected ELT recovery methods were established by accounting for the impact of collecting and transporting the ELT from the collection/sorting centres to the treatment plant and then to the ELT recovery facilities. The ELT from the 42 collection/sorting centres are transported over the road network to the treatment plant and the ELT recovery facilities by a 16 t truck fleet. The CO_2-eq. emissions from the transport of the materials obtained from the ELT treatment plant to the ELT recovery plants are calculated based on current information on either the fastest or the cheapest route connecting a departure point to a destination, using travel times based on the average speed of the drivers and the influence of the traffic.

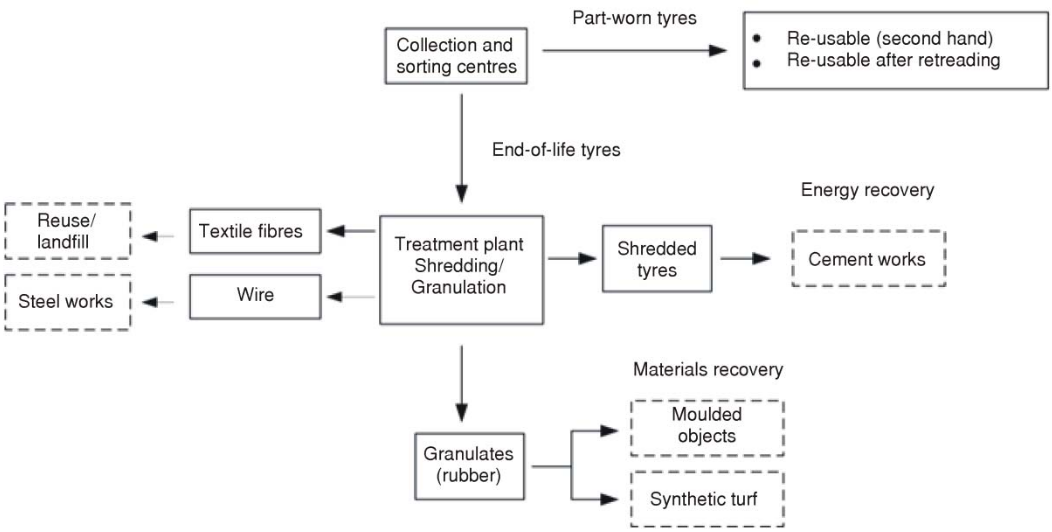

Figure 3. General system of ELT studied in Aragon

To this end, this study assumes that the locations of the ELT recovery plants and the amount of materials that can be processed are known. The distance between the plants can be calculated by consulting road maps and websites (such as www.viamichelin.com). Thus, the distance travelled by a functional unit is easily calculated. Additionally, the traffic influence can be considered applying a correcting factor [22]. Table 2 shows the amount of ELT collected from the collection/sorting centres depending on the different distance radii from the treatment plant established as the centre of the circle area. In 2009, approximately 9054 t/year were transported to the treatment plant.

Table 2. Spatial distribution of ELT collected

Number	Radius [km]	Distance travelled [km]	ELT [t]
1	10	350	4325.15
2	30	450	104.11
3	60	790	321.61
4	90	1170	1136.78
5	120	1560	898.20
6	150	1950	1317.41
7	200	4560	950.93
		Total	9054.18

On the other hand, in order to determine the benefit in net emissions reduction, the emissions avoided due to the substitution of traditional fuels and conventional materials are included, for example: (i) traditional fuels such as petroleum coke and coal by energy recovery in cement works; and (ii) conventional materials such as anthracite, foundry coke and virgin polyurethane by material recycling in steelworks, foundries and moulded objects, respectively.

Boundaries of the system

The stages involved in the ELT recovery methods studied include all of the collection and the transport from the collection/sorting centres to the ELT treatment plant and the ELT recovery facilities, considering cement manufacturing as an energy recovery method from shredded tyres and moulded objects as well as synthetic turf and steel manufacturing as a material recovery method for rubber and wire. Textile fibres are not taken into account within the boundaries of the system.

The rules and limits considered in the analysis are as follows:

– components with weight greater than 1% of the final product weight are considered,
– components that represent less than 1% of the total economic value are not taken into account, and
– phases that contribute less than 1% to the inventory analysis or to the environmental relevance analysis are not considered.

Analysing the system limits (processes, manufacture, transport and waste treatment, inputs-outputs to be considered), they can be:

– second order limits: the production phase, the energy flows and the production of raw material are considered for each component, and
– third order limits: Capital investments and the production of materials necessary for their elaboration. This study did not take the capital goods, such as buildings, machinery, and personnel, into account.

Life cycle inventory

Table 3 shows the main inputs (process water and energy consumption) and the secondary raw material derived from the ELT processing as the main outputs for 1 t of ELT treated in a traditional ELT treatment plant. In addition, the amount of

Table 3. The main inputs and outputs for a traditional ELT treatment plant

	Element	
Input	Process water [kg]	150.00
	Electricity [kWh]	308.00
Output	Recycled rubber [kg]	680.15
	Steel (wire) [kg]	275.50
	Textile fibres [kg]	43.47
	Processing powder [g]	876.00

CO_2-eq emissions avoided from different ELT recovery methods for 1 t of ELT recovered are presented by Clauzade *et al*. [37].

Results and discussions

The analyses carried out by applying the proposed methodology have been referenced to the production and the disposal of ELT in Aragon. According to the aforementioned data from 2009 [9], the overall Aragonese production of ELT is approximately 9054 t/year. Assuming a constant production of ELT, two different scenarios have been considered, with respect to the amount of ELTs generated:

– Scenario 1 (baseline): In this scenario considers that the ELT treatment plant in the region of Aragon has not been moved from its current geographic position. Concerning material recovery processes, it is assumed that 100% of the ELT are sent for mechanical grinding. In addition, the materials obtained from the treatment plant are distributed by 45%, 23% and 25% per tonnes for moulded objects production, synthetic turf and steel works, respectively. Thus, the distance travelled per one tonne of the secondary material from the ELT treatment plant are 33, 40, and 31 km, respectively.

– Scenario 2: The current location of the plant is moved 60 km away from the current location and the scenario of recovery plants is the same. In this scenario it is necessary to recalculate the distances to both the ELT collection points and the ELT recovery plants with respect to the new location of the treatment plant.

For any of the two scenarios the total amount of ELT could be recovered using three different procedures available in the region of Aragón and that, in addition, are permitted by the current regional legislation. These scenarios are delimited by the typical characteristics of the region used as a study case. Nevertheless, the method allows the incorporation of as many alternatives as there are collection points in the geographic area studied.

Tables 4 and 5 summarise the results of these scenarios. Table 4 shows the net total CO_2-eq emissions for scenario 1. The values are negative, indicating an environmental benefit, and the values decrease as the scope radius increases. This behaviour was observed due to the fact that the transportation of ELT obtained from long distances for later use in the ELT centres is not significant in terms of fuel consumption, and thus in the CO_2-eq emissions emitted. From the obtained results it is evident that the original location of the treatment plant brings benefits in terms of CO_2-eq for all the radii analysed.

Table 4. Net CO_2-eq emissions – Scenario 1

ELT recovery scenario *j*↓	1 [t]	2 [t]	3 [t]	4 [t]	5 [t]	6 [t]	7 [t]	← ELT spatial distribution *i*
1	–1.25	–1.23	–1.18	–1.12	–1.05	–0.97	–0.08	

Table 5. Net CO_2-eq emissions – Scenario 2

ELT recovery scenario j↓	1 [t]	2 [t]	3 [t]	4 [t]	5 [t]	← ELT spatial distribution i
2	–0.43	–1.07	–0.83	–0.77	–0.53	

Table 5 shows the results obtained for the second scenario when the position of the treatment plant is varied with respect to that of scenario 1 (keeping the position of the collection points and plants of the different ELT recovery methods constant). This variation of the treatment plant position entails recalculating the travelled distance and establishing the radii, and additionally identifying the number of collection sites that are covered for each case. In particular, radii distances of 30, 50, 60, 90, and 140 km were analysed and represented by ELT spatial distribution numbers 1, 2, 3, 4, 5, respectively in tab. 5.

As shown in tab. 5, when the plant is moved 60 km, there is an environmental benefit for all of the radii analysed, and the greatest benefit was obtained for the radius of position two, where 4329 t of ELT may be recovered. The rest of the radii show a decrease in the benefit as the amount of ELT collected is reduced at the expense of an increase in transport.

Regarding the transportation optimisation, The Clarke and Wright method has been applied to solve the road transportation of ELT from the 42 collection/sorting centres to the treatment plant using a 16 t truck fleet. Only the routes connecting the collection centres to treatment plant are studied, not including those from the treatment plant to the recovery centres. The best achieved solution is obtained in the form of a "saving distance", which is reduced in comparison to the travelled distance obtained for the baseline scenario.

Since that the transportation optimisation resulted in distance savings, tab. 2 is newly estimated considering the best solution for each radius as shown in tab. 6. From results, it can be observed that the total travelled distance between the collection/sorting centres and the treatment plant can be reduced by 14.9% according to the routes shown in the web site of "via Michelin".

Table 6. Spatial distribution of ELT collected

Number	Radius [km]	Distance travelled [km]	ELT [t]
1	10	298	4325.15
2	30	405	104.11
3	60	648	321.61
4	90	1052	1136.78
5	120	1350	898.20
6	150	1800	1317.41
7	200	3662	950.93
		Total	9054.18

Conclusions

The proposed evaluation method makes it possible to analyse the environmental performance, in terms of avoided CO_2-eq emissions, considering the CO_2-eq emissions generated in an ELT treatment plant, the ELT transportation from the collecting/sorting centres to the treatment plant and the treated products transportation from this plant. The method allows for the inclusion of as many ELT recovery methods as those in the study area and the analysis of both the collection sites and the radii for the transport to be incorporated.

In this framework, this method is a powerful tool for the scientific and the engineering communities to carry out comparative analyses of alternative scenarios in order to identify the most environmentally friendly location of an ELT treatment plant. As a case study, the region of Aragon in Spain was evaluated taking into account that the current geographic position of the plant generates environmental benefit for the different radii studied with a maximum of 200 km. In addition, one hypothetical scenario was generated to show the influence of the relationship between the amounts of ELT available in the different collection sites and their distance with respect to the treatment plant. The implementation of this methodology on an ELT management numerical code allows the performance to be taken into account in ELT management decisions.

Regarding the transportation optimisation, The Clarke and Wright method has been applied to solve the road transportation of ELT from the 42 collection/sorting centres to the treatment plant for the baseline scenario. From results, it can be observed that the total travelled distance between the collection/sorting centres and the treatment plant can be reduced by 14.9%

Nomenclature

D – depot, [-]
E_a – CO_2-eq emissions avoided, [t]
E_g – CO_2-eq emissions generated, [t]
S – distance savings, [km]

Greeks symbols

β – difference between emitted and avoided CO_2-eq emissions, [t]

Subscripts

i – spatial distribution considered
j – scenario considered for ELTs recovery methods
x – subsystem or activity considered for i spatial distribution
x' – demand point
y – ELT recovery method considered for j scenario
y' – demand point

Acronyms

ELT – end-of-life tyres
LCA – life cycle assessment

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