Maximising the Circular Economy and Sustainability Outcomes: An End-of-life Tyre Recycling Outlets Selection Model

Abstract

The increasing concern for sustainability and longing for the transition into the circular economy has fostered an immense interest in re-configuring the end-of-life tyre supply networks. However, the existing literature is incapable of providing sufficient guidance in regard to the allocation of end-of-life tyre among recycling outlets to maximise the circular economy and sustainability outcomes. Hence, this study aims to propose a comprehensive list of evaluation criteria to rank recycling outlets, and develop an end-of-life tyre outlets selection matrix. A hybrid method is proposed by integrating fuzzy Analytical Hierarchy Process, fuzzy Technique of Order Preference Similarity to the Ideal Solution, the multi-objective linear programming, and semi-structured interviews. By analysing the empirical data collected from one of the largest European collectors, this study reveals that cement manufacturing, which is the primary recycling outlet, ranks the lowest among the five recycling outlets in terms of the circular economy and sustainability outcome. Nevertheless, synthetic turf manufacturing and moulded objects manufacturing rank the highest in the circular economy and sustainability outcomes, respectively. It is proved that cost and profit are key drivers for recycling outlets selection, subjected to end consumers' perceptions and the ease of end-of-life tyre processing. The ranking and the performance of recycling outlets also signify the competitive relationship between the circular economy and sustainability as excelling in the circular economy outcome would trade-off sustainability performance.

Keywords:

Circular Economy, Sustainability, Multi Criteria Decision Making, Fuzzy AHP-TOPSIS, Multi Objective Programming.

1. Introduction

To date, an accumulating amount of tyre is reaching the End-of-Life (EOL), known as EOL tyre (ELT). Bermejo (2019) reveals that material recycling is the most commonly employed strategy in EU-28 countries in handling the ELT, which is as high as 55%, preceding others such as energy recovery (35%) and remanufacturing or reuse (6%). Within recycling, many recycling outlets are able to utilise the ELT to manufacture new products. For example, it can be recycled into synthetic turf, equestrian floor, rubber asphalt, or moulded products (Hallberg and Kärrman, 2007).

However, the wide varieties of outlets for ELT often create choice difficulties and dilemma. Different authors use different criteria while comparing the alternatives, which provide different outcome and suggestions. For example, Hallberg and Kärrman (2007) recommend the ELT to be recycled and manufactured into cement while Feraldi et al. (2013) recommend rubber asphalt. Beside the failure to arrive at an unequivocal decision on which recycling outlet is the best for an ELT in regard to the Circular Economy (CE) and sustainability outcomes, the literature is also unable to determine the optimum selling quantities and assignment of sales to different alternatives. It is often being evidenced in other fields (e.g. supplier selection) that the resources should be allocated among the alternatives to maximise the desired objectives (Khoshfetrat et al., 2020). Currently, no decision-making model has been proposed to justify which recycling outlet is the most favourable and how ELT should be allocated among them to achieve the CE and sustainable development. The improper allocation of ELT into undesirable recycling outlets would lead to excessive resource consumption (De Almeida and Borsato, 2019) and potential value wastage (Peeters et al., 2015; Priarone et al., 2015). This research gap is intended to be filled by answering the research question one: How to allocate the ELT among recycling outlets in supply networks to maximise the CE and sustainability outcomes?

To construct an effective ELT allocation model, a thorough inclusion of the CE and sustainability criteria is a necessity. However, no framework in the existing literature could guide the comprehensive inclusion of the CE and sustainability criteria. The use of various and contradicting criteria that span across different dimensions and themes are observed in the current literature, such as Hallberg and Kärrman (2007), Oostenrijk and Duuren (2011), and Feraldi et al. (2013). To bridge this research gap, the following research questions two and three will be answered: What are the impacting CE and sustainability criteria and measurements for the ELT recycling outlets selection? How important are they in the decision-making?

The CE and sustainability seem to complement each other in ensuring that the future needs will not be harmed. Nevertheless, the literature shows a contracting result regarding the impact of the CE on sustainability (Geissdoerfer et al., 2017). For example, Ellen MacArthur Foundation (2012) discovers that the CE improves economic sustainability, but contradicts Genovese et al. (2017). Lawton et al. (2014) asserts that the CE stimulates environmental sustainability, but conflicts with findings of Allwood (2014). European Commission (2015) advocates that the CE lifts societal sustainability, but contradicts with Duin and Best (2018). Hence, the relationship between the CE and sustainability remains unclear in the existing literature. This study will fill this research gap by answering the research question four: What is the impact on sustainability while achieving the CE agenda in the ELT recycling industry?

In order to bridge the aforementioned gap, this research aims to design an end-of-life tyre outlets selection model to maximise the CE and sustainability outcomes, based on the thoroughly selected CE and sustainability criteria via an extensive literature review. In this process, the most important criteria to maximise the CE and sustainability outcomes, as well as the relationship between CE and sustainability will be examined. This research can be applied in the industry by providing a model that can rank the ELT recycling outlets and subsequently allocate ELT among the outlets. The most important criteria and instruments identified within this research can also be used to increase CE and sustainability outcome of a company and its supply chain.

The remainder of this paper is structured as below. Section 2 provides a review of the literature. Section 3 exhibits and explains the research methodology by covering Fuzzy-Analytical Hierarchy Process (FAHP), Fuzzy-Technique of Order Preference Similarity to the Ideal Solution (FTOPSIS), the multi-objective linear programming (MOLP), and the non-sorting genetic algorithm (NSGA-II). Section 4 details the numerical calculation and discusses the findings. Section 5 summarises the study and proposes the contribution.

2. Literature Review

2.1. Recycling outlets for the ELT

Due to the pressure of supply risks and sustainability, supply chain partners are working together to bring the EOL products back to the original supply chain (Allwood, 2014; Haupt et al., 2017). Besides the close loop recycling outlet, the EOL wastes could also be allocated to other recycling outlets as inputs to produce new products (Allwood, 2014; Haupt et al., 2017; Pauliuk et al., 2017). For the ELT, the close loop recycling outlet is not a suitable option due to the technical difficulty of ensuring the quality (Cinaralp, 2015). It is normally manufactured as artificial turf, flooring for playgrounds, cement, mould objects, foundries, and rubber asphalt (US Environment Protection Agency, 2010). Pourriahi (2016) and Bermejo (2019) report that 31% of the ELT in EU-28 countries are manufactured into synthetic turf, 25% are manufactured into sports surfaces, 25% are manufactured into moulded objects, 18% are manufactured into cement, and less than 1% is manufactured into foundries.

However, there is an ongoing argument regarding the best recycling outlet for the ELT in the fields of CE and sustainability outcomes. For example, Hallberg and Kärrman (2007) recommends synthetic turf or cement as a better recycling outlet compared to asphalt. It contradicts Schmidt et al. (2009), Clauzade et al. (2010), Corbetta (2013), and Feraldi et al. (2013), which recommend the opposite. It is a result of the segmentary conceptualisation of the CE and sustainability in these researches. For example, most of them merely take environmental sustainability into consideration when evaluating the performance of the ELT recycling outlets (e.g., Hallberg and Kärrman, 2007; Schmidt et al., 2009; Clauzade et al., 2010). Moreover, an insufficient number of the CE measurements from each criterion is investigated (e.g., Oostenrijk and Duuren, 2011). Hence, the literature cannot provide an unequivocal answer to which recycling outlet is the best for the ELT to maximise the CE and sustainability outcomes.

2.2. The CE and sustainability criteria

Although the existing literature makes efforts to evaluate the CE and sustainability outcomes of the ELT outlets, it is revealed that the investigated CE and sustainability criteria and measurements are fragmented and scattered. Hence, it is necessary to build a framework to direct the selection and generation of the relevant criteria to ensure an accurate and comprehensive conceptualisation of the CE and sustainability.

The CE is currently in its pioneering phase, and its evaluation criteria are not widely employed in the decision-making problem (Ellen MacArthur Foundation, 2012). Consequently, this study conducts an exploratory literature review to identify the relevant CE criteria and instruments thoroughly. The search string ({circular economy} OR {CE}) AND ({circularity} OR {evaluation} OR {assessment} OR {measure} OR {indicators} OR {indices} OR {index} OR {indicator} OR {metric} OR {metrics} OR {measurement} OR {dimensions}) was applied under title, abstract and words fields. Key databases including Science Direct, SAGE, Springer, Taylor and Francis, Wiley, Emerald and JSTOR were used to search for articles ranged from 2000 to 2019. Several articles were also identified by a manual search of bibliographies from all retrieved articles. In addition, complementary sources such as company reports were included to extend the coverage of existing CE-indicators (e.g. the European Commission, the European Environmental Agency and the Ellen MacArthur Foundation).

Five CE criteria are revealed, including Monetary, Energy and Environment (Kristensen and Mosgaard, 2020), Material (Sassanelli et al., 2019), Temporal (Helander et al., 2019) and Efficiency (Ellen MacArthur Foundation, 2015). Monetary is the criterion associates with economic instruments such as repairing price (Cayzer et al., 2017). Energy and Environment is the criterion associates with energy and environmental pollution instruments such as renewable energy generation (Huysman et al., 2017). Material is the criterion associates with tangible material instruments, such as the production of unrecoverable waste (Ellen MacArthur Foundation, 2015). Temporal is the criterion associates with instruments that involve time, such as the lifetime of products (Ellen MacArthur Foundation, 2015). Efficiency is the criterion associates with production or design efficiency instruments such as recycling efficiency (Ellen MacArthur Foundation, 2015). The CE criteria and sub-criteria are shown in Table 1. Unlike CE, sustainability is a mature field of research with three commonly used criteria, namely economy, environment, and social (Carter and Rogers, 2008). Economic sustainability is the criterion associates with monetary instruments such as cost and profit (IChemE, 2002). Environmental sustainability is the criterion associates with environmental instruments such as waste gas emission (Schwarz et al., 2002). Societal sustainability is the criterion associates with instruments that involve the well-being of society, such as job creation (IChemE, 2002). The sustainability criteria and sub-criteria are shown in Table2. Due to the different importance of these criteria in the business, the corresponding weight should be allocated to evaluate the CE and sustainability outcomes accurately.

Criteria	Sub-criteria	Source
Monetary (C1)	C_{11}: Average cost of virgin material per kg	Di Maio et al. (2017)
	C_{12}: Average repairing price	Alamerew and Brissaud (2019)
	C_{13}: Fraction of cost spent on the CE technology to total cost of investments	Garza-Reyes et al. (2019)
	C_{14}: Fraction of cost spent on recyclable material to total cost of material	Linder et al. (2017)
	C_{15}: Production cost per kg product	Zhou et al. (2013)
	C_{16}: Profit OR saving per kg recyclable input consumed	Di Maio et al. (2017)
Energy and Environment (C2)	C_{21}: Fraction of energy generated using renewable sources	Kiselev et al. (2019)
	C_{22}: Fraction of energy loss	Urbinati et al. (2019)
	C_{23}: Fraction of energy purchased from renewable sources	Yang (2018)
	C_{24}: Total GHG produced per kg product	Wang (2018)
	C_{25}: Total energy consumed per kg product	
	C_{26}: Total energy generated per kg product	Yang (2018)
Material (C3)	C_{31}: Fraction of the recycler output to the original supply chain	Pauer et al. (2019)
	C_{32}: Fraction of recycled material used per kg product	Pauer et al. (2019)
	C_{33}: Fraction of waste recycled internally	Wang (2018)
	C_{34}: Total weight of unrecoverable waste per kg product	Zhou et al. (2013)
Temporal (C4)	C_{41}: Lifetime of products	Pieratti et al. (2019)
	C_{42}: Time to reach the CE goal	US Chamber Foundation (2017)
Efficiency (C5)	C_{51}: Collection efficiency	Ellen MacArthur Foundation (2015)
	C_{52}: Modularity of product design	Mesa et al. (2018)
	C_{53}: Recyclability of the product	Pauer et al. (2019)
	C_{54}: Recycling efficiency of the recycler	Pauer et al. (2019)
	C_{55}: Rental-ability	Garza-Reyes et al. (2019)

Table 1: CE criteria and sub-criteria for ELT outlets selection.

Criteria	Sub-criteria	Source
Economy (S1)	S_{11}: Operational cost	Chong et al. (2016)
	S_{12}: Capital cost	
	S_{13}: Net profit	
Environment (S2)	S_{21}: Gas emission	Balkema et al. (2002)
	S_{22}: Resources consumption	
	S_{23}: Acidification and eutrophication potential	
	S_{24}: Renewable energy generation	Iacovidou et al. (2017)
Social (S3)	S_{31}: Job creation	
	S_{32}: Working hours and wages	
	S_{33}: Workers health and safety	
	S_{34}: Child labour	
	S_{35}: Local citizen participation	

Table 2: Sustainability criteria and sub-criteria for ELT outlets selection

2.3. Relationships between the CE and sustainability

Many studies have specified the general aim of conducting the CE is to achieve sustainability (Geissdoerfer et al., 2017). This notion has been supported and frequently exhibited in various research and reports. For example, Ellen MacArthur Foundation (2012) and Lawton et al. (2014) claim that CE bring about economical sustainability, by imposing cost savings and annual net benefits (e.g., 3–8 % of annual turnover) for EU-27 businesses. In terms of environmental sustainability, European Environment Agency (2016) claims that CE is able to provide a cutback in greenhouse gas emissions, similar to findings of Lawton et al. (2014) in the food and drinks services, hospitality and fabricated metals sectors. In regard to societal sustainability, European Environment Agency (2016) and European Commission (2015) advocate that practising CE activities are able to provide new direct jobs. As a consequent, activities pertaining to CE have been heavily promoted and adopted in the vision of realising sustainability. For example, Stewart and Niero (2018) discover that CE has started to be integrated into the corporate sustainability agenda of 46 corporations being studied, oriented toward the packaging of products and EOL management. Similarly, Oncioiu et al. (2018) discover that majority of the studied SMEs have engaged in the CE by using renewable energy, adopting energy labelling, and designing smart and environmentally friendly product to enhance their sustainability performance. Nevertheless, the literature shows that the impact of the CE on sustainability is equivocal. These findings contested the common perception towards CE. For example, Genovese et al. (2017) study the effect of CE in manufacturing of ferrous Sulphate and biodiesel and discover that transition into CE is challenging from an economic point of view due to unavailability of EOL products and higher sourcing cost. This finding coincides with findings of Duin and Best (2018) who show that sourcing cost in CE business case is higher, suggesting that CE activities do not necessarily bring about economical sustainability. Further, Cullen (2017) shows that energy inputs and material losses associated with recycling of some materials can take over many of their environmental benefits, as well as consuming more virgin materials in the process. Allwood (2014) analyses major recyclable materials and discovers that recycling of materials such as cement is more energy intensive than new production. Also, the GHG emissions for materials such as paper recycling may be greater than those of primary papermaking. These findings suggest that recycling, the core activity related to CE, do not necessarily lead to environmental sustainability. Moreover, Smits and Woltjer (2018) estimate that the employment effects due to transitioning to CE business is limited due to the high automation level of the CE business. The disputes arisen causing the status quo of CE as well as the applicability of related activities in achieving sustainability to be queried. This exhibits an essential research gap that should be bridged to uncover the proper usage of CE related activities in attaining sustainability goal.

By filling in the above three research gaps, this study would provide a comprehensive list of criteria and items to measure the CE and sustainability outcome of recycling organisations and their supply chains. It advances the existing knowledge by providing theoretical foundation for the construction of a thorough CE and sustainability evaluation framework. Moreover, this research would propose a method on ranking ELT recycling outlets and allocating appropriate amount of resources to them. It supplements the existing literature by incorporating more criteria across different dimensions and including measurements with different units. It also sheds light on potential hindrances and enablers towards achieving CE agendas and sustainable development. Further, the relationship between the CE and sustainability would be identified. This refines the understanding of the effect on sustainability while practising CE agendas, stimulating additional theory-building and conceptual development. It could eventually facilitate the proper usage of CE related activities and potentially shaping the sustainable supply chain strategy in the future.

3. Methodology

Figure 1 shows the main research stages of this study. After identifying the CE and sustainability criteria, FAHP is employed to calculate the corresponding weights. The ranking of the CE and sustainability outcomes for existing outlets is then identified by conducting FTOPSIS. To maximise the CE and sustainability outcomes, a MOLP is formulated. A semi-structured interview is then carried out to bring more fruitful information to explain the ELT recycling outlets selection.

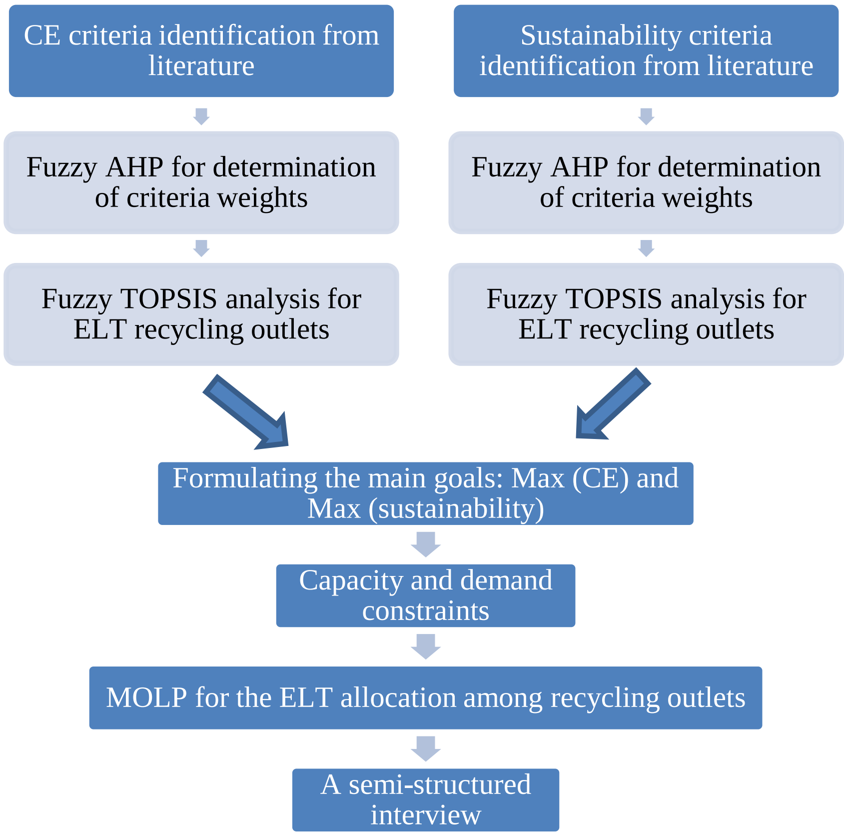

Figure 1: The research framework

3.1. Fuzzy AHP for criteria weights determination

There are several methods can be used to determine the weight of criteria in the literature, such as Analytical Hierarchy Process (AHP) and Analytical Network Process (ANP). Nevertheless, AHP is used in this research oppose to ANP because the latter is only used when the interrelationship between the criteria and sub-criteria prevail. Since there are no evidences proving the interdependence among the ELT recycling outlets selection criteria, AHP that assumes no interrelationship between them is chosen over ANP for this study (Saaty, 1990). AHP is a powerful method in solving multi criteria decision-making problems by examining the decision criteria using pair-wise comparisons. However, the uncertainty that is associated with human thinking and reasoning always present in the pair-wise comparison process because the objects being judged are naturally subjective and cannot be estimated exactly using any scale (Mehrjerdi, 2012). As a remedy, the fuzzy set theory, which is conceived by Zadeh (1965, 1976) to solve the vague nature in decision-making, is therefore incorporated into AHP. In FAHP, data collected from AHP is processed using advanced mathematics, which is proven to be able to strengthen the decision-making process (Chen et al., 2006). Various literature, such as Wang et al. (2012) and Awasthi et al. (2018), has proved its effectiveness in the research.

Triangular fuzzy numbers are used in this study to assess the preferences. A triangular fuzzy number is defined as (l, m, u) where l ≤ m ≤ u. A fuzzy set is defined by its membership function as shown in Eq. (1) and depicted in Figure 2. The definitions of the fuzzy method were introduced in Zadeh (1965, 1976) and Zimmermann (2001).

$$\mu_M(x) = \begin{cases} \frac{(x-l)}{(m-l)}, & l \leq x \leq m \\ \frac{(u-x)}{(u-m)}, & m \leq x \leq u \\ 0, & u < x < l \end{cases} \quad (1)$$

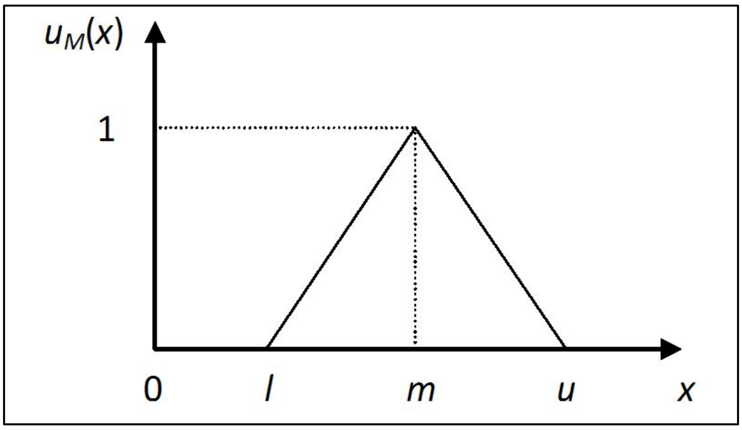

Figure 2: Membership function of triangular fuzzy number M

The procedures of FAHP method presented in Buckley (1985) is utilised in this paper to determine the weight for the CE and sustainability criteria, followed by the de-fuzzification method proposed by Chou and Chang (2008) as well as consistency ratio (CR) calculation in subsequent steps:

Step 1: Decision makers (DMs) are required to compare the CE and sustainability criteria via linguistic terms shown in Table 3.

Saaty scale	Definition	Fuzzy triangular scale (l,m,u)
1	Equally important (E.I)	(1,1,1)
3	Weakly important (W.I)	(2,3,4)
5	Fairly important (F.I)	(4,5,6)
7	Strongly important (S.I)	(6,7,8)
9	Extremely important (Ex.I)	(9,9,9)

Table 3: linguistic terms and the corresponding triangular fuzzy numbers

Step 2: All the DMs matrix of pair-wise comparisons are aggregated and the judgments are synthesized to yield a set of overall priorities as shown in Eq. (2). Each of the element $\tilde{d}_{ij}$ in the matrix is the geometric mean of all the element ij^{th} provided by the DMs.

$$\tilde{A} = \begin{bmatrix} \tilde{d}_{11} & \tilde{d}_{12} & \cdots & \tilde{d}_{1n} \\ \tilde{d}_{21} & \tilde{d}_{22} & & \tilde{d}_{2n} \\ \vdots & & \ddots & \vdots \\ \tilde{d}_{n1} & \tilde{d}_{n2} & \cdots & \tilde{d}_{nn} \end{bmatrix}, \tilde{d}_{ij} = (l_{ij}, m_{ij}, u_{ij}),\ \tilde{d}_{ji} = \frac{1}{\tilde{d}_{ij}} = (\frac{1}{u_{ij}}, \frac{1}{m_{ij}}, \frac{1}{l_{ij}}) \quad (2)$$

Step 3: The fuzzy weights of each criterion i is obtained by multiplying each fuzzy geometric mean value, $\tilde{r}_i$ with the inverse power of vector summation as shown in Eq. (3) and Eq. (4).

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \ldots \oplus \tilde{r}_n)^{-1} \quad (3)$$

$$\tilde{r}_i = (\prod_{j=1}^{n} \tilde{d}_{ij})^{\frac{1}{n}}\ where\ i = 1,2, \ldots, n \quad (4)$$

Step 4: De-fuzzification of fuzzy weight $\tilde{w}_i$ is performed using centre of area method by averaging the three components of the fuzzy set as shown in Eq. (5). Subsequently, the weight of each criterion N_i can be obtained by normalisation. A final consistency of the judgments is calculated using CR to ensure that no mistakes or conflicting ratings are made by the DMs. A CR that is less than 0.1 implies that the judgments are acceptable for the criteria weights (Saaty, 1990).

$$M_i = (l_i + m_i + u_i)/3 \quad (5)$$

3.2. *Fuzzy TOPSIS for ELT recycling outlets ranking*

There are several analysis methods that can be used for alternatives ranking in the literature, such as AHP, ANP, ELECTRE, PROMETHEE, TOPSIS, and VIKOR. Nevertheless, TOPSIS is used in this study as this method is most frequently used method in supply chain and operations research (Behzadian et al., 2012). This method is used widely because it is the most accurate method compared to the aforementioned alternatives (Widianta et al., 2018; Jozaghi, 2018) and it is easy and fast to compute (Kahraman et al., 2009).

TOPSIS was developed by Hwang & Yoon (1981). In this method, the best alternative would be the one that is closest to the positive ideal solution (PIS) and farthest from the negative ideal solution (NIS) (Ertugrul & Karakasoglu, 2009). As aforementioned, vagueness and uncertainty always present in a decision-making process. Thus, the fuzzy theory will also be incorporated into TOPSIS method to resolve the uncertainties and vagueness in the reasoning process. FTOPSIS method consists of the following steps (Lima-Junior and Carpinetti, 2016)

Step 1: The decision matrix for the ranking is established as shown in Eq. (6), with the triangular fuzzy numbers indicating the performance score of each alternative A_i with respect to each criterion C_j. When multiple inputs are provided by the DMs, the a_{ij} of the element $\tilde{x}_{ij}$ will take the lowest value of all a_{ij} provided by all DMs, the b_{ij} of the element $\tilde{x}_{ij}$ will take the mean value of all b_{ij} provided by all DMs while the c_{ij} of the element $\tilde{x}_{ij}$ will take the maximum value of all c_{ij} provided by all DMs.

$$\widetilde{D} = \begin{matrix} & C_1 & C_2 & \cdots & C_j & \cdots & C_n \\ A_1 \\ A_2 \\ \vdots \\ A_i \\ \vdots \\ A_m \end{matrix} \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1j} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2j} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ \tilde{x}_{i1} & \tilde{x}_{i2} & \cdots & \tilde{x}_{ij} & \cdots & \tilde{x}_{in} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mj} & \cdots & \tilde{x}_{mn} \end{bmatrix}, \tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}),\ \tilde{x}_{ji} = \frac{1}{\tilde{x}_{ij}} = \frac{1}{c_{ij}}, \frac{1}{b_{ij}}, \frac{1}{a_{ij}} \quad (6)$$

Where
A_i represents the alternatives i, where i = 1,2, … , m
C_j represents j^{th} criterion, where j = 1, 2, … , n

Step 2: The normalised fuzzy decision matrix $R = [r_{ij}]_{m\,x\,n}$ is tabulated, where its element r_{ij} is calculated as shown in Eq. (7) and Eq. (8). B and C are the sets of the benefit and cost criteria, respectively, following the linear normalisation method in Shih et al. (2007).

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), j \in B,\ c_j^* = \max_i c_{ij}\ \ if\ j \in B \quad (7)$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), j \in C, a_j^- = \min_i a_{ij}\ \ if\ j \in C \quad (8)$$

Step 3: The weighted normalized decision matrix is calculated by multiplying the normalised decision matrix by its associated weights, $\widetilde{w}_j$ obtained from AHP. The weighted normalised value v_{ij} is calculated using Eq. (9).

$$v_{ij} = \widetilde{w}_j \times \tilde{r}_{ij} \text{ where i = 1,2, … ,m and j = 1, 2, … , n} \quad (9)$$

Step 4: Fuzzy PIS (FPIS or A^*) and Fuzzy NIS (FNIS or A^-) are determined using Eq. (10) and Eq. (11).

$$\text{FPIS: } A^* = \{\tilde{v}_1{}^*, \tilde{v}_2{}^*, \cdots, \tilde{v}_n{}^*\} = \left\{\left(\max_i v_{ij}\ \middle|\ j \in J\right), \left(\min_i v_{ij}\ \middle|\ j \in J'\right)\right\} \quad (10)$$

$$\text{FNIS: } A^- = \{\tilde{v}_1{}^-, \tilde{v}_2{}^-, \cdots, \tilde{v}_n{}^-\} = \left\{\left(\min_i v_{ij}\ \middle|\ j \in J\right), \left(\max_i v_{ij}\ \middle|\ j \in J'\right)\right\} \quad (11)$$

Where J is associated with benefit criteria, and J’ is associated with the cost criteria.

Step 5: The distance D_i^* of each alternative A_i from FPIS, as well as the distance D_i^- of each alternative A_i from FNIS is calculated using Eq. (12) and Eq. (13), respectively.

$$D_i^{*} = \sum_{j=1}^{n} d_v(v_{ij}, v_j^{*}) \text{ , } for\ i = 1,2, \dots, m \tag{12}$$
$$D_i^{-} = \sum_{j=1}^{n} d_v(v_{ij}, v_j^{-}) \text{ , } for\ i = 1,2, \dots, m \tag{13}$$

Step 6: The relative closeness to the ideal solution, or the closeness coefficient $\bar{C}_i$ is calculated using Eq. (14) and the alternatives are ranked in descending order. The $\bar{C}_i$ ranges from 0 to 1. The closer the alternative A_i relatives to FPIS, the larger the value of $\bar{C}_i$.

$$\bar{C}_i = \frac{D_i^{-}}{D_i^{-} + D_i^{*}}\ for\ i = 1,2, \dots, m \tag{14}$$

3.3. MOLP for ELT allocation

A MOLP model is formulated in this study as the particular problem includes a different set of objectives that should be attained at the same time (i.e., maximising the CE and sustainability outcomes). The outputs of FTOPSIS are used as coefficients for the objective functions. The integration of FTOPSIS and MOLP is superior to the sole MOLP, in which more criteria with different units can be simultaneously incorporated without affecting the computational time. Moreover, the qualitative data can be used as input under this hybrid model. This method has been widely used in the supply chain and operations research, such as Ghodsypour and O'Brien (1998), Lin et al. (2011), and Kannan et al. (2013).

To maintain the accuracy and reliability of the model, the following assumptions are made:

(i) Only the ELT is sold to the recycling outlet.
(ii) Quantity discounts are not taken into consideration.
(iii) The demand for the ELT is constant and known with certainty.
(iv) No penalties will be incurred if the demand of a recycling outlet is not satisfied.

The objective functions are shown in Eq. (15) and Eq. (16):

$$Max\ (CE) = \sum_{i=1}^{N} w_{CE,i} * X_i \tag{15}$$
$$Max\ (sust) = \sum_{i=1}^{N} w_{sust,i} * X_i \tag{16}$$

Where
X_i = The allocated amount of the ELT for the i^{th} recycling outlet
$W_{CE,i}$ = The overall CE weight (priority value) of the i^{th} recycling outlet
$W_{sust,i}$ = The overall sustainability weight (priority value) of the i^{th} recycling outlet
N = The number of recycling outlets.

The MOLP model is subjected to:

$$f(X_i) = \begin{cases} X_i \le D_i,\ D_i \le C \\ X_i \le C,\ D_i > C \end{cases} \tag{17}$$

$$\sum_{i=1}^{N} X_i = S \tag{18}$$

$$X_i \geq 0 \tag{19}$$

Where
Di = The demand of i^{th} outlets for the planning period
C = The capacity of the waste collector
S = Total sales of previous year

Eq. (17) shows that the allocated amount of the ELT for the recycling outlet must be equal or less than the demand of that outlet, provided capacity is not exceeded. Moreover, the total allocated amount of the ELT must equal to the sales of waste collector from previous year as shown in Eq. (18). Eq. (19) presents the non-negativity restriction on the decision variables.

Genetic algorithm (GA), simulated annealing (SA), and Goal Programming (GP) are commonly used to solve multi-objective problems. Nevertheless, GA is used in this research as it can significantly shorten the computational time since several Pareto optimal sets can be obtained in a single run (Mitchell, 1998). Moreover, GA is less sensitive to the convexity of the Pareto front (Talbi, 2009), making it more effective than SA or GP. NSGA-II, as a derivative of GA, further outperforms other algorithms in terms of the number of Pareto solutions, spacing metrics, and diversifications (Rabbani et al., 2017). It is able to yield a diverse set of solutions that converge near the true Pareto optimal solution within few iterations by using fast sorting procedures that ensure the survival of elite solutions in the next generation, further shortening the computational time (Deb et al., 2000). Moreover, it has now become the standard algorithm to solve multi-objective problems (Talbi, 2009; Adra and Fleming, 2011; Chow and Yuen, 2012). Hence, NSGA-II is applied to optimise the MOLP model in this study.

NSGA-II involves several steps that require the customisation to solve the multi-objective problems, namely chromosome representation and encoding, initialisation of population, parent selection, as well as cross-over and mutation. This research strictly follows the standard procedures proposed by Deb et al. (2000) and Filho and Vergilio (2016). Real number encoding is used in this research, with each gene encoding the value of the ELT allocated to each outlet. To allow maximum variation of the chromosome, a population size of 100 is used (Mitchell, 1998).

In NSGA-II, the parents with less non-domination rank and greater crowding distance are selected for mating and production of offsprings. The crowding distance calculation for m^{th} objective and i^{th} solution situated in that particular front is shown in Eq. (20) and Eq. (21).

$$CD_{im} = \frac{f_m(x_{i+1}) - f_m(x_{i-1})}{f_m(x_{max}) - f_m(x_{min})}, i = 1,2, \ldots, (l-1) \tag{20}$$

$$CD_i = \sum_{m=1}^{M} CD_{im} \quad (21)$$

The crossover probability and mutation rate are set to be 80% and 10%, respectively, in the mating process, to ensure the high degree of variations in the offspring solution (Mitchell, 1998). All the generated offspring from crossover and mutation are ensured to fall within the specified constraints. The offspring that fails to satisfy the constraints are removed from the new population. A termination criterion of 150 iterations of the generated solutions is applied.

The presented hybrid method utilised in this research (i.e., FAHP-FTOPSIS-NSGA-II) possesses some additional benefit as compared to the use of mono method. The integration of FAHP and FTOPSIS into MOLP is superior to the sole use of MOLP, in which more criteria with different units can be simultaneously incorporated without affecting the computational time. Moreover, the qualitative data can be used as an input under this hybrid model. The MOLP will also determine the assignment of resources to different alternatives, whereby using FAHP and FTOPSIS alone will not achieve.

3.4. The semi-structured interview

To find the most suitable research target, three selection criteria were followed: 1) it must be an experienced (at least ten years of operating) and a major company that deals with collection and sales of ELT; 2) it must have at least three supply chains to manufacture new products (e.g., synthetic turf, rubber tiles or moulded objects); 3) it is not owned by the manufacturer. Consequently, a French company, which is one of the largest ELT collectors in Europe, was selected and invited to the study. The company has been operating for 17 years since 2003 with an average annual gross sales of USD 69 million. An interview protocol, including six open-ended questions, was prepared based on the existing literature and the optimised results of the MOLP model. The questions focus on the drivers of the ELT recycling outlets selection, the impacting factors of choosing the current primary recycling outlet, and the importance of the CE and sustainability criteria in the business. Three interviews with mid- and high-level managers were conducted on 3rd April 2020 to accumulate more fruitful information regarding the ELT recycling outlets selection and illuminate the possible hidden connection between the actual business condition and the result suggested by the model. The audio recorded interviews were then transcribed and analysed thematically by close reading and manual coding.

4. Results and Discussion

4.1. The weights of the CE and sustainability criteria

A total of 18 experts in Europe are recruited as the panel of experts via a non-probable, purposive sampling method. The panel is consisted of nine supply chain managers and nine professors. A questionnaire with 332 items was distributed to each expert via email, which they were instructed to indicate the relative importance of criteria using the Saaty scale. The relative weight of importance for each instrument of CE and sustainability criteria are obtained and tabulated in Tables 4 and 5 following the FAHP calculation procedures in Section 3.1. All CR values are less than 0.1, implying that no mistakes or conflicting ratings are made by DMs, and the judgments are acceptable for the weights (Saaty, 1990).

C_1 Monetary						
C_{11}	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}	C_1 Total
3.07%	3.52%	4.44%	5.33%	3.22%	**7.00%**	26.58%
C_2 Energy & Environment						
C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{26}	C_2 Total
3.16%	2.14%	3.24%	**6.82%**	5.40%	3.64%	24.40%
C_3 Material						
C_{31}	C_{32}	C_{33}	C_{34}	-	-	C_3 Total
3.78%	5.67%	3.76%	3.66%	-	-	16.87%
C_4 Temporal						
C_{41}	C_{42}	-	-	-	-	C_4 Total
5.88%	2.43%	-	-	-	-	8.31%
C_5 Efficiency						
C_{51}	C_{52}	C_{53}	C_{54}	C_{55}	-	C_5 Total
3.90%	4.22%	**7.29%**	5.25%	3.18%	-	23.84%

Table 4: Weights for the CE sub-criteria

S_1 Economic					
S_{11}	S_{12}	S_{13}	-	-	Total
7.79%	5.07%	**10.27%**	-	-	23.13%
S_2 Environmental					
S_{21}	S_{22}	S_{23}	S_{24}	-	Total
9.13%	**15.24%**	7.67%	9.88%	-	41.92%
S_3 Society					
S_{31}	S_{32}	S_{33}	S_{34}	S_{35}	Total
5.14%	7.29%	**10.39%**	8.34%	3.79%	34.95%

Table 5: Weights for the sustainability sub-criteria

According to Table 4, the three most important instruments within CE criteria are C_{53} - Recyclability of the product (7.29%), C_{16} - Profit OR saving per kg recyclable input consumed (7.00%), and C_{24} - Total GHG produced per kg product (6.82%). Monetary criteria are slightly more important than other groups of criteria in increasing the CE outcomes of a recycling outlet. Table 5 reveals the three most important sustainability instruments are S_{22} - Resources consumption (15.24%), S_{33} - Workers health and safety (10.39%), and S_{13} - Net profit (10.27%). Environmental sustainability is the most important group among the three dimensions in improving the sustainability outcomes of a recycling outlet.

4.2. Rankings of the ELT recycling outlets

An ELT collector company based in France is invited to take part in this research and provides data for this study. There are five recycling outlets for the ELT in that company, namely A1 (tyre-to-synthetic turf), A2 (tyre-to-sports surface), A3 (tyre-to-moulded objects), A4 (tyre-to-cement), and A5 (tyre-to-foundries). The performance of each recycling outlets is evaluated against the CE and sustainability criteria using the 7-point Likert Scale ratings. The five outlets are ranked by FTOPSIS following procedures shown in Section 3.2. The result is listed in Table 6. It can be seen that A1 is ranked first under CE criteria, followed by A2, A3, A5, and A4. Moreover, A3 is ranked first under sustainability criteria, followed by A2, A1, A5, and A4.

Outlets	CE			Sustainability		
	CC_i	Normal weight	Rank	CC_i	Normal weight	Rank
A1	0.7988	0.2966	1	0.4836	0.2026	3
A2	0.7040	0.2614	2	0.5761	0.2413	2
A3	0.5326	0.1977	3	0.6724	0.2816	1
A4	0.2644	0.0982	5	0.3276	0.1372	5
A5	0.3936	0.1461	4	0.3276	0.1372	4

Table 6: CC_i and rankings of the ELT recycling outlets

As shown in Figure 3, the five outlets are placed in a four-quadrant matrix according to their normal weights. The "Most favourable" quadrant represents the outlet that is high in both the CE and sustainability outcomes. The "Less favourable" quadrants show that excels in either the CE or sustainability outcomes would trade off another. The "Least favourable" quadrant embodies that the outlet is low in both the CE and sustainability outcomes. A1, A2, and A3 fall into the "Most favourable" quadrant while A4 and A5 fall into the "Least favourable" quadrant. It is also noticed that A1 falls closer to the high CE axis, suggesting that A1 is favourable when the CE outcome is much preferred to that of sustainability. Further, A3 lies closer to the high sustainability axis, suggesting that A3 would be favourable when the sustainability outcome is much desired.

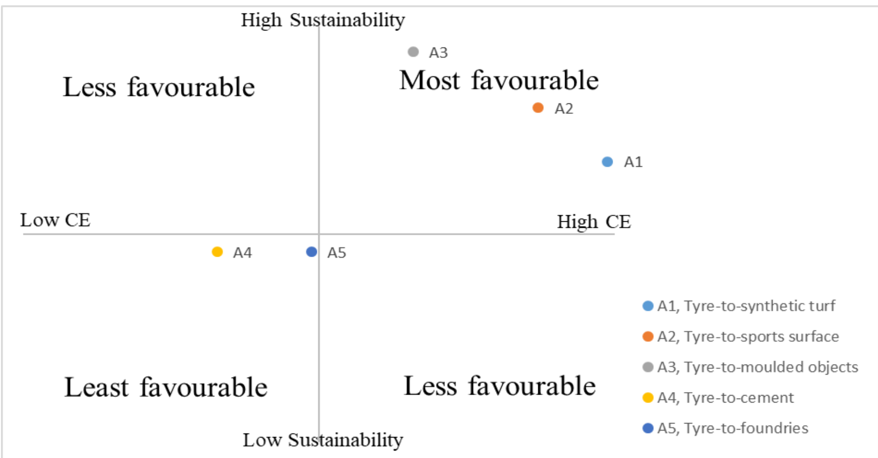

Figure 3: The CE and sustainability outcomes of recycling outlets

4.3. The ELT allocation among recycling outlets

Although Figure 3 could explain the selection strategy of the ELT recycling outlets to some extent, it is unable to shed light on what is the exact amount of the ELT that should be allocated among recycling outlets to maximise the CE and sustainability outcomes. Hence, a MOLP is formulated to find the solution.

Table 7 lists the business data collected from the French company. It is also known that the company's annum capacity regarding the ELT is 369,603 tonnes. Moreover, EU28 demands for each outlet retrieved from Pourriahi (2016) and Bermejo (2019) are summarised in Table 7. These figures are used as constraints to effectively optimise the proposed MOLP model.

Outlets \ ELT amount (percentage)		Company sales		EU28 demands	
A1	Tyre-to-synthetic turf recycling	40,000	(14.4%)	565,000	(31%)
A2	Tyre-to-sports surface recycling	40,000	(14.4%)	452,000	(25%)
A3	Tyre-to-moulded objects recycling	20,000	(7.1%)	452,000	(25%)
A4	Tyre-to-cement recycling	170,000	(61.2%)	326,000	(18%)
A5	Tyre-to-foundries recycling	8,000	(2.9%)	9,000	(1%)
Total		278,000	(100%)	1,804,000.00	(100%)

Table 7: Sales and demands of each outlet

By introducing the figures in Tables 6 and 7 to the model, the objective functions are listed below:

$$Max\ (CE) = \sum_{i=1}^{N} w_{CE,i} * X_i$$
$$= 0.2966\, X_1 + 0.2614\, X_2 + 0.1977\, X_3 + 0.0982\, X_4 + 0.1461\, X_5$$

$$Max\ (sust) = \sum_{i=1}^{N} w_{sust,i} * X_i$$
$$= 0.2026\, X_1 + 0.2413\, X_2 + 0.2816\, X_3 + 0.1372 X_4 + 0.1372\, X_5$$

Subject to:

$$X_1 + X_2 + X_3 + X_4 + X_5 = 278000$$
$$X_1 \leq 369603, X_2 \leq 369603, X_3 \leq 369603,\ X_4 \leq 326000, X_5 \leq 9000$$
$$X_i \geq 0\ , i = 1,2,3,4,5$$

The MOLP is solved using NSGA-II coded in MATLAB. An initial population of 100 yields 573 Pareto solutions. There is no single universal solution for the allocation of the ELT to maximise the CE and sustainability outcomes simultaneously. However, there is a set of equally efficient solutions that can maximise one objective while trading off another, depending on which objective is being emphasised. The CE and sustainability outcome of each set is mapped into the satisfaction level ranged from 0% to 100% using Eq. (22), where Z_{max} is the maximum value and Z_{min} is the minimum value of the objective function for objective k. Therefore, the ratio between the CE and sustainability satisfaction levels is denoted as 0:100. Similarly, 25:75, 50:50, 75:25 and 100:0 are denoted to Sets 2, 3, 4, and 5, respectively. As shown in Table 8, Set 1 provides the lowest CE outcome and the highest sustainability outcome; Set 2 provides the low CE outcome and the high sustainability outcome; Set 3 provides the moderate CE and sustainability outcomes; Set 4 provides the high CE outcome and the low sustainability outcome; Set 5 provides the highest CE outcome and the lowest sustainability outcome.

$$\mu_{Z_k} = \frac{Z(x) - Z_{min}}{Z_{max} - Z_{min}} \times 100\%, \; Z_{min} \leq Z(x) \leq Z_{max} \quad (22)$$

		Base Case	The ELT allocation				
			Set 1	Set 2	Set 3	Set 4	Set 5
			CE:SUS = 0: 100	CE:SUS = 25: 75	CE:SUS = 50: 50	CE:SUS = 75: 25	CE:SUS = 100: 0
Allocation	A_1	40,000	97	63,434	11,304	31,752	**201,927**
	A_2	40,000	14,129	758	**180,103**	**241,980**	72,723
	A_3	20,000	**255,163**	**213,124**	83,567	3,442	114
	A_4	170,000	5	11	13	55	1
	A_5	8,000	8,599	657	3,006	753	3,229
Total		278,000	278,000	278,000	278,000	278,000	278,000
CE		44137	55425	61244	67393	73467	79396
Increment		-	(+ 26%)	(+ 39%)	(+ 53%)	(+ 66%)	(+ 80%)
SUS		47810	76463	73142	69696	65903	58934
Increment		-	(+ 60%)	(+ 53%)	(+ 46%)	(+ 38%)	(+ 23%)

(* CE = CE outcome, SUS = Sustainability outcome)

Table 8: The ELT allocation among recycling outlets

According to Table 8, A4 and A5 receive the least amount of the ELT due to their weak performance in improving the CE and sustainability. In Sets 1 and 2, most of the ELT is allocated to A3, while some portions are allocated to A1 and A2. It is due to the superior accomplishment of A3 in improving the sustainability outcome, and the model should also concurrently maximise the CE outcome. If all resources are allocated to A3, it is undoubtedly that the sustainability outcome will be even higher (i.e., 78257), but the CE outcome will be reduced to only 54,960. In Set 3, most of the ELT is allocated to A2 while some portions are allocated to A1 and A3. It causes the CE outcome to be almost at par with sustainability outcome (i.e., CE: SUS=50:50). This is because A2 is ranked second under both the CE and sustainability criteria and carrying almost the same weight (i.e., 0.2614 and 0.2413). Particularly, this set of allocation does not incline towards either of the objectives, making it suitable for the situation when both the CE and sustainability carry an equal level of importance. Set 4 is highly similar to Set 3, but with more ELT is allocated to A1 and A2 instead of A3. This causes a higher increment to the CE outcome. In Set 5, most of the ELT is allocated to A1, while some portions are allocated to A2 and A3. It is due to the superior accomplishment of A1 in improving the CE outcome, and the model should also concurrently maximise the sustainability outcome. If all resources are allocated to A1, it is undoubtedly that the CE outcome will be even higher (i.e., 82,455), but the sustainability outcome will be reduced to only 56,323. In general, moving from Set 1 to Set 5, the majority of the ELT is diverted from A3 to A2 and finally to A1. This trend of the ELT allocation enables the CE outcome to increase from 55,425 to 79,396. Moreover, all allocation sets improve both the CE and sustainability outcome tremendously compared to the base case. It is noteworthy that the highest attainable increment of the CE outcome is 80% (i.e., Set 5), and the highest attainable increment of the sustainability outcome is 60% (i.e., Set 1).

4.4. The relationship between the CE and sustainability

The ELT allocation profile also reveals the relationship between the CE and sustainability. As shown in Figure 4, the sustainability outcome is plotted against the CE outcome. The scatter plot demonstrates that the sustainability outcome decreases almost linearly as the CE outcome increases. Moreover, achieving any amount of the CE outcome will trade-off the sustainability outcome in an almost equal magnitude.

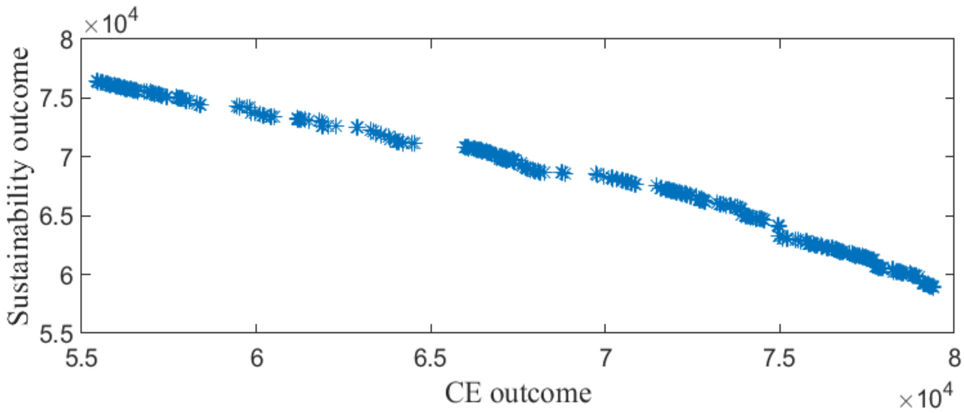

Figure 4: The relationship between the CE and sustainability outcome

Several studies insist that practicing the CE agenda can help in achieving the sustainability (Rashid et al., 2013; European Environment Agency, 2016; Geissdoerfer et al., 2017). Nevertheless, they did not incorporate the comprehensive CE and sustainability criteria and measurements when testing the relationship, which potentially deviates the results from reality and causes biases.

Murray et al. (2015) and Geissdoerfer et al. (2017) argue that the CE and sustainability have different prioritisations. The CE prioritises vertically benefiting the economy and environment, while sustainability focuses on a horizontal development of environmental, economic, and social dimensions. Hence, excelling in the CE agenda does not necessarily promote sustainability. It is in accordance with the literature such as Andersen (2007), Allwood (2014), Genovese et al. (2017), Cullen (2017) and Duin and Best (2018), which suggest a trade-off relationship between the CE and sustainability. This study also proves that the ELT supply chain can disregard the sustainability criteria, such as child labour and workers' health and safety, in pursuit of a higher CE outcome in the fields of operating costs and product lifetime, which ultimately causes the sustainability outcome to reduce.

4.5. Drivers and Barriers towards ELT recycling outlets selection

As listed in Tables 7 and 8, there is a huge difference between the current and the suggested

ELT allocation among recycling outlets in the company. In fact, 61% of the ELT are sold to A4 (tyre-to-cement), but only 14.4% of the ELT are sold to A1 (tyre-to-synthetic turf) or A2 (tyre-to-sports surface), despite the higher CE and sustainability outcomes. A semi-structured interview with the manager is conducted to investigate the reasons and rationality. It is discovered that the drivers for the ELT recycling outlet selection in the company and industry are primarily cost and profit. If the financial burden could be reduced, companies are willing to cooperate with the recycling outlet that has the high CE and sustainability outcomes, as manager A explains:

> "*... Ideally, it will be legislation that is advising and guiding the outlet selection. But now, it is driven mainly by profit and cost since the market is very competitive. We are considered lucky if we get $50/ tonne max by selling the ELT just to cover the cost. Some companies in the industry which have financial supports from the government select the outlet with the best-known technology to recycle the ELT and sell the products. Currently, we are aiming to gain more profit by selling the ELT to the high-value technical product manufacturer who is willing to pay more…*"

The interview also resonates with the results of FAHP on the importance of the CE and sustainability criteria in the ELT recycling outlets selection, as manager B explains:

> "*... There are some partners in the supply chain that are aiming to be more sustainable, increasing the use of recycled materials to 30-40%, from merely 5% today. It is also envisaged to reach 80% use of recycled materials in the future. Meaning that the future will be much affected by sustainability and circularity. Also, the current manufacturing of Carbon Black (CB) extracted from crude oil is extremely unsustainable as it requires 2.5 tonnes of crude oil to produce 1 tonne of CB and release many CO_2 in the process. The substitution of the CB used in manufacturing with the CB recovered from the ELT produces less CO_2, which is much more sustainable and circular, negating the need for primary production of CB. Evidently, CE and sustainability have become more and more important nowadays and will be prominent aspects in the near future…*"

The interview further reveals a crucial barrier to improve the CE and sustainability outcome, which is consumers' perception of recycled products. It highlights the role of media and press in boosting the CE and sustainability outcomes by educating and guiding consumers towards a better understanding of the use of recycled materials in many of the consumer products. Moreover, the difficulty of processing the ELT also directly influences the selection of recycling outlets, as manager C explains:

> "*…Recycling outlets, such as A1 (tyre-to-synthetic turf) and A2 (tyre-to-sports surface), have had their reputation greatly damaged by the media and press who constantly tarnish the image of synthetic turf made by recycled tyre, albeit many reports suggest that it is safe. As a result, the negative consumers' perception towards them has been*

causing the market to shrink and starting to disappear. Consequently, the products that have direct contact with the body, such as synthetic turf, sports surface and moulded objects, have received great hurdles in using the ELT as raw materials. On the other hand, the products that do not have direct contact with the body, such as cement, would become the main outlet for most of the ELT collected in the company. Further, the shredded tyre can enter cement kiln directly without extra processing to remove the iron or fibre within it, as the iron will be combusted to iron oxide and further reinforcing the cement, reducing the cost to process the ELT prior to manufacturing…"

This result aligns with the Govindan et al. (2014), which discovers that the demand for eco-friendly products is very limited. It is because of the quality of recycled products perceived by the customer is lower than that of products made from virgin raw materials (Essoussi and Linton, 2010). This is especially true in using the ELT in consumer products (Sheppard, 2019). The result is also in accordance with World Business Council for Sustainable Development (2018), which discovers that A4 (tyre-to-cement) is extraordinarily successful due to the mature technology, effective supply chains, and the low processing cost. Table 9 summarises the drivers and barriers towards the ELT recycling outlets selection.

	Impacting Factor
Selection Drivers	1) Current: cost and profit 2) In the future: sustainability and circularity
Selection Barriers	1) Consumers' perception of recycled products 2) The technical difficulty of processing the ELT

Table 9: Drivers and barriers for the ELT recycling outlets selection

5. Concluding Remarks and Implications

The existing literature predominately uses environmental sustainability criteria to investigate the ELT recycling outlets selection while repeatedly neglects the CE criteria. It causes the contradicting result of allocating ELT to the suitable outlets and a vague relationship between the CE and sustainability. This study evaluates the ELT recycling outlets and allocates the optimal amount of the ELT to outlets based on the thoroughly selected CE and sustainability criteria, aiming to maximise the CE and sustainability outcomes. The most important instruments that improve CE and sustainability outcome, as well as the relationship between CE and sustainability are examined. By analysing the data collected from a French ELT collector via a hybrid model, this study identifies A1 (tyre-to-synthetic turf) as the best outlet to improve the CE outcomes and A3 (tyre-to-moulded objects) as best outlet in promoting the sustainability outcomes. There is a substantial difference between the suggested ELT allocation and the actual ELT allocation in the company due to the crucial impacts of cost and profit considerations, consumers' perception of the recycled products, and the technical difficulty in processing the ELT. It is also discovered that the most important instruments that can promotes CE is "recyclability of the product" while the most important instruments that can promotes sustainability is "resources consumption". Further, this research identifies a trade-off relationship between the CE and sustainability.

This study sheds light on theoretical and managerial implications. The comprehensive list of criteria and items to measure the CE and sustainability outcome can be used as the theoretical foundation for the construction of a thorough CE and sustainability evaluation framework. The method proposed in this research to rank and allocate resources among the ELT recycling outlets will supplement the existing literature by incorporating more criteria across different dimensions and including measurements with different units. This study supports the notion that the CE has distinguished focus compared to sustainability. The CE treats economic criteria as the top priorities, while environmental and social criteria act as the core of sustainability. This study discovers a trade-off relationship between the CE and sustainability in the context of the ELT by thoroughly incorporating all relevant criteria. It also identifies drivers as well as barriers of selecting a recycling outlet for the ELT. Hence, it could significantly extend the existing ELT literature in the fields of the CE and sustainability.

The identification of most important criteria and instruments in the CE and sustainability within this research offers practitioners a starting point to develop critical CE and sustainability practices in their organisations, which can ultimately accelerate sustainable development. Managers could also pragmatically utilise the proposed systematic approach to effectively identify the CE and sustainability impact and evaluate the ELT recycling outlets in an integrative and strategic fashion. Moreover, the generated ELT recycling outlets selection matrix in Figure 5 provides practical guidance for companies and their supply chains under different CE and sustainability preference levels. For example, A3 (tyre-to-moulded objects) lies in the I quadrant, which is the most suitable recycling outlet when the CE preference is low and the sustainability preference is high. If the company and its supply chain intend to have a balanced focus on the CE and sustainability, the majority of the ELT should be allocated and shifted to A2 (tyre-to-sports surface), which lies on the line of “Sustainability = CE”. Furthermore, if the company and its supply chain prefer the CE than sustainability, the majority of the ELT should be allocated and shifted to A1 (tyre-to-synthetic turf), which lies on the II quadrant. Furthermore, the result of the proposed MOLP model catalyses the transition towards the CE while ensuring sustainability. In addition, managers should recognise the identified barriers towards ELT recycling outlet selection in this study, subsequently paying more attention on eradicating the hindrance that obstructs an effective ELT recycling. Practitioners could target the criteria used in the ELT recycling outlet selection process as benchmarks to guide their organisations or supply chains in improving CE and sustainability outcomes. A better retention and utilisation of ELT could safeguard and preserve the limited resources in the world for the future generation, which eventually contributes to the well-being of people and societies.

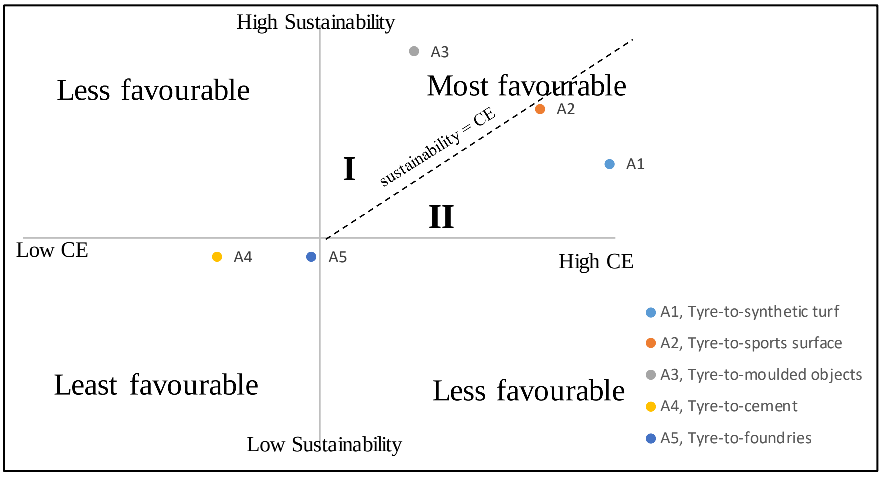

Figure 5: The ELT recycling outlets selection matrix

This study contains some limitations. The proposed MOLP model assumes that there is no quantity discount and the demand of the ELT is stable without considering the competition in the market. More variables should be considered in the model for future studies. Moreover, although NSGA-II is superior in the fields of Pareto solutions, spacing metrics, and diversification, other algorithms could be employed in future studies to compare the optimised ELT allocation. For example, a hybrid of simulated annealing or Goal Programming method with game theory could be used to optimise the ELT allocation, by considering competition in the market.

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