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Maximising the Circularity and Sustainability: An End-of-Life Tyre Recycling Outlets Selection Model

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by

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Abstract

An end-of-life product may re-enter a supply chain via different end-of-life strategies, with priority given to Reduce, followed by Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Energy Recovery. Collectively, they are known as R-hierarchies or imperatives, which utilise different methods to treat an end-of-life product, transforming it into a useful product before it is reintroduced back to forward supply chain. Today, the introduction of open loop supply chain in a supply network has increased the number of alternatives to treat and consume the end-of-life product within each end-of-life strategy, making the selection of suitable alternative more challenging. For example, within the recycling strategy of an end-of-life tyre (ELT), it can either be recycled into a new tyre again or into the making of artificial turf, moulded product, sports surface, cement, pyrolysis char, asphalt, foundries reducing agent and civil engineering aggregates. The selection of alternatives is even more convoluted and complex when different criteria, comprising of various dimensions and items of different unit of measurements are used for alternatives selection purposes.

Tyre is selected as the subject of this study because of the high volume of tyre reaching end-of-life tyre annually, coupled with the elevated demand for the rubber within it. It is also one of the end-of-life products with the highest number of recycling alternatives, making the selection of alternatives bearing high research value.

Nevertheless, a gap is observed pertaining to the alternatives ranking and selection in tyre recycling industry, where conflicting ranking and suggestions are discovered in the literature. This gap exists because of different measurements are used in the ranking of alternatives, which render the accuracy of the results and reliability of the evaluation. Besides, the criteria used are also discovered to be contradicting, representing another gap in the literature that should be investigated.

Hence, this study focuses on examining the selection of recycling alternatives of end-of-life tyre, particularly under the effect of circularity and sustainability. Circularity is an economic system aimed at eliminating waste and the continual use of resources; while sustainability is the ability for resources to be maintained at a certain rate or level, such that the future generation can meet their own needs for resources. Circularity and sustainability are both significant criteria that received increasing concern in the literature, with immense importance within society, especially in the end-of-life product research. This study aims to propose a comprehensive list of evaluation criteria under circularity and sustainability to rank recycling alternatives, and subsequently develop an end-of-life tyre alternatives selection matrix. To achieve the aim, a hybrid method, which integrates fuzzy Analytical Hierarchy Process, fuzzy Technique of Order Preference Similarity to the Ideal Solution, the multi-objective linear programming, and semi-structured interviews, are proposed in this study.

A Delphi study, which consists of 18 subject experts, was conducted to evaluate the relative importance of each dimension and item within circularity and sustainability criteria, via

pairwise comparison in a self-completed online questionnaire. The responses from all respondents are aggregated and analysed using fuzzy Analytical Hierarchy Process to reveal the relative importance. It is discovered that within circularity criteria, monetary dimension represents the most important dimension while recyclability of the product being the most important item. Within the sustainability criteria, environmental sustainability and resources consumption are the most important dimension and item respectively.

To further analyse the finding from Delphi study, an end-of-life tyre collector company based in France was invited to take part in this research and provided data for this study. The company supplies the end-of-life tyre collected to five recycling alternatives, which utilise the recycled rubber to make synthetic turf, sports surface, moulded objects, cement and foundries. The managers from the company were invited to provide rating for the five recycling alternatives via a survey. The responses from the managers were aggregated and analysed using fuzzy Technique of Order Preference Similarity to the Ideal Solution (TOPSIS), in obtaining the score and ranking of each recycling alternative. By analysing the empirical data collected, this study reveals that cement manufacturing, which is the primary recycling alternative, ranked the lowest among the five recycling alternatives in terms of the circularity and sustainability. Nevertheless, synthetic turf manufacturing and moulded objects manufacturing ranked the highest in the circularity and sustainability, respectively.

In this study, a multi-objective linear programming model is developed to determine the best allocation of tyre in the five recycling alternatives, by considering the score of the alternatives as well as all the resources constraint of the company. The model is solved using a non-sorting genetic algorithm-II to reveal the optimum resources allocation among the five alternatives that will provide highest circularity and sustainability. A qualitative interview is then conducted to further support and explain the barriers towards integrating the model output into the business. It is proved that the key drivers for recycling alternative selection are cost and profit, subjected to ease of end-of-life tyre processing as well as end consumers' perceptions towards the recycled products. Furthermore, the model output also reveals a competitive relationship between the circularity and sustainability, as excelling in the circularity would trade-off sustainability.

This research contributes to knowledge by uncovering the comprehensive list of criteria and items to measure circularity and sustainability of the ELT recycling supply chain, which is crucial in directing the construction of a more effective framework or strategy in future research. This research also introduces a hybrid method that is able to, more effectively, determine the allocation of resources among contending alternatives because of its ability to incorporate various dimensions and items that consist of different units and nature (i.e., quantitative or qualitative), which can be applied directly in relevant research problems. Practitioners can make use of the contributions as aforementioned to device a scorecard to achieve more circular and sustainable business and supply chain. A framework is also being proposed to aid managers select the most desirable alternatives by visualising it in a 2 x 2 circularity-sustainability matrix. Further, managers can follow the proposed hybrid methods to more effectively allocate the resources among the recycling alternatives.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AHP - Analytic Hierarchy Process
ANP - Analytic Network Process
B2C - Business to Customer
C2C - Customer to Customer
CE - Circular Economy
CI - Consistency Index
CLSC - Closed-Loop Supply Chain
CP - Compromise Programming
CR - Consistency Ratio
CSC - Circular Supply Chain
DM - Decision Maker
DP - Dynamic Programming
EI - Equally Important
ELECTREE - Elimination and Choice Expressing Reality
ELT - End-Of-Life Tyre
EOL - End-Of-Life
EPR - Extended Producer Responsibility
EU - European Union
Ex. I - Extremely Important
FAHP - Fuzzy Analytic Hierarchy Process
FI - Fairly Important
FNIS - Fuzzy Negative Ideal Solution
FPIS - Fuzzy Positive Ideal Solution
G - Good
GA - Genetic Algorithm
GHG - Greenhouse Gases
GP - Goal Programming
LP - Linear Programming
M - Medium
MADM - Multi Attribute Decision Making
MAUT - Multi-Attribute Utility Theory
MAVT - Multi-Attribute Value Theory
MCDM - Multi Criteria Decision Making
MG - Medium Good
MILP - Mixed Integer Linear Programming
MMO - Max-Min Operator
MODM - Multi Objective Decision Making
MOLP - Multi Objective Linear Programming
MP - Medium Poor
NLP - Non-Linear Programming
OA - Outer Algorithm
OSHA - Occupational Safety and Health Administration
OLSC - Open Loop Supply Chain
P -Poor
PROMETHEE - Preference Ranking Organization Method for Enrichment Evaluation
PSS - Product-Service System
RI - Random Index
SA - Simulating Annealing
SAW - Simple Additive Weighting
SCM - Supply Chain Management
SD - Standard Deviation
SDGs - Sustainability Development Goals
SI - Strongly Important
TBL - Triple Bottom Line
TS - Tabu Search
TOPSIS - Technique for Order of Preference by Similarity to Ideal Solution
UV - Ultraviolet
VIKOR - VlseKriterijumska Optimizacija I Kompromisno Resenje
VG - Very Good
VP - Very Poor
WI - Weakly Important

1 Introduction

1.1 Introduction

This chapter introduces the study and is delivered as follows. Section 1.2 discusses the background and overview of the problem in relation to the study. Section 1.3 presents the aim and objectives of the study, and followed by unit of analysis of this study in Section 1.4. The organisation of the thesis is discussed in Section 1.5.

1.2 Background and Overview of Problem

Today, the human population in the world is increasing exponentially at a fast pace, which could exceed 10 billion after three decades, where three planets' worth of natural resources are required to sustain the high demand of resources (Jowit, 2008; Tse et al., 2015, United Nations, 2019). The blooming of human population is accompanied by high harvesting rate of raw materials (European commission, 2017), waste generation and accumulation rate (Ellen MacArthur Foundation, 2013; Tse et al., 2015) as well as more severe environmental pollution (Steffen et al., 2015). Combining with the single-use lifestyle that enthused by “take-make-dispose” (Braungart and Mcdonough, 2002; Webster, 2015), untreated waste is currently polluting every corner of the Earth (McKie, 2016).

This is more prominent in the context of tyre products in rubber industry (European commission, 2017). To date, an accumulating amount of tyre, which is roughly 1.53 billion pieces per annum, is reaching the End-of-Life (EOL), known as EOL tyre (ELT) (Hoyer et al., 2020). ELT may re-enter a supply chain via different EOL strategies, following a hierarchy of importance of Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Energy recovery, with an aim of treating the ELT and retaining its useful resources, instead of disposing it into landfill. These R-hierarchies or imperatives, utilise different methods in treating the EOL product before it is transformed into a useful product that re-enters the supply chain (Cramer, 2017; Potting et al., 2017). Currently, Recycling is the most commonly employed strategy in EU-28 countries (now EU-27) in handling ELT, preceding other strategies such as energy recovery, remanufacturing and reuse, with a usage abundancy of roughly 55%, 33%, 7% and 6% respectively (WBCSD, 2018; Bermejo, 2019). Recycling is used more extensively due to the stringent quality requirement of ELT to allow the use of other EOL strategies situated higher in priority.

Within recycling, many recycling alternatives utilise ELT in the making of new products because of the introduction of open loop supply chain (De Angelis et al, 2018; Mishra et al., 2018). Instead of recirculating the ELT in the original supply chain, they are introduced to another supply chain as input, giving an alternative use for the ELT (Farooque, 2019). For example, an ELT can either be recycled into a new tyre again, or into the making of artificial turf, moulded product, sports surface, cement, pyrolysis char, asphalt, foundries reducing agent and civil engineering aggregates (Hallberg and Kärrman, 2007).

However, the selection of alternatives is highly difficult due to the wide variety of alternatives available, which often resulting in a choice dilemma. Different criteria comprising of various dimensions and items of different unit of measurements, are used by different researchers when comparing the alternatives, which provide different results and suggestions. For example, Hallberg and Kärrman (2007) recommended the ELT to be recycled and manufactured into cement and civil engineering application rather than asphalt, while Feraldi et al. (2013) and Clauzade et al. (2010) recommended otherwise.

Besides the discrepancy and unequivocal decision in regard to alternatives selection, the lack of methods to determine optimum selling quantities of ELT as well as the assignment of sales to different alternatives are being observed. It has been evidenced in other fields, for instance, supplier selection where the resources should be allocated among all available alternatives by considering the demand and resources available as a constraint in order to maximise the desired objective (Khoshfetrat et al., 2020). Currently, no decision-making model has been proposed to effectively evaluate the recycling alternatives and subsequently determine the allocation of ELT among them to support circular and sustainable development. It has been frequently proven that the inappropriate assignment of resources into undesirable alternatives would lead to excessive resource consumption (De Almeida and Borsato, 2019) and potential value wastage (Peeters et al., 2015; Priarone et al., 2015).

Circularity and sustainability are used extensively in comparing the ELT recycling alternatives. Circularity is an economic system aimed at eliminating waste and the continual use of resources (Boulding, 1966; Webster, 2015; Geissdoerfer et al., 2017); while sustainability is the ability for resources to be maintained at a certain rate or level (Portney, 2015; Thiele, 2016; Cambridge Dictionary, 2020). There are two reasons behind their popularity. Firstly, they are the most suitable criteria to be used to measure the performance related to waste or resources consumption (Geissdoerfer et al., 2017; Zore et al., 2018; Pieroni et al., 2019). Secondly, there are numerous economic, environmental and societal challenges, which include increases in human population and consumption, poverty, resource utility and scarcity as well as climate change and environmental degradation. Together with linear economy lifestyle, the global patterns of production, consumption and trade are not circular and sustainable.

To construct an effective ELT allocation model under the effect of both circularity and sustainability, a comprehensive inclusion of both of the criteria is highly required. However, the literature is lack of a framework that is able to guide the comprehensive inclusion of circularity and sustainability criteria, which would ultimately contribute to the accuracy of the results and reliability of the evaluation by reflecting the actual circularity and sustainability of alternatives. The use of numerous criteria that span across different themes and dimensions are observed in the current literature, including greenhouse gases produced and energy consumption (Hallberg and Kärrman, 2007), recyclability of products and operating cost (Oostenrijk and Duuren, 2011), as well as job creation (Corbetta, 2013).

The inclusion of both circularity and sustainability criteria in a model was argued to be redundant by some scholars, referring that excelling in circularity would simultaneously achieve sustainability and circularity criteria would encompass sustainability criteria (Hansen et al., 2014; Lawton et al., 2014; Horbach et al., 2015). Nevertheless, this idea is contested by findings which discovered that circularity could not bring about sustainability (Geissdoerfer et al., 2017). For instance, Genovese et al. (2017), Allwood (2014) and Duin and Best (2018) argued that achieving circularity could not improve economic, environmental and societal sustainability, respectively. Hence, the relationship between the circularity and sustainability remains unclear and it represents an ongoing debate in the professional discourse, signifying another gap within the existing literature.

This study thus aimed at closing the gaps as exhibited above by addressing the lack of comprehensiveness in the criteria used to compare recycling alternatives within the literature, subsequently devising a generic resources allocation model that could more effectively achieve the circularity and sustainability agendas in widespread applications.

Still, this research is proposing a resources allocation model and providing a solution that could be differed from what is being practiced currently in the business-as-usual scenario. Often, the changes to the business-as-usual are accompanied with resistances (Rizos et al., 2016; Scipioni et al., 2021). This is due to the innate human nature that is reluctant to change the current state one is in (Rizos et al., 2016). To ensure the output of this research can successfully overcome this hurdle, it is important to understand what would obstruct the changes from the current business-as-usual to the more circular and sustainable practice, and what is the associated enablers, particularly in the ELT context.

1.3 Aim and Objectives of the Study

To fulfil the aforementioned gaps, this research aims to:

a) Identify key circularity and sustainability dimensions and items that are suitable to compare the recycling alternatives and determine their relative importance of each dimension and item in decision-making.
b) Develop a model that can be used to rank the recycling alternatives of ELT and allocate ELT among the alternatives, such that the value of the ELT in the supply network can be maximised from the perspectives of circularity and sustainability.
c) Reveal the relationship between circularity and sustainability.
d) Identify barriers towards the uptake of circular and sustainability practices and their enablers.

In order to achieve the research aim, several research questions are populated as below.

Research Question 1:
What are the key dimensions and items within circularity and sustainability criteria for the ELT recycling alternatives selection?

It is discovered that there is a discrepancy pertaining to the ranking of recycling alternatives in the ELT recycling industry, for example, Feraldi et al. (2013) and Clauzade et al. (2010) recommended ELT to be recycled and manufactured into asphalt rather than cement or civil engineering application while Hallberg and Kärrman (2007) recommended otherwise.

The discrepancy in the studies is mainly due to the fragmented conceptualisation of the circularity and sustainability criteria, resulting in different as well as limited dimensions and items to be used for the alternatives ranking process in the studies (Kløverpris et al., 2009; Fiksel et al., 2011; Feraldi et al., 2013). For example, only 4 circularity items originated from 3 circular dimensions and 5 sustainability items originated from 3 sustainable dimensions are used in the alternatives ranking process (See Section 3.2).

To date, no prior study has simultaneously considered all dimensions and items for both the circularity and sustainability criteria in a holistic manner for the ranking of alternatives process (Feraldi et al., 2013).

The first research question is thus intended to determine the key dimensions and items within circularity and sustainability criteria in the context of ELT recycling industry. This is important because the current criteria used to measure performance of recycling alternatives, especially circularity, is highly fragmented. This would impede the accurate representation of circularity of the alternatives, resulting in imprecise decision-making. This situation is further exacerbated due to the lack of research studies that analyse and collate the fragmented circularity, subsequently providing guidance on how to measure circularity accurately.

Research Question 2:
How important is each dimension and item within circularity and sustainability criteria in decision-making?

Upon performing a decision-making, some dimensions (or items) are perceived to be more important than other dimensions (or items) in the perception of decision-makers (Saaty, 2008). It is argued that the dimensions and measurement items will not necessarily carry the equal weight in the decision-making process (Peterson, 2017). Yet, it can be observed that an equal importance is always given to each dimension and item in the alternatives ranking process in the ELT recycling literature (Kløverpris et al., 2009; Fiksel et al., 2011; Feraldi et al., 2013).

Not only this has over-simplified the problem, but it also distorts the result, leading to infeasible suggestion and inaccurate decision-making. It is strongly suggested that the relative importance of dimensions and measurement items to be pre-determined, so that an accurate result can be obtained to facilitate a more rigid decision-making (Saaty, 2008; Peterson, 2017).

As a result, the second research is proposed to determine the relative importance (i.e., weight) of each dimension and item within circularity and sustainability criteria in decision-making. This is important because not only that the correct dimensions and items are required for effective measurement of circularity and sustainability, but also the correct relative importance of each dimension and item.

Research Question 3:
How to allocate the ELT among recycling alternatives in supply networks to maximise the circularity and sustainability?

Currently, the ranking of recycling alternatives in the ELT recycling industry posseses some flaws. Besides using limited dimensions and items from circularity and sustainability criteria, it is assumed that all the dimensions and items will carry an equal weight in decision-making. Additionally, current model will only finish at recommending a few desirable recycling alternatives for the ELT without considering the actual demand for resources and their constraints (Kløverpris et al., 2009; Fiksel et al., 2011; Feraldi et al., 2013). This is insufficient as well as impractical considering that the demand and resources constraints are always present in reality (Kornai, 1979; Fawcett and Pearson, 1991). Often, owe to the demand and resources constraints, resources are required to be allocated among the alternatives to ensure that the constraints are satisfied, while achieving anticipated goals.

Thus, the third research question is designed to investigate how best to allocate the ELT among the several contending recycling alternatives to maximise circularity and sustainability, by carefully considering the comprehensive list of dimensions and items, as well as their relative weight, obtained by answering research questions 1 and 2, along with the actual demand for resources and their constraints.

This is vital as it is almost impossible to only allocate resources to one desirable alternative, considering various constraints and demand in real life. Furthermore, it is also very complicated when multiple objectives (i.e., circularity and sustainability) are involved in this situation.

Research Question 4:
What are the barriers and enablers that influence the uptake of circular and sustainable practices in ELT recycling industry?

Currently, there are some studies focusing on investigating barriers and enablers that influence the uptake of circular and sustainable practices in different contexts, such as SMEs (Rizos et al., 2016; Scipioni et al., 2021), coffee value chain (Van Keulen and Kirchherr, 2021), automotive industry (Urbinati et al., 2021) and fashion (Dissanayake and Weerasinghe, 2021). Nevertheless, there is a lack of sector-specific understanding of barriers and enablers that influence the uptake of practices in the, increasingly important, ELT recycling industry.

Consequently, the fourth research question will lead to revealing the barriers and enablers in the ELT recycling industry, which can be used to explain the discrepancies between the modelling results and actual business. This is critical as it does not only outline the possible hindrance towards accepting circularity practices, but also disclosing the drivers that will motivate circularity and sustainable practices in the ELT recycling industry.

Research Question 5:
What is the impact on sustainability while achieving the CE agenda in the ELT recycling industry?

Presently, there are conflicting findings in the literature in regard to the relationship between circularity and sustainability. It is discovered that circularity does not necessarily bring about sustainability (Geissdoerfer et al., 2017). As previously mentioned, Genovese et al. (2017), Allwood (2014) and Duin and Best (2018) argued that achieving circularity does not improve economic, environmental and societal sustainability, respectively. Until today, the ambiguous relationship between the circularity and sustainability remains as an ongoing debate in the professional discourse.

The fifth research question is thus designed to study the impact of circularity on sustainability and their relationship. It is imperative to provide a proof of the relationship using real business data to reveal the actual relationship between circularity and sustainability, by means of utilising a more comprehensive list of dimensions and items in the circularity and sustainability criteria. This finding will shed lights on whether circularity measurement can be used as a stand-alone measurement in measuring the performance of a supply chain in the aim of attaining sustainability, since it is often assumed that circularity encompass sustainability.

The research gaps corresponding to the development of each research question are summarised in Table 1.1.

Table 1.1: Research gaps corresponding to each research question (Source: Author).

Research gap	Research question
A) Conflicting ranking and suggestions are discovered in the literature due to limited dimensions and items of sustainability and circularity criteria are used for ELT recycling alternatives ranking and selection. No prior studies have simultaneously considered all relevant dimensions and items in a holistic manner.	1) What are the key dimensions and items within circularity and sustainability criteria for the ELT recycling alternatives selection?
B) Equal importance is given to each dimension and item in the alternatives ranking process in the literature	2) How important is each dimension and item within circularity and sustainability criteria in decision-making?
C) There is currently no framework/ guideline/model that is able to assist in ranking recycling alternatives and	3) How to allocate the ELT among recycling alternatives in supply networks

optimise the allocation of resources among alternatives	to maximise the circularity and sustainability?
D) There is a lack of sector-specific understanding of barriers and enablers that influence the uptake of circular and sustainable practices, particularly in the ELT recycling industry.	4) What are the barriers and enablers that influence the uptake of circular and sustainable practices in ELT recycling industry?
E) The impact on fulfilling CE agenda have on sustainability is unequivocal	5) What is the impact on sustainability while achieving the CE agenda in the ELT recycling industry?

1.4 Introduction to the Unit of Analysis

The unit of analysis for this research is tyre industry in the EU. This research will be conducted based on a supply chain perspective, involving the most important 4 entities in a typical resource recovery from waste supply chain, namely the collector, recycler, manufacturer and users for data collection purposes (Jain et al., 2018) (See Section 3.3 for further detail). The unit of analysis includes 5 recycling alternatives, which are comprised of different supply chain that make use of materials from recycled ELT into manufacturing of different products, namely artificial turf, sports surface, moulded products, cement, and foundries as shown in Figure 1.1. They are selected based on their market shares in EU and their emerging application (Bermejo, 2019; Clauzade et al., 2010; Torretta et al., 2015). Together, the five alternatives being studied represent 93% of the market that recycled ELT to manufacture new products (See Section 3.1 for further detail). This study will be focusing on measuring circularity and sustainability of the selected supply network using comprehensive circularity and sustainability criteria identified from this research.

Nevertheless, because it is impossible to collect the necessary data from the whole supply chain members due to difficulty of access (Arbulu et al., 2013; Elrod et al., 2013), a critical company that has the knowledge of its supply chain partners was invited to provide responses on behalf of the supply chain members, thus representing the entire unit of analysis. In this case, a collector will be able to fit this role, as it will has the knowledge regarding various downstream partners' performance.

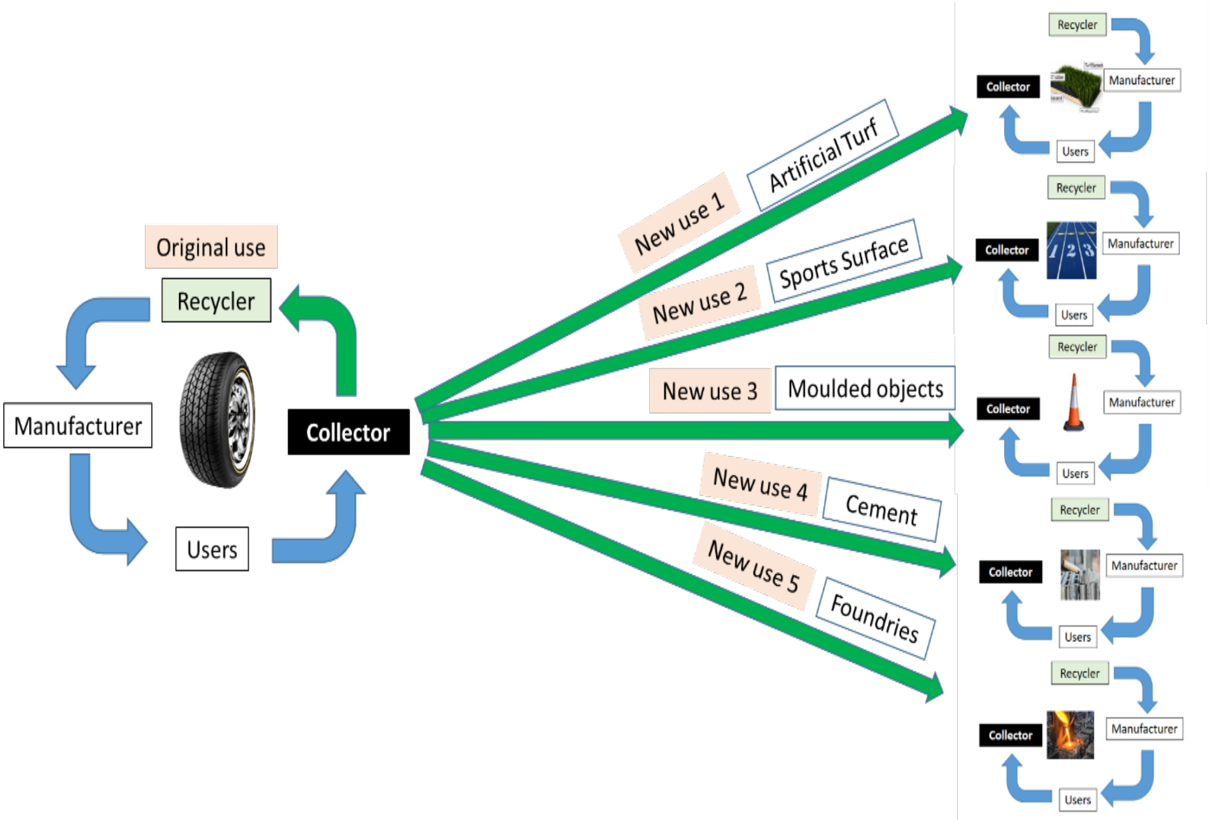

Figure 1.1: Unit of analysis (Source: Author).

1.5 Organisation of the Thesis

The structure of the thesis is organised as follows.

Chapter 1: **Introduction**, gives the introduction to the study, which includes the background and overview of the problems, as well as the aim and objectives of the study. The introduction of the unit analysis and the organisation of the thesis are also presented.

Chapter 2: **Literature Review**, provides a comprehensive literature review on circular economy, circular supply chain, circularity and sustainability, where the concept and its definition are discussed. Much research work has been carried out to measure circularity and sustainability, and the work will be critically analysed in this chapter.

Chapter 3: **End of Life Tyre's Circular Supply Chain**, gives a contextual and extensive literature review on ELT recycling alternatives available. This chapter also synthesises the literature to examine the dimensions and items used within circularity and sustainability criteria, specifically in comparing ELT recycling alternatives.

Chapter 4: **Research Method and Methodology**, provides the methodology necessary to carry out the research. This chapter also provides the ontological and epistemological assumption when approaching the research problems which are divided into several phases.

Chapter 5: **Results and Discussion**, discusses the results obtained from each phase of the research. This chapter examines the relative importance of each dimension and item within circularity and sustainability criteria, as well as identifies the most important item in reflecting the circularity and sustainability in the context of ELT recycling. The effect of allocation of ELT among recycling alternatives on the circularity and sustainability is also being examined. The discrepancy between the model and company practices is also discussed, revealing the drivers and barriers towards the best practice. Finally, the relationship between circularity and sustainability is also explored in this chapter.

Chapter 6: **Conclusions**, concludes the thesis and summarises the work conducted and the results achieved. A summary of how the objectives of this research were addressed, and followed by an account on the expected research contribution. This final chapter summed up by giving valuable concluding remarks and recommendations based on the implications of the findings, as well as the future work to be carried out to explore alternative scope of studies beyond this research.

2 Literature Review

This chapter reviews the literature and is delivered as follows. Section 2.1 introduces the concept of circular economy. Section 2.2 discusses the effect of circular economy on evolution of supply chain. Section 2.3 reviews the circularity indicators currently available in the literature. The concept of sustainability is discussed in Section 2.4. The impact of excelling in circularity on sustainability is reviewed in Section 2.5. Section 2.6 reviews the sustainability indicators in the literature. Finally, the theoretical underpinning of the research is being presented in Section 2.7.

It is important to investigate the extent of circular economy in shaping today's supply chain, which could further justify the use of circular economy as one of the criteria to rank the competing recycling alternatives. The concept of sustainability and the impact of excelling in circularity, also needed to ble explored. This is to demonstrate the need of sustainability criteria along with circularity criteria in ranking of the competing recycling alternatives. Since the use of circularity and sustainability criteria to rank the competing recycling alternatives in the context of ELT is limited, it is crucial to review the currently available circularity and sustainability indicators, and subsequently to define the ways to measure and rank the competing recycling alternatives.

2.1 Circular Economy

2.1.1 Linear Economy

Linear economy, also known as linear production model, is a consumption model that has been dominating our world for centuries. It represents a single-use lifestyle which is enthused by "take-make-dispose" approach toward the consumption of resource (Braungart and Mcdonough, 2009; Webster, 2017). Nevertheless, when a product is disposed as it reaches its End-of-Life (EOL), the energy, effort and materials that are put into making of the product are lost simultaneously, causing the nutrients within the products to be wasted in the process. Since no materials are recovered from the disposed products in the linear economy context, new materials must be continually extracted to manufacture a new product to satisfy the customers' demand (Braungart and Mcdonough, 2009). The industrial infrastructure in linear economy also focuses on manufacturing, delivering the products quickly and cheaply without considering much else. Energy derived using fossil fuel is chosen over renewable energy or clean energy to further reduce the operating cost, severely polluting the environment in exchange of cost efficiency (Webster, 2017).

Despite of the shortcoming, this model is used predominately in the past decades and remains feasible as long as our planet's raw materials supplies are sufficient to cope with the demand and the waste produced can be assimilated adequately by the nature (Boulding, 1966; George et al., 2015). Lately however, it is indicated that the global demand–supply curve and waste accumulation rate are demonstrating a trend of caution. It is estimated that humans are using 30% more resources than Earth can replenish every year, and global demand for raw materials will grow to around 82 billion tons in 2020 as compared to 65 billion tons in 2010, suggesting that our planet's resources could barely satisfy the rising demands (Ellen MacArthur Foundation, 2013; Jowit, 2008). The demand for supplies soars due to the increases in the world population, which is a result of advancement in medicine, welfare and peace-making activities. It is projected that the world population will exceed 8 billion by 2030 and 10 billion by 2050, which as a result, two and three planets' worth of natural resources by 2030 and 2050 respectively will be required to sustain the high demand of resources (Jowit, 2008; Tse et al., 2015, United Nations, 2019). Similar trend is also observed for waste generation and accumulation rate due to increasing human population in the world (Ellen MacArthur Foundation, 2013; Tse et al., 2015). High product consumption and the corresponding waste that are created is currently polluting every corner of the Earth, with an annual total weight closes to the weight of the entire human population of the planet, causing environmental damage and result in unpaid social costs (McKie, 2016).

Besides the aforementioned reasons that forbid linear economy, a study performed by Steffen et al. (2015) also shows that severe environmental pollution was observed in the past decades, further inhibiting the practice of linear economy. The study concludes that four among the nine worldwide processes that underpin life on Earth have exceeded "safe" levels, putting the state of environmental wellbeing at risk. The pollution is a result of the use of fossil fuel to generate power for the manufacturing process in linear economy, which has been increasing by a factor of 5 since the population bloom from 1950 to 2019 (Steffen et al., 2015).

2.1.2 Circular Economy as a Solution

The impracticality of linear economy hatches a new concept known as Circular Economy (CE). In short, CE can be understood as an industrial system that shifts towards the use of renewable energy and considers nothing is produced to be waste, where the waste can be re-utilised after being recycled or used as raw material for other production (Ellen MacArthur Foundation, 2015; Webster, 2017). CE promotes the deed to take back the disposed waste into the production by reuse, remanufacture or recycling of the waste, such that the waste will be circulating in the consumption cycle as long as possible. Ultimately, the main problems of linear economy as aforementioned (i.e., resources limitation, excessive waste generation and environmental pollution) can be resolved (Boulding, 1966; Webster, 2015).

There are many other methods and philosophy that are proposed to tackle the aforementioned problems, such as green, sustainability and lean. Nevertheless, these methods are deemed as reactive method compared to proactive method like CE, as the former initiatives are merely slowing down the rate of resource consumption and waste generation, delaying the inevitable resources depletion (Ellen MacArthur Foundation, 2015). CE, however, reutilises the waste created in the system completely, either by reusing or recycling as raw material for other production, negating the need to harvest for raw materials, eventually curbing the depletion of natural resources and eliminating waste generation (Webster, 2017).

Even though CE is viewed as a promising solution to linear economy, it still remains as a concept that is difficult to grasp, mainly due to CE being an umbrella concept that envelops too many sub-concepts within it, as well as having too many definitions without having one definition that is generally accepted by all different users of CE. The sub-concepts that are enveloped within CE umbrella concept are resource recovery (Li et al., 2013; Gregson et al., 2015), resource efficiency (Hu et al., 2011), industrial symbiosis, urban metabolism, eco-design, zero waste, materials criticality, design for recycling, remanufacturing, upcycling/down cycling and cascade models, waste prevention and minimisation (Velis, 2015). It is also discovered that there are as many as 114 definitions of CE that have been published among academic and practitioners (Kirchherr et al., 2017). Some definitions that are frequently being cited and are deemed to envelope overall core value, philosophy, method and scope of the umbrella concept are chosen as basis for further development (Schut et al., 2015, p.15; Geissdoerfer et al., 2017, p.759; Kirchherr et al., 2017).

> *"A circular economy is an industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models." (Ellen MacArthur Foundation, 2013, p.7)*

> "*In a circular economy the value of products and materials is maintained for as long as possible; waste and resource use are minimised, and resources are kept within the economy when a product has reached the end of its life, to be used again and again to create further value." (European Commission, 2015)*

> *"The circular economy is one that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value at all times, distinguishing between technical and biological cycles." (Ellen MacArthur Foundation, 2015, p.2)*

> *"The circular economy refers to an industrial economy that is restorative by intention; aims to reply on renewable energy; minimises, tracks, and hopefully eliminates the use of toxic chemicals; and eradicates waste through careful design." (*Webster, 2017, p.52*)*

> *"The core of CE are the '3R' principles—reduction, reuse, and recycling of materials and energy. […] The approach is expected to achieve an efficient economy while discharging fewer pollutants. The strategy requires complete reform of the whole system of human activity" (Yuan et al., 2006, p.5)*

> *"CE is a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling"* (*Geissdoerfer et al., 2017, p.766*)

> *"The circular economy seeks to stretch the economic life of goods and materials by retrieving them from post-production consumer phases. This approach too valorizes*

closing loops, but does so by imagining object ends in their design and by seeing ends as beginnings for new objects." (Gregson et al., 2015, p.9)

""The central idea is to close material loops, reduce inputs, and reuse or recycle products and waste to achieve a higher quality of life through increased resource efficiency." (Peters et al., 2007, p.5943)

These definitions of CE converge around six features, which are also commonly and frequently addressed in the majority of CE literature, namely Reducing (or eliminating) waste generation, Reducing (or eliminating) resources input, Reducing (or eliminating) environmental pollution via use of renewable energy, Increasing value of the waste, Increasing resources utility and Increasing economy prosperity. These six features also represent the goal of transitioning into CE from linear economy. The description of each of the feature is provided as follows.

CE is a system that **reduces (or eliminates) waste generation.** This feature has been the core feature and goal in CE definition. A CE adopter would intentionally design a product that is recoverable at its EOL so that it can be fully returned to the consumption cycle instead of being discarded in landfill (Ellen MacArthur Foundation, 2013; Webster, 2017). The concept of waste and EOL in linear economy no longer exists as resources can be fully recovered from the waste, thus reducing and possibly eliminating waste generation. Besides the design of products, the CE adopter can also utilise technology to dematerialise a product, such as moving from paper based books to e-books, which eliminates the source of waste entirely from its origin (Hieronymi, 2012). One could also utilise product-service system, PSS (See Section 2.1.3), a business model that leases a product to customers and the product would be taken back to the business owner for resources recovery instead of being disposed by the customers once it reaches its EOL, reducing the possibility of the EOL product to be discarded into landfill and increasing chances for resources recovery (Tukker, 2015). These strategies are created to attain the core goal of CE, which is the reduction (or elimination) in waste generation.

CE is a system that **reduces (or eliminates) resources input**. This feature is being addressed explicitly (European Commission, 2015; Potting et al., 2017),) and implicitly (Ellen MacArthur Foundation, 2013; Webster, 2017) in the CE definition and literature. It can be achieved when EOL products are actively being returned to consumption cycle to be reused or recycled. The needs for raw materials will reduce when the resources in the EOL products are recovered to substitute the primary raw materials. Undesired resources recovered from the waste, or recovered resources that do not satisfy quality constraint, could also become the input for alternative supply chain to create new products, creating prosperity while negating the needs to harvest virgin raw material (Pauli, 2015). "Waste equal food" has thus been a key idea of CE, promoting the reutilisation of resources in substitution for scarce virgin raw materials (Braungart and Mcdonough, 2009).

CE is an industrial system that **reduces (or eliminates) environmental pollution, primarily via the use of renewable energy.** Reduction of environmental pollution is the primary effect of shifting from using non-renewable energy sources (i.e., fossil fuels) to renewable energy.

Currently, approximately 75% of the energy generated in the world is originated from combustion of fossil fuels extracted from the lithosphere (Korhonen et al., 2018). The combustion of fossil fuels release gaseous emission to the biosphere in a high concentration that the nature could not assimilate, resembling a linear economy that "take" the non-renewable energy sources, "make" energy and "dispose" it in the form of gaseous emission in great excess (Korhonen et al., 2018). Besides depleting the natural reserves of fossil fuels, the gaseous emission released will create various pollution problems such as global warming and acid rain, which are detrimental to the ecosystem. CE thus aimed at tackling this phenomenon by promoting the use of renewable energy, which does not exhaust any natural resources nor create any environmental pollution.

CE is a system that **increases the value of the waste**, as exemplified in Ellen MacArthur Foundation (2015, p.2). Currently, there are many EOL strategies such as reuse, remanufacture, refurbish, recycling and recovery (Sihvonen and Ritola, 2015). For each strategy, there are many different alternatives that would yield different values, primarily measured in terms of profit generated per kg waste consumed (Tuck et al., 2012). CE emphasises the value embedded in the materials to be utilised in the application that could provide the highest benefit, aiming at maximising the value of the waste (Asif et al., 2016, Rashid et al., 2013, Mihelcic et al., 2003). In CE, when multiple EOL strategies are available, the strategies and business opportunity will be weighed via various analysis tools (e.g.: Chan and Tong, 2007; Ghazalli and Murata, 2011; Song et al., 2015) or frameworks such as waste hierarchy (e.g.: Price and Joseph, 2000; Sihvonen and Ritola, 2015; Ness and Xing , 2017), in selecting the strategy that could make the most of the value in the waste. According to the waste hierarchy, strategies such as reuse, refurbish and remanufacture are prioritised over material recovery (recycling), as most recycling is actually downcycling which reduces the quality of material over time (Braungart & McDonough, 2009, p.56). Energy recovery is the least prioritised EOL strategy in the hierarchy as it destroys the ability of the waste to be returned to the consumption cycle entirely. CE thus aimed at increasing and maximising the value of waste, via careful weighing of the EOL strategies and business cases.

CE is a system that **increases resources utility.** There are two methods that CE can increase resources utility. Firstly, the materials within an EOL of a product are reintegrated into production cycle via different resource recovery methods, using them for as long as possible and increasing their utility before they are eventually discarded. Secondly, CE argued that every underutilised resource is a wasted resource, thus sharing of products are recommended among consumers to increase the utility of resources and the intensity of uses before it reaches its EOL (Sposato et al., 2017). A new consumption culture is thus emphasised in CE (see section 2.1.3), where consumers share the use of the function of a physical product instead of owning and consuming it individually (Tukker, 2015; Korhonen et al., 2018).

CE is a system that **increases economy prosperity.** It is discovered that it is the most prominent aim of CE by analysing 114 definitions of CE in the literature (Kirchherr et al., 2017). The economic prosperity can be achieved when the concept of industrial symbiosis, which considers waste streams as new valuable resources in other processes is being applied

(Chertow, 2000). This concept enables transformation of waste into resources that can be sold to another supply chain as a source of revenue, increasing economic prosperity. It also ensures that resources are used for as long as possible and more value can be extracted from them, creating further economic wealth (Ness and Xing, 2017). Since CE also seeks to increase the value of waste by carefully selecting EOL strategy and business cases, the economic prosperity is also being enhanced tremendously in this process.

By synthesising the literature, this research defines CE as below:

> "CE is a system that shifts towards the use of renewable energy and replaces the 'end-of-life' concept with restoration, where resources are recovered from end-of-life waste and are used again and again, seeking to maximise both the utility and value of the resources, eventually enhance economic prosperity and eliminate the waste generation, resources input and environmental pollution."

The literature review of CE indicates that CE serves as a very promising solution to the current issues in the society as afore described in Section 2.1.1. Nevertheless, CE is still overlooked in much research, especially within the context of this study, which is the EOL tyre (ELT) recycling industry. Thus, this research is intended to inculcate CE as the core of the research, to fill the gap of CE for being overlooked in the academic (refer to Table 2.1 for CE characteristics).

2.1.3 Circular Economy Strategies

There are various strategies to achieve aforementioned CE goals and improve them (i.e., reduce/eliminate waste generation, reduce/ eliminate resources input, reduce/ eliminate environmental pollution, increase the value of the waste, increase resources utility and increase economy prosperity). Potting et al. (2017) and Cramer (2017) suggested 11 CE strategies with different priority depending on the level of circularity. The 11 CE strategies are Refuse, Rethink, Renew, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover. This research extends the work of Potting et al. (2017) and Cramer (2017) by combining and reorganising the 11 CE strategies into Prior-to-life strategies and EOL strategies.

In this research, Prior-to-life strategies are the strategies related to the activities that are done before a product is manufactured and consumed, while EOL strategies represent the strategies related to the activities that are done to a product after it reaches its EOL and being collected at a collection centre.

2.1.3.1 Prior-to-life CE Strategies

Among the 11 CE strategies put forward by Potting et al. (2017) and Cramer (2017), 4 CE strategies can be categorised as Prior-to-life strategies, namely Refuse, Rethink, Renew and Reduce. These strategies are performed before a product is manufactured, usually at the product design phase, aiming to improve the circularity of supply chain by reducing unnecessary parts in the product to curb unwanted waste during and after the product consumption.

Refuse can be defined as a strategy that prevents raw material usage (Cramer, 2017; Potting et al., 2017), which could significantly improve circularity by ensuring that waste will not appear in a product prior to manufacturing. For example, packaging that will eventually be discarded is avoided where possible in product.

Rethink can be defined as a strategy that makes product use more intensively via a new consumption model. Under this model, products are made to last as well as made to be shared (e.g.: in a central location) to prevent consumers from owning a physical product, which would otherwise be used only once awhile when owned individually, as CE views every underutilised resource as a wasted resource (Tukker, 2015; Korhonen et al., 2018). Sharing effectively increases the utility of resources and the intensity of uses before it reaches its EOL (Sposato et al., 2017). For example, carpool with neighbours which would otherwise not be used fully by an individual.

Renew can be defined as a strategy that redesigns products in view of circularity (Cramer, 2017). There are many design methods that fit this strategy, which collectively known as Design for X (DfX), where X indicates various purposes (Sassanelli et al., 2020). For example, Design for Disassembly and Reassembly, Design for Environment, Design for End of life, Design for Modularity, Design for Long Life Use of Products, Design for Recycling, Design for Recovery, Design for Remake, Design for Standardization, Design for Upgradability and so on. These design methods ensure a product fits CE vision and ensure EOL strategies can be applied to the product once it reaches its EOL, thus increasing the circularity of the product and supply chain.

Reduce can be defined as a strategy to decrease natural resources and raw material usage in a product. For example, the packaging of product can be exchanged with more durable packaging material to reduce the amount of packaging used per unit of food.

2.1.3.2 End-of-life CE Strategies

Among the 11 CE strategies, 7 CE strategies can be classified as EOL strategies, namely Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover, which are applicable for waste that reaches its EOL and preparing to return to supply chain. Higher priority is given to Reuse, followed by Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover.

Reuse can be defined as a strategy to re-use a discarded product (i.e., second-hand) which is still in good condition and is able to fulfil its original function in a closed-loop supply chain (CLSC). Reusing a product is the top priority among the 7 EOL strategies, as it fully eliminated the waste by re-using the product entirely, thus eliminating the needs to harvest for more materials to produce more similar products. At the same time, it also increases the product utility and generates economic opportunity by selling the product in a second-hand market.

Repair can be defined as a strategy to fix all faults, defects or damages in a defective device so that it can be used again by performing its original function (Ijomah and Danis, 2012; Potting et al., 2017). Repair can be carried out in the field by a service technician or by a manufacturer or specialist at a dedicated service or repair facility.

Refurbish can be defined as a strategy to restore an old product and bring it up to date (Potting et al., 2017) by replacing broken parts as well as parts with cosmetic damages (Sumter et al., 2018). Refurbishment ensures a product or component is cleaned and restored in order to make a resell (Brissaud et al., 2006). Unlike repair, refurbishment is performed in a factory setting with more stringent operational specifications, involving expanded tool sets, paints, solvents, cleaning solutions and other surface treatment capabilities (Ijomah and Danis, 2012).

Remanufacture can be defined as a strategy to use parts of the discarded products in a new product with the same function (Potting et al., 2017). Remanufacturing is more complex than refurbishment as it requires rebuilding of a product after a detailed and comprehensive disassembly and reassembly process, which would then be inspected and tested to ensure it is back to at least its original equipment specified state or meets newly manufactured product standards (Seaver, 1994; Ijomah and Danis, 2012). Remanufacture includes thorough cleaning, testing and diagnosis of all the disassembled parts, to produce product that is "as good as new" or "better than new" (Butzer et al., 2014), compared to refurbished product that is "as good as new" or "less than as new" (Ellen MacArthur Foundation, 2015) or repaired products with overall condition less than remanufactured or refurbished alternatives (King et al., 2006). Even though refurbishment produces a product with better quality, the processes are too complex and involved too much solvents and equipment for thorough cleaning, testing and diagnosis, which would produce more waste and incur more cost, thus it is given less priority as EOL strategies for EOL products.

Repurpose can be defined as a strategy to use a discarded product or its parts in a new product with different function. This strategy is similar to reutilisation of EOL product as a whole in Reuse strategy, but instead of CLSC, this strategy reutilises the product as a whole in an open loop supply chain (OLSC). For example, ladders can be repurposed as book shelves, cheese graters repurposed as lights or earring holders, strainers repurposed as light shades, tennis rackets repurposed as mirrors, guitars repurposed as decorative shelves, tyres repurposed as boat fenders, drums repurposed as bins and worn-out clothes repurposed as rags (Beaty, 2014). Nevertheless, this EOL strategy is not any better than the aforementioned strategies as the product has entered a new supply chain for new usage. It is often thought that the quality of the waste is best preserved when it is being returned to CLSC the original supply chain, while it deteriorates when it enters OLSC for new usage.

Recycle can be defined as a strategy that reprocesses the EOL product to salvage for materials with the same or lower quality, returning them into the supply chain (Worrell and Reuter, 2014; Cramer, 2017; Potting et al., 2017). The recycled materials, known as recyclates, can be returned to the supply chain and used as a substitute for raw virgin materials in product manufacturing. The energy required for recycling is generally substantially less than the energy required to produce the material from ores, making recycling a better option than virgin material harvesting.

Recover can be defined as a strategy that involves incineration of materials for energy recovery. This strategy is the least favoured strategy as the materials are destroyed in the process for energy generation, rendering its subsequent utility entirely.

Generally, the reuse of products as a whole is Reuse or Repurpose, depending on the supply chain the EOL product enters (i.e., Reuse for CLSC and Repurpose for OLSC). On the contrary, the recovery of materials from EOL product that requires mechanical shredding of the products are Recycling. The 11 CE strategies categorised into prior-of-life and end-of-life strategies are arranged into a hierarchy according to priority and circularity as shown in Table 2.1.

Table 2.1: CE-strategies hierarchy arranged by priority and circularity (Source: Author).

CE strategies		Priority	Circularity	Popularity
Prior-of-life	Refuse	High	High	Low
	Rethink			
	Renew			
	Reduce			
End-of-life	Reuse			
	Repair			
	Refurbish			
	Remanufacture			
	Repurpose			
	Recycle			
	Recover	Low	Low	High

The characteristics of circularity:

- Low waste output
- Low resources input
- Low pollution
- High resources utility
- High resources value
- High economic prosperity

It is shown that CE aimed at cutting waste output by instating various prior-of-life strategies to the supply chain. CE also endeavoured to maximise the value of the waste (primarily in terms of profit generated by kg waste consumed (Tuck et al., 2012)) by inspecting and prioritising various EOL strategies available to an EOL waste (Kirchherr et al., 2017). By doing so, the resources required to input into the supply chain will be greatly reduced as resources within the waste are retained in the supply chain via EOL strategies. Similarly, the economic prosperity will also be improved when the most appropriate EOL strategy is selected.

The hierarchy in Table 2.1 shows that the priority of EOL strategy is given to Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle and Recover, in the order of reduction in circularity. The EOL product can be reutilised as a whole, using strategies such as Reuse, Repair, Refurbish or Repurpose if the quality of the product is still decent and the degree of faults is low. Certain EOL products such as bottles, PET bottles, lumber, textiles and tyre can be repurposed as decoration or as furniture. If the quality of the product as a whole is not in satisfactory, strategies such as remanufacture and recycling can be employed, where the EOL product can be dissembled into components to be remanufactured or shredded into recyclates, to be used in manufacturing a range of different products. Some EOL products can even be energy recovered due to the high calorific content.

Nevertheless, by inspecting various EOL strategies that are currently applied to the EOL products (see Section 2.2.2), it is revealed that Recycling is the mostly used EOL strategy as compared to other EOL strategies as shown in Table 2.2. This essentially makes the EOL strategy, with lower priority and circularity such as Recycling or Recovery, to have a higher popularity compared to other EOL strategies as shown in Table 2.2. This also reveals that the current business context is very Recycling focus and not other EOL strategies.

Based on Table 2.2, strategies such as Reuse, Refurbishment and Remanufacturing are less employed because these strategies are highly relying on the quality of the EOL product being collected. For example, the Reuse, Refurbishment and Remanufacturing of WEEE, e.g.: digital copier, inkjet printer, vacuum cleaner, washing machine, single use camera and television set, are hindered if there is a great amount of dirt or grimes collected on them (Rose et al., 1998).

Table 2.2: EOL strategies for various EOL products (Source: Author).

EOL waste (EU)	Source	EOL strategies utilised % (mil T)							Landfill or unknown	Total collected % (mil T)
		R1	R2	R3	R4	R5	R6	R7		
Tyre	WBCSD, 2018, p.25; Bermejo, 2019	5.59% (0.20)	6.70% (0.24)	-	-	-	54.75% (1.96)	32.96% (1.18)	0.00% (0.00)	100% (3.58)
Plastic bottle	Bishop et al., 2020	-	-	-	-	-	76.3% (1.90)	6.4% (0.16)	17.3% (0.42)	100% (2.48)
Plastic packaging	Plastic Europe, 2019	-	-	-	-	-	42.0% (7.48)	39.5% (7.03)	18.5% (3.29)	100% (17.80)
Glass bottle	Butler and Hooper, 2019; European Container Glass Federation, 2020	4% (0.68)	-	-	-	-	76% (13)	-	20% (3.4)	100% (17)
Paper and cardboard	European Paper Recycling Council, 2019	-	-	-	-	-	72% (57.5)	-	28% (22.3)	100% (79.8)
Steel (machinery/ automotive)	Sansom and Avery, 2014	5%	-	-	-	-	91%	-		100%
Textiles	CBI Ministry of Foreign Affairs, 2020	50% (1.14)	-	-	-	-	50% (1.15)	-	0% (0.0)	100% (2.29)
WEEE	Baldé et al., 2017	-	-	-	-	-	35% (4.3)	-	65% (8.0)	100% (12.3)
Furniture	Forrest et al., 2017	-	-	-	-	-	10% (1.5)	90% (9.0)	0% (0.0)	100% (10.5)

R1= Reuse, R2= Repair, R3= Refurbish, R4=Remanufacture, R5= Repurpose, R6= Recycle, R7= Recover

The aforementioned EOL strategies possess a common weakness, where they are only applicable if the EOL waste is successfully collected post consumption. To ensure the EOL strategies can be executed successfully, several strategies have been designed to improve the collection rate of the post-consumed EOL products, such as Product-Service System (PSS) as well as initiatives such as Extended Producer Responsibility (EPR) (Fischer and Pascucci, 2017; Jensen and Remmen, 2017; Goyal et al., 2018).

PSS allows the manufacturer to sell the function of a product via leasing, retaining the ownership of the physical product. This allows the manufacturer to collect the product when it reaches its EOL and treat it, instead of being disposed by the customers. For example, Rolls-Royce offers “Power-by-the-hour” to airlines, leases out the power and functionality of a gas turbine engine rather than the product itself and charges their customers according to the effective run time of their engine (Smith, 2013). PSS allows the cost incurred on customers to be bought down by the introduction of leasing business model. In addition, it also guarantees the product to be collected by the manufacturer once the product reaches its EOL, allowing an EOL strategy to be applied subsequently.

EPR is not like PSS where the manufacturer retains the ownership of a product. Instead, it is a responsibility that is imposed on the manufacturer by higher authorities such as government, which extends the producers' responsibility for a product to the EOL stage of a product's life cycle. Under EPR, manufacturers are required to collect the EOL products they have manufactured and treat them, instead of permitting them to be landfilled (Fischer and Pascucci, 2017; Jensen and Remmen, 2017; Goyal et al., 2018).

Despite of the effectiveness of the aforementioned CE strategies hierarchy in aiding the selection of EOL strategy and improving the overall circularity of supply chain, the hierarchy is limited for two reasons: The CE strategies hierachy is not a one-size-fit-all strategy that is applicable to all EOL products. Furthermore, when multiple opportunities or alternatives arise under a specific EOL strategy (e.g.: multiple alternatives to recycle and to utilise materials from the EOL product), the CE strategies hierachy is unable to distinguish a more suitable alternative among the available choices. For example, an EOL tyre can be recycled to produce synthetic turf or cement, but the CE strategies hierachy fails to identify a more prominent alternative among them. This research thus aims to fill the gap by deriving a framework that is capable of selecting the most suitable alternatives, specifically under recycling strategy, as it is the most popular strategy among the 11 EOL strategies as shown in Table 2.1 (Butler and Hooper, 2019; European Paper Recycling Council, 2019; Bishop et al., 2020), in spite of being the most complicated EOL strategy compared to the 11 EOL strategies because of the involvement of many alternatives (see Section 2.2.2).

2.2 Circular Supply Chain

2.2.1 Evolution of Supply Chain

Supply chain, started as **linear supply chain**, focuses on the management of supplies and strives to cope with the demand in a cost effective and timely manner to improve customer satisfaction (Cooper and Ellram, 1993; Christopher, 1998). However, the management of supply chain that was purely driven by reducing cost and improving quality of products (i.e., performance, features, reliability, conformance, durability, serviceability, aesthetics and perceived quality (Gavin, 1984)), would trade off the environmental impact and was soon proven to be undesirable. The negative impact on the environment had motivated supply chain to evolve into green/environmental supply chain, which is dedicated to protect the environment by simultaneously managing the supply chain by bringing the best of both economic and environmental care, integrating environmental concerns into the organisations by reducing unpleasant consequences of production and consumption processes (King and Lenox, 2001; Simpson and Power, 2005; Mollenkopf et al., 2010). The addition of social issue, for example improving job opportunities and care for the stakeholders' wellbeing, was soon incorporated into the prime activities of supply chain, along with economic and environmental care, making a supply chain more effective in addressing the current issue of the world (i.e., economic, environmental, social issues). Together, the three became the core pillars that shape the new facade of supply chain, namely sustainable supply chain (Carter and Roger, 2008).

Sustainable supply chain aimed at carrying out day-to-day operations such a way that the need of the present is met without compromising the ability of future generations to meet their own needs, satisfying the three pillars of sustainability (i.e., economic, environmental, social) (Carter and Roger, 2008). The transition into sustainable supply chain is affecting both the organisation's supply chain and logistics network, by focusing not just to lower the costs but ensuring just-in-time delivery or combating negative environmental impacts (Seuring and Müller, 2008). Organisations in a sustainable supply chain extend their corporate social responsibilities to care more in their surroundings, by creating welfare to the community, combating child labour, and ensuring health and safety of workers and local citizens that live close to their proximity (Andersen and Skjoett-Larsen, 2009; Tate et al., 2010; Chi, 2011). Besides, more collaborations are made such as sharing distribution to reduce half-empty vehicles on the road, or investing on alternative modes of transportation that maximise the economic, environmental and social aspect of sustainability (Carter and Roger, 2008; Florescu et al, 2019).

Nevertheless, the issue of resource scarcity is still not being well resolved as the linear economy production model is still being practiced under the sustainable supply chain (Farooque, 2019). It lacks initiatives that bring back the EOL products into the supply chain, closing the supply chain loop. At such, supply chain soon started to implement reverse logistics to retrieve the EOL products created along the supply chain. The collected EOL products are reuse/remanufacture/recycle as much as possible, such that less EOL products are sent to the landfill and buried as waste. Since the resources recovered from EOL products can displace the usage of virgin raw materials, thus less virgin raw materials have to be harvested from the nature to cope with the daily demand (Govindan, Soleimani, and Kannan, 2015).

Consequently, a **closed-loop supply chain**, or CLSC is formed. CLSC reuses products, parts, materials and energy of the recovered EOL products, as shown in Figure 2.1. When an EOL product is collected after usage, it would be sorted and tested to determine a suitable EOL strategy depending on its quality (Leino et al., 2016; Cramer, 2017; Potting et al., 2017). The EOL product that is still functionable can be reused in a different market and sold with a lowered price. The EOL product that has damaged parts can be repaired or remanufactured (see Section 2.1.3.2) and then sold on. Meanwhile, the EOL product with poorer quality can be disassembled into parts that can be used in remanufacturing or recycled into materials that can substitute raw virgin materials. The EOL product with the poorest quality can be incinerated to recover energy (Bloemhof et al., 2009). The primary focus of CLSC is to circulate the materials in the EOL product as long as possible in the original supply chain, adhering to the philosophy of CE, at the same time making the CLSC sustainable.

Figure 2.1: The processes of a closed-loop supply chain (Source: Bloemhof et al., 2009).

However, the limitation of waste streams to return only to original supply chain in a CLSC restraints the full potential of the EOL products collected. Some CLSC possesses stringent quality measures that disallow the use of a degraded waste, causing the waste to be sent to landfill instead of being recovered. Some CLSC uses a less preferred EOL strategy such as energy recovery due to quality issue of the recovered waste, which can be otherwise be fully reused in an alternative supply chain, thereby increasing the utility and value of the EOL products (Bloemhof et al., 2009). Thus, instead of recirculating the EOL products to the original supply chain in CLSC, the EOL products can be introduced to alternative supply chain as input, giving an alternative use for the EOL products. This initiative can be seen in various supply chains such as recycling of PET bottles into fibre production or furniture (Haupt et al., 2017; Huysman et al., 2017), recycling of glass bottles into foam glasses, glass sands or alternative cementitious materials (ACM) in concrete (Haupt et al., 2017), recycling of papers and cardboards into insulation materials (Haupt et al., 2017), recycling of cotton-based clothing into fibrefill for furniture (Ellen MacArthur Foundation, 2013, p.33), recycling of automotive or machinery high quality steels into concrete reinforcement bars (Allwood, 2014; Pauliuk et al., 2017), as well as recycling of tyres as artificial turf, flooring for playgrounds and tyre derived aggregates used as foundation for roads (Schmidt et al., 2009; Clauzade et al., 2010; Feraldi et al., 2013). The initiatives to feed the waste into alternative supply chain instead of original supply chain, is known as open loop supply chain (OLSC) (Özceylan, 2016;

Kalverkamp, 2018; Farooque, 2019). It is also known as "up-cycling" or "down-cycling" (Graedel et al., 2011; Pauliuk et al., 2017) or "cascade use" (Kalverkamp et al., 2017; Bais-Moleman et al., 2018).

By integrating OLSC into the CLSC, **circular supply chain**, or CSC is created, which better integrates CE principles into supply chain management (SCM) by involving OLSC (De Angelis et al, 2018; Mishra et al., 2018; Farooque, 2019). CSC is superior to its predecessor (i.e., closed-loop supply chain) in arriving at CE's goal, because the resources recovered from post-consumer products are no longer restricted within the original supply chain (producer's supply chain), but flow to the secondary supply chains and/or new auxiliary channel members in the OLSC (Moula et al., 2017). The involvement of OLSC (i.e., the secondary supply chain), allows the new use of the unwanted waste in a CLSC or even better use of waste produced in the supply chain, by collaboration with others within and outside of the sector to maximise the utility of the waste, which could then bring about resource efficiency, and consequently, profitability (Weetman, 2016). An OLSC can be the same sector as the CLSC, or different sector as shown in Figure 2.2. For example, an EOL tyre manufactured in the UK can be re-treaded and reused as a second-hand tyre in other developing countries. It could also be recycled into making of artificial turf for lawn.

The concept of CSC opposed to traditional supply chain is depicted in Figure 2.2, by the involvement of CLSC and OLSC in achieving zero waste (Kalverkamp, 2018; Kalverkamp and Young, 2019). From the figure, it can be seen that linear supply chain that was used to be consisting of only forward SC in the past had slowly progressed into a network type that integrates reverse logistics, gradually closing the supply chain loop by bringing the generated waste back into the SC network, practising CLSC and subsequently, CSC. The waste flow that is initially directed to the landfill in linear supply chain is sent back to the supply chain via reverse logistics in CLSC. The involvement of OLSC in the CSC enables more possibility for the waste to return to the supply chain, thus significantly diverting the waste from landfill disposal, achieving zero waste. The multitude of opportunity arisen for the waste due to the introduction of OLSC, which also allows circular thinking to perforate into all supply chain stages and functions, and to reutilise the waste such that no waste is created.

Figure 2.2: Linear, closed-loop and circular supply chains (Source: Farooque, 2019).

2.2.2 CLSC and OLSC for EOL Products in a Circular Supply Chain

Wastes are unusable or unwanted materials, or any substances which are discarded after primary use, or are defective, worthless and no longer useful (Worrell and Reuter, 2014). Some major types of waste are agricultural wastewater, biodegradable waste, biomedical waste, brown waste, chemical waste, construction waste, demolition waste, electronic waste, food waste, green waste, hazardous waste, heat waste, industrial waste, litter, marine debris, mining waste, municipal solid waste, open defecation, post-consumer waste, radioactive waste, scrap metal, sewage, toxic waste and wastewater (Worrell and Reuter, 2014).

For demonstration purpose, Table 2.3 exhibits some EOL strategies that are applicable to some waste (i.e., tyres, plastic PET bottles, and paper and carboard). Based on Table 2.3, the EOL products can be reused, repaired, refurbished, remanufactured, repurposed, recycled or recovered, whether in the CLSC or OLSC. The introduction of OLSC, whether the same sector or different, further added more alternatives for the EOL products in each EOL strategy. For example, the EOL strategies applicable for traditional tyres CLSC are reuse, repair, refurbish and recover. The OLSC introduced to ELT have added more reuse, repair, refurbish and recovery alternatives in another supply chain of the same sector, and even more alternatives via supply chain of different sectors for repurpose, recycling and recovery. Particularly, recycling strategy has more alternatives as compared to other EOL strategies as shown in Table 2.3. For instance, ELT can be recycled into the production of new tyres, aggregates for civil engineering application (Shirule and Hussain, 2015), artificial turf, moulded objects or sports surface (Schmidt et al., 2009; Clauzade et al., 2010; Feraldi et al., 2013). The introduction of OLSC made the selection of EOL strategies and alternatives very complicated. Currently, no standardised framework is designed for this endeavour and causes the selection of alternatives highly difficult and much more challenging after the introduction of OLSC in CSC.

Table 2.3: EOL strategies for some selected EOL waste in CLSC and OLSC (Source: Author).

EOL waste examples	CLSC	OLSC	
		Same sector	Other sector
Tyres	**Reuse** at second hand market **Repair or Refurbish** by retreading the tyre **Recycle** to produce new tyre **Recover** as energy (Feraldi et al., 2013)		**Repurpose** as coffee table (Beaty, 2014) **Recycle** to produce aggregate for civil engineering application (Shirule and Hussain, 2015), artificial turf, sports surface, etc. (Schmidt et al., 2009; Clauzade et al., 2010; Feraldi et al., 2013) **Recover** as energy (Feraldi et al., 2013)
Plastic (PET) bottle	**Reuse** after thorough cleaning (Iacovidou et al., 2019) **Recycle** to produce bottle-grade PET (Haupt et al., 2017)		**Repurpose** as vase (Beaty, 2014) **Recycle** to produce packaging/ PET fibers/ sleeping bags/ fleece jackets (Haupt et al., 2017) /polymer blended bitumen road (Siddiqui and Pandey, 2013) **Recover** as energy (Siddiqui and Pandey, 2013)
Paper and Cardboard	**Reuse** of paper and cardboard **Recycle** into fibres for paper or cardboard production (Haupt et al., 2017; Virtanen and Nilsson, 1993)		**Repurpose** as container (Beaty, 2014) **Recycle** as insulation material (Haupt et al., 2017; European Paper Recycling Council, 2019), furniture (Barboutis and Vassiliou, 2005) **Recover** as energy

Among many types of the waste, tyre waste is chosen as the waste to be studied for a few reasons. Firstly, the rubber within the tyre is highly in need to tackle the supply issue of rubber in the EU. Currently, natural rubber has been listed as one of the critical raw materials with high supply risk and a high economic importance, along with 26 other materials in the EU (European commission, 2017). The reliable and unhindered access of the critical raw materials like rubber is a major concern for EU industry and value chain. Today, the sustainability issue of rubber plantation as well as continually low price of rubber make the plantation less attractive, causing the supply to be lowered substantially, with foreseeable downward trend in the near future, with a projected supply deficit of 7.7% every year globally (The Association of Natural Rubber Producing Countries, 2020). The rubber plantation that is needed to cope with the supply is not welcomed as the plantation would replace forests that globally unique and threaten species (Warren-Thomas et al., 2015; Butler, 2015). Rubber plantations are biological deserts relative to natural forests, where animals are known to greatly reduce (up to 75% for certain bird, bat and beetle species) or disappear completely from forests that have been converted to rubber. The heavy use of fertilisers and pesticides in rubber plantation also adversely affect freshwater species due to the chemical run off via leachate that contaminates the freshwater.

Today, the majority of the rubber used in manufacturing is still obtained via harvesting rubber naturally from rubber trees, while only 1% of the rubber used is acquired via recycling of rubber products (European commission, 2017). European Commission thus urges for enhanced recycling of rubber products, especially tyres as a substitute to natural rubber, to mitigate the supply risk of natural rubber.

Secondly, the demand for natural rubber has greatly increased every year, outpacing the supply rate. The demand is mostly originated from tyre companies, which consumed around 70 percent of the world's natural rubber (Research in China, 2017). The global demand for natural rubber in the car and light commercial vehicle tyre manufacturing are found to have increased by 10% within a short period of time, from 11 million tons in 2011 to above 12 million tons in 2016 (Wiriyapong, 2016; Research in China, 2017; Wagner, 2019). Nevertheless, it is predicted that the rubber supply could not cope with the upsurge in demand. It is estimated that the gap between the demand and supply will occur and continue to widen, from -0.1 million tons in 2016 to -0.6 million tons in 2021 (Research in China, 2017; The Association of Natural Rubber Producing Countries, 2020). When natural rubber is insufficient to cope with the rising demand, EOL rubber products such as tyres, which are rich in rubber, will ultimately fill the demand by re-entering the supply chain via recycling. Among all the supply chain that can make use of the recycled rubber, which supply chain can have a better use of it in terms of circularity and sustainability is a subject of special interest.

Thirdly, it is mandatory for the ELT generated within the EU to re-enter the supply chain instead of to the landfill, which is now prohibited in the EU (European commission, 2017). Today, the legislation has been passed in the EU to ensure ELT will be collected and treated via EOL strategies. An ELT with negligible deterioration is required to be reused in second-hand market or refurbished by re-treading the tyres. An ELT that does not pass the quality check is required to be recycled into components and used in manufacturing of other products either in CLSC or OLSC. Alternatively, it should be burnt in kiln for energy recovery as the last resort. This made the EOL strategies and alternatives selection for EOL tyre the top priority as compared to the other products, to provide aid in the selection of most suitable EOL strategies and alternatives in terms of circularity and sustainability.

Lastly, tyre is one of the EOL products with the highest number of recycling alternatives, as illustrated in Table 2.3. The abundance of alternatives make the selection of alternatives very challenging, making ELT one of the most attractive waste streams to be studied in determining the most suitable alternative (Sienkiewicz et al., 2012). More in-depth discussion on this can be found in Chapter 3.

2.3 Circularity Indicators

In a CSC, an EOL product can be returned to the consumption cycle via CLSC or OLSC, using different EOL strategies, such as Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle or Recover, arranged in the descending order of priority, as discussed in the previous section. Among the various EOL strategies, Recycling appears to be the mostly used strategy as depicted in Section 2.1.3. The introduction of OLSC further complicates the EOL strategies selection because each EOL strategy is presented with many alternatives, especially in the Recycling strategy as shown in Section 2.2.2. Drawing from the literature review, this research thus focuses on the Recycling strategy as it is the most utilised EOL strategy and the most complicated strategy due to the introduction of many alternatives by OLSC.

A small fraction of research studied the feasibility and benefits of utilising Recycling alternatives introduced by OLSC, comparing their performance over one another as well as with the CLSC (Huysman et al. 2017; Pauliuk et al., 2017). However, the comparison often yields conflicting results due to different indicators are used for performance evaluation. As a result, there is no consensus arrived which is able to serve as holistic guide or framework, equipped with suitable indicators to justify the preference of specific alternative. At such, this has motivated this research to study on methods to evaluate the performance of the various Recycling alternatives, using a more complete range of indicators. This gap will be further exemplified in the subsequent sections.

It is difficult to select the most suitable alternative given that the performance assessment for the different alternatives is highly challenging. There are many supply chain performance assessments using different indicators (Govindan et al., 2017; Chae, 2009). An indicator is a variable (parameter) or a function of the variables to summarise complex information, providing information about a system (Singh et al., 2012). The supply chain performance assessment indicators measure different aspects, ranging from collaboration, coordination, competitiveness, innovation, flexibility, agility to resources utilisation, using various financial and non-financial terms (Varsei et al., 2014; Govindan et al., 2017; Gunasekaran and Kobu, 2007).

Nevertheless, the aforementioned indicators are leaning towards linear economy as the waste problems are not being properly addressed. To ensure a successful transition into CE, circularity indicators appeared to be the most suitable method to compare and contrast the performance of the alternatives. Furthermore, the use of circularity indicators will foster a deeper understanding and a better integration of CE into businesses, setting suitable CE targets and benchmarks for industrial practitioners. Today, circularity indicators are actively being designed by various researchers and institutions to measure circularity of alternatives within a CSC (Bocken et al., 2017).

To futrther advance the understanding of circularity indicators, a literature review is performed, focusing on reviewing the dimensions and items commonly used in constructing an effective circularity indicator. In order to identify all existing literature in an unbiased, transparent and reproduceable way, a systematic literature review is employed in this research (Fink, 2014). The main search terms in this literature review are ‘circularity’ and ‘indicators’. To ensure a complete inclusion of CE indicators, this analysis combines the synonym of indicators in the search string, such as measure, index and value as defined in Gallopín (1996). Similar words or synonyms that are used in previous systematic review articles are also included, such as “indicators”, “measuring” and “assessment” in Elia et al. (2017), “metric”, “assessment”, “tool” and “indicator” in Parchomenko et al. (2019), and “indicators”, “indices”, “index”, “metrics”, “measure”, “assessment” and “evaluation” in Saidani et al. (2019). The final search strings {circular economy} AND ({circularity} OR {performance}) AND ({evaluation} OR {assessment} OR {measure} OR {measurement} OR {indicator} OR {indicators} OR {indices} OR {index} OR {metric} OR {metrics} OR {dimensions}) AND NOT {sustainability} are used in the database search, under title and abstract.

The review is based on both peer-reviewed journal articles and conference proceedings in English. The databases used for the search include Science Direct, SAGE, Springer, Taylor and Francis, Wiley, Emerald and JSTOR. The publication years of the included papers ranged from year 2006 to June 2019. This time period was chosen because Merli et al. (2018) disclosed an increase in publications on CE from 2006 with relatively few publications prior to 2006. The included subject areas are environment, economics, social science, engineering, business and management, material, decision, and multidisciplinary science.

The computer search is also supplemented with bibliographic cross-referencing of the articles obtained in the search. In addition, complementary sources such as reports from company, institution and public lobbying groups are also included to extend the coverage of existing CE indicators (e.g., the European Commission, the European Environmental Agency and the Ellen MacArthur Foundation). This is because CE indicators are not only being developed by academics, but also actively created by practitioners such as consultants or companies to support businesses and policy-makers (Parchomenko et al., 2019; Saidani et al., 2019).

The papers identified are manually assessed to exclude irrelevant literature. Firstly, papers that concerning circulairty indicators on a macro level are excluded (e.g.: GDP, per capita figures, national waste output, etc.) as they are irrelevant at a supply chain level. Secondly, papers that focusing on business model or technology development are excluded, because these papers do not propose any circularity indicator. Thirdly, the circularity indicators referring to CE practices or business models are excluded as they cannot feasibly and directly evaluate circularity. The remaining papers are assessed according to the quality and clarity of the proposed indicators. The indicators that do not explicitly measure circularity are omitted from further analysis. Similarly, the indicators that are inadequate in demonstrating clear circularity measurement or clear methodology are also omitted.

The search identified 210 articles in total. After excluding irrelevant literature, the analysis found 98 relevant papers using 50 common sets of circularity indicators, originated from 41 journal articles, 1 conference proceeding and 8 technical reports, with a total of 50 articles. The materials obtained are recorded in Table 2.4, with the 50 sets of CE indicators listed in the first column, the abbreviation in the second column and source in the last column.

The circularity indicators are inspected, focusing on investigating the uses of different circularity dimensions within the circularity indicators. The common circularity dimensions identified from the 50 papers are C_1-monetary, C_2-energy and environment, C_3-material, C_4-temporal and C_5-efficiency, as shown in Table 2.4. The dimensions are cross-checked with review articles to ensure appropriate dimension clustering and can be used to represent circularity adequately. In this analysis, the involvement of a particular dimension in each CE-indicator is denoted by the symbol "✔" and the total number of dimensions involved in each CE indicator is recorded under the column "*f*" in Table 2.4 (see detailed description in Section 2.3.1).

Table 2.4: CE indicators, dimensions, and its source (Source: Author).

CE Indicator	Abbv	Dimensions						Source
		C_1	C_2	C_3	C_4	C_5	f	
Five Category Index Method	FCI	✔	✔	✔			3	Li and Su (2012)
Circular Economy Toolkit	CET	✔	✔	✔	✔	✔	5	Evans and Bocken (2013)
Evaluation Indicator System of Circular Economy	EISCE	✔	✔	✔		✔	4	Zhou et al. (2013)
Closed-Loop Calculator	CLC	✔		✔	✔	✔	4	Kingfisher (2014)
Material Reutilization Part	C2C		✔	✔		✔	3	C2C (2014)
Assessing Circular Trade-offs	ACT	✔	✔	✔		✔	4	Circle and PGGM (2014)
Circular Economy Index	CEI	✔					1	Di Maio and Rem (2015)
Material Circularity Indicator	MCI			✔	✔	✔	3	Ellen MacArthur Foundation (2015)
Resource Productivity	RP	✔		✔			2	Wen and Meng (2015)
Recycling Rate	RR					✔	1	Haupt et al. (2017)
Recycling Indices	RI		✔			✔	2	Van Schaik and Reuter (2016)
Resource Duration Indicator	RDI				✔	✔	2	Franklin-Johnson et al. (2016)
Circularity Calculator	CC	✔		✔	✔	✔	4	ResCoM (2016)
Circular Economy Toolbox US	CETUS		✔	✔	✔	✔	4	US Chamber Foundation (2017)
Circularity Material Indicator	CIRC			✔	✔	✔	3	Pauliuk et al. (2018)
Circular Economy Performance Indicator	CEPI		✔			✔	2	Huysman et al. (2017)
Circular Economy Indicator Prototype	CEIP	✔		✔		✔	3	Cayzer et al. (2017)
Circularity Potential Indicator	CPI			✔	✔	✔	3	Saidani et al. (2017)
Product-Level Circularity Metric	PCM	✔					1	Linder et al. (2017)
Sustainable Circular Index	SCI			✔	✔	✔	3	Azevedo et al. (2017)
Value-based Resource Efficiency	VRE	✔					1	Di Maio et al. (2017)
Circular Pathfinder	CP	✔		✔	✔	✔	4	ResCoM (2017)
Circularity Design Guidelines	CDG		✔		✔	✔	3	Bovea and Pérez-Belis (2018)
Circular Economy Evaluation Index	CEEI	✔	✔	✔			3	Wang (2018)

Circularity Measurement Toolkit	CMT	✓	✓	✓		✓	4	Garza-Reyes et al. (2018)
Combination Matrix	CM			✓	✓	✓	3	Figge et al. (2018)
Ease of Disassembly Metric	eDIM					✓	1	Vanegas et al. (2018)
Estimated Disassembly Time	EDT					✓	1	Mandolini et al. (2018)
Sustainability Indicators Circular Economy	SI-CE			✓		✓	2	Mesa et al. (2018)
Measuring a Circular Supply Chain Management	MCSCM	✓	✓	✓	✓	✓	5	Jain et al. (2018)
Evaluation of Circular Economy	EoCE		✓				1	Yang (2018)
Performance of Circular Economy	PoCE		✓	✓			2	Liang et al. (2018)
Circular Economic Valuation	CEV			✓		✓	2	Czikkely et al. (2018)
Multi Dimensions Decision Analysis-CE	MCDA-ML		✓	✓		✓	3	Niero and Kalbar (2019)
CE Indicator	CEI		✓	✓		✓	3	Kiselev et al. (2019)
Eco-efficiency of CE	EE		✓				1	Liu et al. (2019)
Forest-wood Chain	FWC	✓	✓		✓	✓	4	Pieratti et al. (2019)
Circularity of Material Quality	Qc		✓	✓			2	Steinmann et al. (2019)
Quality Assessment and circularity Potential	QA&CP			✓		✓	2	Eriksen et al. (2019)
circularity Assessment	CA		✓	✓		✓	3	Pauer et al. (2019)
CE Benefit Indicators-Recyclability Benefit Rate	RBR		✓	✓	✓	✓	4	Huysveld et al. (2019)
Circonomics Index	CI	✓		✓			2	Kayal et al. (2019)
Measuring CE	mCE	✓		✓		✓	3	García-Barragán et al. (2019)
Product Recovery Multi-Dimensions Decision Tool	PRmcdt	✓	✓				2	Alamerew and Brissaud (2019)
Supply Chain Circularity	SCC				✓	✓	2	Kuhl et al. (2019)
Measuring CE-Multiple Correspondence Analysis	MCA	✓	✓	✓	✓	✓	5	Parchomenko et al. (2019)
Resource Efficiency	RE		✓	✓			2	Willskytt and Tillman (2019)
Introduction of Circular Products	IoCP	✓	✓	✓		✓	4	Urbinati et al. (2019)
Multi-dimensions Evaluation to Promote Circularity	MCE		✓	✓			2	Grippo et al. (2019)
Environmental Pressures of a Circular Economy	EPCE	✓	✓				2	Helander et al. (2019)

C_1-monetary, C_2-energy and environment, C_3-material, C_4-temporal, C_5-efficiency and *f*-frequency

2.3.1 Circularity Dimensions

Since CE is currently in its pioneering phase, recent efforts are still dedicated to confirm the technical viability of CE, thus circularity are not widely employed in decisions making (Ellen MacArthur Foundation, 2013:79). Consequently, exploratory literature review is crucial to identify the relevant circularity dimensions (and their relevant items) for circularity measurement. Review articles that analyse the circularity dimension used are being consulted to identify the common dimension employed in the literature. Ellen MacArthur Foundation (2015) analysed the dimensions used to measure circularity of Denmark and countries in EU-27 and classified them into 4 dimensions, namely resource productivity, circular activities, waste generation and greenhouse gas emission. Wisse (2016) critically analysed the literature and discovered that the dimension used for measuring circularity can be classified into material flow, eco-efficiency as well as their hybrids. EASAC (2016) reviewed the current macro-indicators developed by 10 advocates and 2 nations, and subsequently classified the relevant instruments into 6 broad dimensions, namely economy performance, material flow, environmental, sustainable development, organisational behaviour and societal behaviour. Elia et al. (2017) reviewed the main environmental assessment methodologies to measure the adoption of CE and classified them into 4 main dimensions, i.e. material flow criteria, energy flow, land use and consumption and life cycle. Kristensen and Mosgaard (2020) analysed and performed a data-driven coding on 30 circularity indicators and discovered that some predominant dimensions are cost-based, environmental, resource-efficiency and time based, mainly focusing on economic (monetary) aspects, with environmental and especially social aspects included to a lesser extent. Ultimately, the dimensions used in the literature are categorised into five common dimensions, namely C_1-monetary, C_2-energy and environment, C_3-material. C_4-temporal and C_5-efficiency as tabulated in Table 2.5.

Table 2.5: Circularity dimensions in review articles (Source: Author).

Source	Monetary	Energy and Environment	Material	Temporal	Efficiency
Ellen MacArthur Foundation (2015)	✔	✔	✔		✔
Wisse (2016)		✔	✔		✔
EASAC (2016)	✔	✔	✔		
Elia et al. (2017)		✔	✔		
Kristensen and Mosgaard (2020)	✔	✔	✔	✔	✔
This research	✔	✔	✔	✔	✔

Monetary represents one of the commonly employed dimensions in constructing circularity indicator, as one of the key features in CE principle is the ability to contribute to the economy prosperity while practicing CE agenda (Stahel, 2013; Murray et al., 2017). Monetary dimension encompasses all the items related to money or currency that is specifically targeting CE elements (see items shown in the Section 2.3.2). Money, or currency as used in the monetary dimension, is functioned as a common language in the world as a measure of value since it is the medium of exchanges and unit of account in daily life (Arthur, 2005). It is used predominantly in business to inform the cost and profit of a business. A business's profit is the total amount of money remaining after the company pays its costs. In the contrary, costs are the expenses involved in developing, manufacturing and selling the business's products and services (Arthur, 2005; Aiello and Bonanno, 2013). Ultimately, generating a profit is the key business objective as it is the most important source of cash flow and finance for a business in determining the success of the business. The cost and profit in this dimension are specifically associated to circularity element, such as cost in purchasing virgin and recyclable materials, cost invested in CE technology, cost of production of CE products as well as profit per unit recyclable material consumed, which would greatly influence circularity of a business.

Energy and environment dimension envelopes the items associated to the energy consumption pattern and extent of environmental pollution of an alternative. Energy is required for various industrial function such as heating or cooling the office or site, lightings, products manufacturing and logistics (Shove and Walker, 2014). Depending on the source of the energy, some energy generated are accompanied by the released of greenhouse gasses that are difficult to be assimilated or attenuated by the nature, contributing greatly to the environmental problem (Korhonen et al., 2018). One typical example of such source is fossil fuel, which is accounted for approximately 75% of the energy generated in the world. This dimension concerns with the source of the energy and the amount of that energy is being used, because excessive consumption of energy generated using fossil fuels will create environmental problem and at the same time exhausting the non-renewable resources, which greatly deviates from circularity goal (i.e., to lower or eliminate resources input and environmental pollution) (Li et al., 2010; Ellen MacArthur Foundation, 2013). Consequently, capturing the energy consumption pattern and its source is important for this dimension to ensure the consumption style will not burden the nature and negatively affecting the circularity (Ehrenfeld and Gertler, 1997; McDonough and Braungart, 2010). A supply chain that fits CE vision must monitor their performance in this dimension and ensures that it runs only on renewable energy with no energy leakage and no environmental pollution to surrounding. Besides the greenhouse gases emitted by burning of fossil fuels for energy generation, some human activities within the supply chain will also generate greenhouse gases and contribute to overall greenhouse gases. This dimension concerns on the environmental problem created by all sources of greenhouse gases, as it is the main motivation to development of CE practice (MacArthur Foundation, 2017).

Material dimension associated with the materials used in the supply chain. Material is a substance of which a thing is made or composed. In industry, material is the substances used as inputs to the manufacturing processes in producing a more complex material or a product (Cambridge Dictionary, 2021). This dimension concerns particularly with the source of materials input to the supply chain as well as the handling of the undesired output materials (i.e. waste or EOL products). A business is free to choose the source of its material input, whether from recycled products or harvested from virgin materials reservoir. Choosing to source its material from recycled products contributes directly to the two goal of CE, which will reduce or eliminate the waste in our society as well as reduce the harvesting of raw virgin materials (De Angelis et al, 2018; Mishra et al., 2018). Further, a business is also free to choose the handling method of the undesired output materials. The waste can be recycled internally to prevent material wastage or discarded as unrecoverable waste in landfill (Graedel et al., 2011; Zhou et al., 2013; Pauliuk et al., 2017). The material recoverable from waste or EOL products can also be reintegrated into forward supply chain to manufacture a new product, whether it is manufacturing of a same product in CLSC or different product in OLSC.

Temporal is next dimension that is started to gain popularity in circularity indicator construction. Temporal refers to time. It is used abundantly in measuring system to indicate duration of events, measureable in hours, days, months or years depending on the context (Bluedorn, 2002). It can be used as a basis to compare the duration of events or the intervals between them. This dimension concerns about the duration of a product would last before it reaches its EOL (i.e., product lifetime) as well as duration of a project to achive desired circularity goal (i.e., project lifetime). The CE goal for higher resources utility can be attained if a product is having a long product lifetime, because it can be retained in the consumption cycle longer, increasing its intensity of usage. Because of the long product lifetime, less raw materials are required to manufacture new products to substitute it, thus reducing raw material input. A long product lifetime would also reduce turnover of products, thus reducing material wastage (Bakker et al., 2014; Franklin-Johnson et al., 2016). This will contribute in achiving 3 CE goals (i.e., lower or eliminate waste output, resources input and to increase resources utility). Further, project lifetime is useful in indicating how commited a business is in adopting CE practices, reflecting its dedication in achieving CE goals. Temporal dimension has gradually becoming a common subject in the literature, which report the duration of the resources that are retained in the consumption cycle, ensuring they are preserved as long as possible without the needs for farming more raw materials to manufacture a new product, ultimately increasing utility of resources (Ellen MacArthur Foundation, 2015).

Lastly, efficiency is the dimension that has undisputable importance and has been frequently used in constructing the circularity indicator (Ellen MacArthur Foundation, 2015). Efficiency is the ability to avoid wasting materials, money, efforts, time and energy in doing something or in producing a desired result (Cambridge Dictionary, 2021). It can also be understood as the ability to do things successfully without creating waste. Efficiency also indicates the level of performance of a process. An efficient process is the process with capability to achieve the highest amount of output by using the least amount of inputs, thus able to minimise amount of waste, expense, or unnecessary effort (Farrell, 1957). This dimension concerns particularly with the efficiency of CE practices, such as efficiency in collecting, dissembling and recycling EOL products, seeking to achieve the highest amount of output and avoid wasting resources in producing it. Particularly, efficiency of CE related practice could reveal the level of resources that can be recovered from EOL products, which excelling in the dimension would encourage circulation and retention of resources in the SC. Further, this dimension also concerns with the efficiency of resources usage, by capturing the rental-ability of the products to indicate the possibility of the products to be shared, since a product that is less frequently used is considered a form of wastage.

Nevertheless, by referring to the column "f" in Table 2.4, only 3 indicators have included all 5 dimensions within them, while the majority of the indicators (i.e., 15 indicators) have included only 2 dimensions. This represents another gap in the circularity indicators found in the literature. It is argued that an effective circularity indicator should cover all the aforementioned dimensions to provide a holistic evaluation of the circularity of CSC.

Similar to this research, Sassanelli et al. (2019) discovered that only 44% of the circularity indicators being studied involved the use of all dimensions defined in the study, highly comparable to the findings of Kristensen and Mosgaard (2020) in the analysis of 30 circularity indicators. These results signify that there is an incomplete inclusion of dimensions in circularity indicators, which can also be observed in many research in the literature. For example, monetary dimension is highly prioritised in Stahel (2013), Murray et al. (2017) and Potting et al. (2017). However, energy and environment dimension is considered more important in Sassanelli et al. (2019) and Kristensen and Mosgaard (2020). On the contrary, material dimension is highlighted in Aguilar-Hernandez et al. (2018), Avdiushchenko and Zajaç (2019) and Sassanelli et al. (2019). Albeit low, temporal dimension has started to gain attention and has been emphasised in Franklin-Johnson et al. (2016) and Helander et al. (2019). Lastly, Efficiency dimension is particularly emphasised in De Angelis et al. (2018) and Jain et al. (2018).

Incomplete inclusion of dimensions used for circularity measurement are frequently being observed and being criticised in Blomsma and Brennan (2017) and Avdiushchenko and Zajaç (2019). Rebound effect during CE transformation will occur if incorrect evaluation of circularity measurement is made due to incomplete inclusion of dimensions, rendering the functionality and utility of CE strategies and actions (Avdiushchenko and Zajaç, 2019). This raises the mandate to include all dimensions for the circularity indicator in this research (Sassanelli et al., 2019; Kristensen and Mosgaard, 2020).

2.3.2 Circularity Items

There are many measurements that can be used to indicate circularity of a competing recycling alternative (e.g., profit per kg recycable input consumed, lifetime of product, recyclability of product etc). These measurements are known as items and can be clustered together under each dimension depending on their similarity (Su et al., 2013). Items clustered under the same dimension are more similar to each other compared to those in other dimension. It is discovered that within each circularity dimension, there are several items being commonly applied. An iterative process is used to identify the items used in circularity indicators, consisting of item description, identification and the noting down of the items that are being presented in the circularity indicators (Miyake, 1986). Each time a new item is identified, additional sources of item definitions are taken into account to create a more commonly established understanding. This proceeding can be referred to as emergent coding or inductive content analysis, which is frequently used in other disciplines and is recommended if knowledge about a research field is fragmented (Elo and Kyngäs, 2008). Once the items are fully identified, they are categorised into the 5 dimensions as described in the previous section, namely C_1-monetary, C_2-energy and environment, C_3-material, C_4-temporal and C_5-efficiency. Overall, there are 23 items that serve as building block to construct the circulairty indicator. The items are described in following section and the definitions are summarised as shown in Table 2.6.

The items within the dimension C_1-monetary are the measurements related to cost and profit that are specifically related to circularity (Arthur, 2005; Aiello and Bonanno, 2013). The cost involved is consisting of cost of virgin material (Zhou et al., 2013; Di Maio et al. 2017; Linder et al., 2017), cost for repairing (Evans and Bocken, 2013; Kingfisher, 2014), cost spent on CE technology (Cayzer et al., 2017; Garza-Reyes et al., 2018), cost spent on recycable materials (Evans and Bocken, 2013; Zhou et al., 2013; Linder et al., 2017) and cost of production (Zhou et al., 2013; Alamerew and Brissaud, 2019; Urbinati et al., 2019). The profit within this dimension is the total profit or saving made per unit recycable input consumed (Li and Su, 2012; Parchomenko et al., 2019; Pieratti et al., 2019). Particularly, the per kg cost of virgin material (C_{1a}) also has the ability to indicate the presence of scarce raw material in production, such as gold, which is not encouraged in CE (Di Maio et al., 2017). A virgin material usually has higher cost due to its limited abundancy in the world (Di Maio et al., 2017; Linder et al., 2017). Thus, consuming such virgin material in supply chain are violating the CE vision that aimed at reducing resources input into the supply chain, especially scarce resources. Cost for repairing (C_{1b}) indicates the price to repair the damaged product. According to McCollough (2014) the repairing cost that is much lower compared to cost of purchasing a new product would encourage the consumer to repair the product instead of replacing it with a new product. This will extend the usage of a product before it is discarded as waste, ensuring that the material to be retained in the consumption cycle until it reaches its designated EOL, ultimately achiveing the CE goal to reduce waste and resources input, while increasing resources utility and economic prosperity by generating new business stream (Kingfisher 2014; McCollough, 2014). Cost spent on CE technology (C_{1c}) is the money spent on installing CE related technology, such as waste recycler, disassembly robot, alternative raw materials, etc (Garza-Reyes et al., 2018). It is argued that more money spent in CE technology implies a company is more willing to participate in CE endeavour, by changing its operation and business model to incorporate CE related strategies (Cayzer et al., 2017; Garza-Reyes et al., 2018). This item can thus act as a proxy indicator to reveal the degree of CE adoption in a supply chain. Investing in CE technology would not only help to minimise waste generation and pollution, it also reduces resources input and increasing resources utility. Cost spent on recycable materials (C_{1d}) indicates the money spent in purchasing recyclable EOL product that will be recycled, where the materials are retrieved for manufacturing of new products (Zhou et al., 2013; Linder et al., 2017). Similar to C_{1c}, this item is also acting as a proxy indicator to reveal the degree of CE adoption in a supply chain, as this item indicates the willingness of a company to retrieve material from waste, thus curbing waste generation and resources input, greatly aligned with the CE goals (Cayzer et al., 2017). Cost of production (C_{1e}) indicates the cost of manufacturing a product which includes the cost for energy, electricity, water as well as administration cost (Alamerew and Brissaud, 2019; Urbinati et al., 2019). According to Kayal et al. (2019), a circular supply chain must have a production cost that is as low as possible, by generating its own energy and electricity while reusing the resources such as water. This item sheds light on how the subject being studied performs in pollution reduction (as a result of using renewable energy) as well as waste and resources input reduction, which support CE goals. Profit OR saving per kg recyclable input consumed (C_{1f}) signifies the profit made by a recycler company in selling the recycled EOL post-consumer waste or saving made by manufacturer when substituting virgin materials with the use of recycled materials (Parchomenko et al., 2019; Pieratti et al., 2019). A company that is having higher profit per unit waste implies more monetary value had been added to the waste consumed, thus maximising the value of the waste (Helander et al., 2019). Ideally, a high profit that is accompanied with low production cost indicates the ability to maximise monetary value of waste and the ability to improve resource productivity (Li and Su, 2012; Geng et al., 2012).

The items within dimension C_2-energy and environment are associated to the pattern of energy consumption and the environmental pollution accompanied with it. Particularly, the source of energy is the subject of interest in circularity measurement. CE encourages the generation of own energy on-site and not purchased from energy providers, using mainly the renewable sources (Fogarassy et al., 2017; Garza-Reyes et al., 2018; Kiselev et al., 2019). This also aligns with the EU Energy Directive, 2010/31/EU and new Directive, 2018/844/EU, which instates that any new buildings from 2020 onwards must be "nearly zero energy", which requires energy generation on-site to reduce energy demand and replacing fossil energy sources with renewable ones (Bot et al., 2019). Consequently, the first item within C_2 is fraction of energy generated using renewable sources (C_{2a}). Generation of energy onsite negates the need to purchase energy from power stations that are usually relying on non-renewable resources such as coal, fossil fuels, uranium, etc for energy generation (Bot et al., 2019; Kiselev et al., 2019). In terms of energy generation on-site, generation of energy using renewable energy sources such as solar, wind, tidal, biomass, etc is much better than generation of energy using non-renewable energy resources, as the latter still resembles a linear economy system of consumption that consumes finite resources (Yang, 2018; Liu et al., 2019). A CE oriented business harvests raw material only from the waste stream and uses only renewable sources for energy generation in all operational and logistical activities (Garza-Reyes et al., 2018; Yang, 2018). The next item within this dimension is fraction of energy loss (C_{2b}) (Li and Su, 2012; Yang, 2018; Liu et al., 2019). It indicates the energy loss in operation such as energy dissipated in unit operation or energy loss in buildings (Li and Su, 2012; Liu et al., 2019). A CE oriented business must ensure negligible energy leakage to the surroundings to denote the productivity and efficiency of energy consumed, as leakage is considered a form waste and pollution, which also heighten resources consumed for energy generation (Bot et al., 2019; Parchomenko et al., 2019). The fraction of energy purchased from renewable sources (C_{2c}) is the next item in this dimension (Pauer et al., 2019; Parchomenko et al., 2019; Urbinati et al., 2019). Unlike C_{2a}, this item concerns on the fraction of energy purchased from renewable sources such as solar, wind, tidal, biomass, etc. Some businesses within the supply chain have been established for a long time and is not subjected to the EU energy directive requirement in achvieng "nearly zero energy" for their buildings, thus they are not currently obliged to change their business routine to include energy generation on-site (Bot et al., 2019). Therefore, there are still purchasing their energy from energy providers. Nevertheless, they can opt to purchase energy from the providers that generate it using renewable sources, thus reducing the reliances on polluting power stations that rely on non-renewable resources (Parchomenko et al., 2019; Urbinati et al., 2019). Today, most of the activities carried out in businesses require electricity or energy (e.g., for transportation and heating) (Neelsen and Peters, 2011). The electricity and energy consumed are usually generated using burning of fossil fuels in power plants (Parchomenko et al., 2019), which release greenhouse gas (GHG) to the surrounding and pollutes our environment, causing global warming that leads to extinction of animal species and climate changes. The next item concern with the total GHG produced per kg product (C_{2d}), which is a by-product of consuming electricity and energy in the business. GHG, also known as Carbon footprint, is one of the widely used environmental indicators. A CE focused business must imparts negligible environmental impact such as GHG to ensure sound human health and environment wellbeing (Scheepens et al., 2016; Urbinati et al., 2019). The next item, total energy consumed per kg product (C_{2e}) indicates the total energy required to produce a unit (kg) of product (Zhou et al., 2013; Wang, 2018; Liang et al., 2018). It is used as a proxy indicator to show the efficiency of production process, as a poorly designed production process will usually have high energy consumption, which required to be re-designed to bring down the overall energy consumption (Steinmann et al., 2019). This also aligns with CE goal aiming at reducing resources input into the business. The last item, namely the total energy generated per kg product (C_{2f}), is similar to C_{2a} but complementing it by providing a full picture of the sources of energy used for energy generation (Huysman et al., 2017; Garza-Reyes et al., 2018; Pieratti et al., 2019). This is because some businesses would generate their energy on-site but using fossil fuels, which would violate the vision of CE that promotes generation of energy using renewable energy sources (Bot et al., 2019).

The items within dimension C_3-material dimension describes the source of materials input to the supply chain as well as the handling of the undesired output materials (i.e. waste or EOL products). At EOL, the EOL products can be retrieved and reintegrated into forward supply chain to manufacture a new product either via the original supply chain or the open loop supply chain. The first item, fraction of recycler output to original supply chain (C_{3a}) concerns with the amount of items retrieved via the original supply chain (upcycling); it is often thought that the quality of the waste is best preserved when it is being returned into the original supply chain, and it will deteriorate when retrieved by the foreign supply chain (Pauliuk et al., 2018; Niero and Kalbar, 2019; Parchomenko et al., 2019). The next item describes the source of materials input to the supply chain, especially the fraction of recycled material used per kg product (C_{3b}). A CE oriented business will incorporate high amount of recycled materials instead of using only virgin raw material in the product making (Wen and Meng, 2015; Cayzer et al., 2017). This action aligns with CE goal that aims at reducing waste and virgin resources input to the business, also increasing the utility of materials (Azevedo et al., 2017; Saidani et al., 2017). A business will also produce many intermediate waste that can be recycled internally or discarded, such as used water or solid intermediates (El-Hussiny and Shalabi, 2011). The following items concern with how the businesses handle intermediate waste by either recycling them internally (C_{3c}) (Graedel et al., 2011; Pauliuk et al., 2017; Willskytt and Tillman, 2019) or discarding them as unrecoverable waste (C_{3d}) (Zhou et al., 2013; Mesa et al., 2018; Grippo et al., 2019). A CE oriented business would recycle all used water or solid intermediate internally, aiming to achive CE goal that envisages waste and resources input reduction as well as improve resources utility. The business will try their best to reduce unrecoverable waste and transform them into either technical or biological nutrient that can be returned to the surroundings (Liang et al., 2018), as high level of unrecoverable waste signifies the inefficiency of a company in utilising its material resources and unmotivated in reutilising the waste as resources (Figge et al., 2018; Grippo et al., 2019). Ideally, to arrive at the aim of zero waste in CE, a high recycling rate and minimal amount of unrecoverable waste is produced in the supply chain. High fraction of recycled material must be used in unit product to ensure most of the waste are returned to the forward supply chain and be incorporated in the new product manufacturing, thus ensuring minimal waste is sent to landfill and negating the needs for raw virgin materials in product manufacturing.

The items within dimension C_4-temporal, included product lifetime and project lifetime, are measureable in months or years depending on the context (Bluedorn, 2002). Product lifetime (C_{4a}) measures the duration of material that would be retained in the consumption cycle until it reaches its EOL, giving an indication of resources utility (Franklin-Johnson et al., 2016; Azevedo et al., 2017; Bovea and Pérez-Belis, 2018). Besides increasing resources utility, material with long product lifetime also indicates that the material would remain in the consumption cycle for a longer period of time, thus its value can be retained. Further, the demand for new resources required to manufacture a new product to replace that product will also be reduced, achiving the CE goal aiming at reducing virgin resources input (Franklin-Johnson et al., 2016). The next item is project lifetime (C_{4a}), which refers to the time to reach CE goal (e.g. time planned to reach 90% recycling rate of waste water) (Kingfisher, 2014; US Chamber Foundation, 2017). This item also serves as a proxy indicator to measure commitment of a company practising CE or invest in CE technology, which could drastically shorten the time to reach CE goal. This item has also been deemed as an important aspect to boost interest of practitioner in adopting CE practices (Kirchherr, 2017).

The items within dimension C_5-efficiency describe the efficiency of CE practices in achieving the highest amount of output without creating waste (Farrell, 1957). The first item is collection efficiency (C_{5a}), which is the efficiency related to collection process, one of the core activitities in the CSC (Jain et al., 2018; Eriksen et al., 2019 ; Niero and Kalbar, 2019). The waste that is generated during the collection process and dissambling of EOL (e.g., removal of coating from collected EOL products) implies low collection efficiency, and thus reducing the useful proces output (Gou et al., 2008; Ellen MacArthur Foundation, 2015). A process with high collection efficiency will retrieve all the materials and retain them in the consumption cycle without discarding the materials as waste (Ameli et al., 2019). The collection efficiency also reveals the level of resources that can be recovered from EOL products, i.e. the circulation and retention of resources in the SC, achieving the goal of CE aiming at reducing waste and resources input as well as increasing resources utility. The next item describes the modularity of the product design (C_{5b}). Modular design is an approach towards product design that consists of distinct detachable modules for efficienct upgrading, replacement and disassembly (Gu et al., 1997). A CE oriented business must ensure that the product is designed with high modularity to increase the possibility of the EOL products with worn parts to be repaired, refurbished or remanufactured easily (Bovea and Pérez-Belis, 2018; Mandolini et al., 2018). High modularity also ensures the product can be easily disassembled at EOL, so that it can be easily broken down into components to be reused or recycled, preventing the EOL product to be discarded in landfill as a whole due to inability to separate the non-detachable modules (Evans and Bocken, 2013; Vanegas et al., 2018). This will directly contribute to the CE goal aiming at reducing waste and resources input, as well as increasing resources utility. The next item concerns with the recyclability of product (C_{5c}) (Franklin-Johnson et al., 2016; Czikkely et al., 2018; Pauer et al., 2019). This item indicates the fraction of the product that is recyclable, since not all parts of the product are recyclable (Parchomenko et al., 2019). A CE focused business will ensure that the product they manufactured is highly recyclable, so that the materials within the product can be retained in the consumption cycle and not be discarded as waste (Jain et al., 2018). This can be achieved by ensuring that no harmful additives are added to the product which render the ability of the product to be recycled (Simon et al., 2021). High recyclability ensures materials in EOL products to be successfully recovered, thus reducing waste and increasing the utility of resources. The subsequent item concerns with the recycling efficiency of the recycling process in CSC (C_{5d}). Recycling process is one of the core activities in the CSC for many products, as described in Section 2.1.3, which makes this item equally important as other items (Van Schaik and Reuter, 2016). Recycling efficiency indicates the efficiency of a recycler to produce highest amount of recycled materials without creating waste. A high recycling efficiency implies more EOL products are successfully recycled and will be retained in the consumption cycle and less materials will be discarded as waste (Mesa et al., 2018; Niero and Kalbar, 2019). This directly affects the possibility of EOL products to return to the forward supply chain successfully, and at the same time, reflects the ability of products to be retained in the consumption cycle (Ellen MacArthur Foundation, 2015). The last item within dimension C_5 describes the ability of the product to be rented or leased during its use phase, known as rental-ability (C_{5e}). The rental-ability can either be business-to-customer (B2C) and customer-to-customer (C2C) (Pei et al., 2021). Option of rental via B2C changes the ownership of the product to the business, thus ensuring that the products reaching its EOL will be returned back to the business and be treated accordingly, reducing probability of EOL to be discarded into landfill (Cayzer et al., 2017; Garza-Reyes et al., 2018; Pei et al., 2021). Option of rental via both B2C or C2C also ensures the product usage can be maximised by renting the product while it is not in use, greatly increasing resources utility and productivity (Kuhl et al., 2019). This is because a product that is less frequently used is considered a form of wastage (Saidani et al., 2017). Further, the needs of a consumer to own a product will also be reduced, thus decreasing the demand for virgin resources to manufacture more products.

Table 2.6: The items involved in circularity indicators (Source: Author).

Dimension	Items	Description
Monetary (C1)	C_{1a}: Average cost of virgin material per kg	This criterion is used as proxy indicator to reflect the scarcity of the material used in production. A higher cost indicates that a scarce resource is consumed in the production process, for example gold or rare earth metals.
	C_{1b}: Average repairing price	This criterion indicates the price to repair the damaged product. A repairing cost that is lower compared to cost of purchasing a new product would encourage the consumer to repair the product instead of buying a new product. This can extend the usage of a product before it is discarded as waste, ensuring that the material will be retained in the consumption cycle until it reaches its designated EOL.
	C_{1c}: Fraction of cost spent on CE technology to total cost of investments	This criterion indicates the money spent on installing CE related technology, such as waste recycler, disassembly robot, alternative raw materials, etc. (see examples from world economic forum: https://www.weforum.org/agenda/2017/09/new-tech-sustainable-circular-economy/). More money spent in these categories implies a company is more willing to participate in circular economy endeavour, by changing its operation and business model to incorporate CE related strategies.
	C_{1d}: Fraction of cost spent on recyclable material to total cost of material	This criterion indicates the money spent in purchasing EOL waste or recyclable product, which will be recycled and used to manufacture new products. More money spent in this category implies a company is more willing to participate in circular economy endeavour, by bringing back the waste into the supply chain.
	C_{1e}: Production cost per kg product	This criterion indicates the cost of manufacturing a product which includes the cost for energy, electricity, water as well as administration cost. A true circular supply chain generates its own energy and electricity, and reuses the resources such as water, keeping the production cost as low as possible.
	C_{1f}: Profit OR saving per kg recyclable input consumed	This criterion indicates the profit made by a recycler company in selling the recycled EOL post-consumer waste or saving made by manufacturer when substituting virgin materials with recycled materials. A company that is having higher profit per unit waste implies more value had been added to the waste consumed, thus maximising the value of the waste.

Energy and Environment (C2)	C_{2a}: Fraction of energy generated using renewable sources	This criterion indicates the energy generated within the company on-site and not purchased from energy providers. Generation of energy onsite negates the need to purchase energy from power stations that usually rely on non-renewable resources such as coal, fossil fuels, uranium, etc. Generation of energy using renewable energy sources such as solar, wind, tidal, biomass, etc is much better than generation of energy using non-renewable energy resources. A true circular economy harvests raw material only from the waste stream and uses only renewable energy (purchased or generated on-site) in all operational and logistical activities.
	C_{2b}: Fraction of energy loss	This criterion indicates the energy loss in operation such as energy dissipated in unit operation or energy loss in buildings. Lower energy loss in a company indicates an efficient use of the energy resources. A supply chain in circular economy will have negligible energy leakage to the surroundings.
	C_{2c}: Fraction of energy purchased from renewable sources	This criterion indicates the amount of energy utilised in the company that is obtained from renewable energy sources such as solar, wind, tidal, biomass, etc. Higher utilisation of renewable energy negates the needs to fire up costly and polluting power stations and reduces reliance on non-renewable resources. A true circular economy harvests raw material only from the waste streams and uses only renewable energy in all operational and logistical activities.
	C_{2d}: Total GHG produced per kg product	This criterion indicates the overall impact imparted on to the environment by the processes carried out in the company. Carbon footprint, which measures greenhouse gas (GHG), is one of the widely used environmental indicators. GHG includes carbon dioxide and methane, which cause global warming leading to extinction of animal species and climate changes. Lower environmental impact ensures sound human health and environment wellbeing. A supply chain in the true circular economy will impart negligible environmental impact to the surroundings.
	C_{2e}: Total energy consumed per kg product	This criterion indicates the total energy required to manufacture a unit (kg) of product. A high energy required to produce a product can be used as a proxy indicator to show the low efficiency production process or poorly designed production technology, which should be improved such that the energy consumption is lowered.
	C_{2f}: Total energy generated per kg product	This criterion indicates the energy generated within the company on-site and not purchased from energy providers. A supply chain in true circular economy will generate its own energy on-site to be used in all operational and logistical activities.

Material (C3)	C_{3a}: Fraction of recycler output to original supply chain	This criterion indicates the fraction of recycler output that is being fed into original supply chain (upcycling) instead of foreign supply chain (downcycling). It is often thought that the quality of the waste is best preserved when it is being recycled into the original supply chain, and it deteriorates when recycled into the foreign supply chain.
	C_{3b}: Fraction of recycled material used per kg product	This criterion indicates the fraction of product constituted of recycled material. A manufacturing company who utilises more recycled materials in the manufacturing of its product is deemed to be aligned more closely to CE, by cutting down virgin resources consumption and promoting re-utilisation of waste as a substitute of the virgin resources.
	C_{3c}: Fraction of waste recycled internally	This criterion indicates the amount of wastewater and solid waste that are generated in the company and being recycled internally. Higher amount of wastewater and solid waste recycled internally indicates the tendency of the company to embrace CE, by retaining the waste created and re-utilising it.
	C_{3d}: Total weight of unrecoverable waste per kg product	This criterion indicates the weight of waste including solid, liquid and gas that are not being recovered and emitted to surrounding landfill, sewer and air. A high value of unrecoverable waste emitted signifies the inefficiency of a company in utilising its material resources and unmotivated in reutilising the waste as resources. A company practises CE must minimise its emission leakage as much as possible, by transforming waste into either technical or biological nutrient that can be returned to the surroundings.
Temporal (C4)	C_{4a}: lifetime of products	This criterion indicates the expected lifetime of a product until it reaches its end-of-life. A longer lifetime indicates the product would remain in the consumption cycle for a longer time, retaining its value as well as reducing the demand for new resources required to manufacture a new product to replace that product.
	C_{4b}: Time to reach CE goal	This criterion indicates the time planned to reach any CE goal, for example the time planned to reach 90% recycling rate of wastewater. Time to reach CE goal can be used as a proxy indicator to show the commitment of a company practising CE or invest in CE technology, which could drastically shorten the time to reach CE goal.

Efficiency (C5)	C_{5a}: Collection efficiency	This criterion indicates the efficiency of process in collecting and dissembling EOL post-consumer products (for instance if a coating needs to be removed from the material before recycling then there will be a mass loss and waste generation). Higher efficiency implies more materials are retained in the consumption cycle and will not be discarded as waste.
	C_{5b}: Modularity of product design	This criterion indicates the extent of modularity of a product, where higher modularity increases the possibility of the product to be upgraded and refurbished, replacing any worn parts. High modularity also ensures the product can be easily disassembled at EOL, so that it can be easily broken down into constituent components to be reused or recycled, reducing disassembly time.
	C_{5c}: Recyclability of product	This criterion indicates the fraction of the product that is recyclable. Not all parts of the product are recyclable. Higher percentage of recyclability implies more parts in the product can be recycled, and can be retained in the consumption cycle and not be discarded as waste.
	C_{5d}: Recycling efficiency of recycler	This criterion indicates the efficiency of recycler to recycle the end-of-life post-consumer products. Higher recycling efficiency implies more end-of-life products are successfully recycled and will be retained in the consumption cycle and less material will be discarded as waste.
	C_{5e}: Rental-ability	This criterion indicates the ability of the product to be rented or leased to another consumers, so that its uses can be maximised, and at the same time, reducing the need of a consumer to own a product, thus decreasing the demand for more virgin resources to manufacture more products. Option to rent a product to consumers by a manufacturer also changes the ownership of the product to the manufacturer, ensuring that the end-of-life post-consumer products will be returned back to the manufacturer and be treated accordingly.

After indentifying the 23 key items that are commonly used in circulairty indicator construction via inductive content analysis, the number of items used in constructing each of the circularity indicator is determined. This is performed by inspecting each circularity indicator individually to determine how many items are involved. For example, 4 items are involved in the construction of FCI, namely C_{1f}, C_{2b}, C_{3c} and C_{3d}. The involvement of partcular item in the circularity indicator is marked with the symbol "✔" and the results are shown in Table 2.7.

According to Table 2.7, some circularity indicators consist of only 1 key item, namely eDIM and EDT. Nevertheless, the majority of circularity indicators consist of 2 or more key items. The highest amount of key items involed in the circularity indicator construction is 16. To date, none of the circularity indicators includes all 23 key items to measure circularity, which causes the circularity measurement to be biased and affecting the accurracy of measurement, signifying a gap in the literature. This research intends to overcome this limitation by including all key items in circulairty measurement, such that the circularity of the research target can be accurately reflected.

Table 2.7: The items involved in each CE-indicator (Source: Author).

C-ind	Items	C_1						C_2						C_3				C_4		C_5				
		C_{1a}	C_{1b}	C_{1c}	C_{1d}	C_{1e}	C_{1f}	C_{2a}	C_{2b}	C_{2c}	C_{2d}	C_{2e}	C_{2f}	C_{3a}	C_{3b}	C_{3c}	C_{3d}	C_{4a}	C_{4b}	C_{5a}	C_{5b}	C_{5c}	C_{5d}	C_{5e}
FCI	4						✔		✔							✔	✔							
CET	10		✔		✔						✔				✔		✔	✔		✔	✔	✔		✔
EISCE	9	✔			✔	✔	✔		✔			✔			✔		✔						✔	
CLC	4		✔												✔				✔					✔
C2C	5									✔	✔				✔		✔					✔		
ACT	7		✔	✔						✔					✔						✔	✔		✔
CEI	2				✔		✔																	
MCI	6														✔		✔	✔		✔		✔	✔	
RP	2						✔								✔									
RR	2																			✔			✔	
RI	2									✔													✔	
RDI	4																	✔		✔		✔	✔	
CC	7					✔								✔	✔		✔	✔		✔		✔		
CETUS	6							✔			✔				✔				✔			✔	✔	
CIRC	3													✔				✔				✔		
CEPI	3										✔		✔										✔	
CEIP	4			✔											✔							✔		✔
CPI	6														✔			✔		✔	✔		✔	✔
PCM	2	✔			✔																			
SCI	3														✔			✔					✔	
VRE	4	✔			✔	✔	✔																	
CP	6		✔												✔			✔			✔	✔		✔
CDG	4										✔							✔			✔	✔		
CEEI	4						✔				✔	✔				✔								
CMT	14			✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔							✔	✔		✔
CM	4																✔	✔				✔	✔	

eDIM	1																				✓			
EDT	1																				✓			
SI-CE	4																✓				✓	✓	✓	
MCSCM	7		✓		✓							✓			✓		✓	✓				✓		
EoCE	4							✓	✓	✓		✓												
PoCE	4										✓	✓				✓	✓							
CEV	2														✓							✓		
MCDA-ML	6										✓			✓	✓					✓		✓	✓	
CEI	6							✓				✓		✓		✓	✓						✓	
EE	6							✓	✓	✓	✓	✓	✓											
FWC	5						✓				✓		✓					✓				✓		
Qc	2											✓			✓									
CP	3																✓			✓			✓	
CA	6									✓	✓			✓	✓							✓	✓	
RBR	4										✓				✓			✓					✓	
CI	4					✓	✓									✓	✓							
mCE	3					✓										✓							✓	
PRmcdt	4		✓			✓	✓				✓													
SCC	2																	✓						✓
MCA	16						✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓		✓		✓	✓	✓
RE	3										✓				✓	✓								
CP	6					✓			✓	✓					✓		✓				✓			
MCE	2										✓						✓							
EE	3					✓	✓				✓													
This research	23	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

2.4 Sustainability

Sustainability has its root in forestry, where it was first used in German forestry circles in 1713, published in a book "Sylvicultura Oeconomica" written by Hans Carl von Carlowitz (Pisani, 2006). In his book, Carlowitz suggested the term "nachhaltende Nutzung", which means sustainable use of forest resources, by replacing the old trees being harvest with an equal number of young trees to maintain a balance between them.

Sustainability came to prominence in 1987, when the United Nations World Commission on Environment and Development, published its report "Our Common Future", or usually known as Brundtland report which is named after its chairman, the Norwegian prime minister Gro Harlem Brundtland (WCED, 1987; Dresner, 2008). This report urged for the protection of environment while developing the economy, by integrating sustainability into development, thus the new approach known as sustainable development, to ensure the need of present is met without jeopardising the ability of future generations to meet their own needs (Portney, 2015).

Today, sustainability is defined as the "*quality of being able to continue over a period of time*" (Cambridge Dictionary, 2021) or "*the ability to be maintained at a certain rate or level and avoidance of the depletion of natural resources*" (Oxford Dictionary, 2021). Other definitions also exist, such as "*stabilising the currently disruptive relationship between Earths' two complex systems –human culture and the living world*"(Hawken, 2007).

A common idea that converges around the definitions is to maintain the current status of a subject and the preventing it from collapsing, whether it is an institution, a business or a practice. Some typical examples are the practice to extract resources such as water, woods or oils, where the extraction of resources at a rate faster than it can be naturally replenished will produce a community starving in resources. Similarly, a business or institute with revenue consistently in red and is unable to pay the expenses will end in bankruptcy (Thiele, 2016).

Sustainability concerns the maintaining and ensuring the long-term survival of an institution, a business, or a practice, through supporting and upholding the welfare of those participants within it (Thiele, 2016). It also concerns with the welfare of other stakeholders, both in current and future generations, who become impacted by the action taken by the institution, business, or practice (WCED, 1987). The consequences of all our actions will cross border and generations, affecting everyone sooner or later. For example, the natural resources used in manufacturing the goods we used will exhaust the resources reserves and result in resources scarcity. The waste generated today while manufacturing or consuming the goods will pollute the river and soils, impact the health of our children's children. The carbon dioxide that released from energy plants, factories and our vehicles will increase the planet's temperature, causes disruption in the climate and destroys natural habitats, making the environment unsuitable for living (Pisani, 2006; Portney, 2015; Thiele, 2016).

Sustainability is described as standing on three pillars of economy, environment and society, or grounded on the "triple bottom line" (TBL) of profit, planet and people. These three pillars stand or fall together and could not exist without one another. An institution, a business or a practice cannot undermine any of the pillar while pursuing another, as there is a bottom line that must be achieve for each pillar. The concept represents a collective framework for sustainability which was proposed by Elkington (1998) in his book "*Cannibals with Forks: The Triple Bottom Line of 21st Century Business*". Because of its simplicity and comprehensiveness, this term has become widespread among academic and practitioner ever since.

The environment pillar of TBL entails the conservation of resources and ecosystems as well as preservation of pollution-free land, atmosphere and water. The economic pillar of TBL requires the efficient and responsible use of resources for the institution, business or practice, so that it can produce an operational profit to continue its operation. Social pillar is about creating opportunities and institution for people to achieve a good social wellbeing, allowing individual to access to education and human rights, which results in the wellbeing of the collective lives in organisation, community and country in the long term (Dresner, 2008; Portney, 2015; Thiele, 2016). The detailed discussions of TBL are shown in Section 2.6.1.

Carter and Rogers (2008), among other scholars, illustrated how TBL can be incorporated into supply chain management and logistics, highlighting that all the three pillars must be fully considered for supply chain to sustain in the markets. Slack et al. (2010) also emphasises the needs of TBL to be applied, so that the business is able to "*create acceptable profit for its owners*" as well as "*minimising the damage to the environment and enhancing the existence of the people with whom it has contact*".

Consequently, in a sustainable supply chain, a minimum performance must be achieved in the environmental, economic and social dimensions, in line with the notion of order qualifiers a company must fulfil before it is able to even compete for orders (Seuring and Muller, 2008). Under the influence of sustainability, the management of material, information, and capital flows as well as cooperation among companies along the supply chain, will always consider all goals from the three dimensions of sustainable development, i.e., economic, environmental and social into account, deriving from customer and stakeholder requirements (Seuring and Muller, 2008).

The goal of practicing sustainability in supply chain is to achieve sustainable development, which is defined as "*the development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs*" (WCED, 1987). Sustainability development contains two key concepts, namely the concept of 'needs' and the idea of limitation. In the first concept, the essential needs for every person in the world, especially the poor should be given overriding priority. The second concept concerns about the limitations imposed by the current state of technology and social organisation on the environment's ability to meet present and future needs (WCED, 1987).

Ever since the Brundtland report in 1987, the concept of sustainable development has been expanded from its initial framework. In 2015, the United Nations has developed 17 global goals, known as Sustainable Development Goals (SDGs), which is designed as a blueprint to achieve a better and more sustainable future for every mankind. The 17 SDGs are “No Poverty”, “Zero Hunger”, “Good Health and Well-being”, “Quality Education”, “Gender Equality”, “Clean Water and Sanitation”, “Affordable and Clean Energy”, “Decent Work and Economic Growth Industry”, “Innovation and Infrastructure”, “Reduced Inequality”, “Sustainable Cities and Communities”, “Responsible Consumption and Production”, “Climate Action”, “Life Below Water”, “Life on Land”, “Peace and Justice Strong Institutions” and “Partnerships to achieve the Goal” (United Nation Development Programme, 2020).

One example of the unsustainable consumption in supply chain lies within energy consumption. For example, global consumption of fossil fuels has increased 7.5% for oil, 24% for coal, and 20% for natural gas from 2005 to 2014 because there are only few policy attempt to limit fossil fuel consumption (Covert et al., 2016). The high demand and over consumption of fossil fuels causes the price of fossil fuels to rise, ultimately affect the cost of production of goods and delivery of services and heighten the supply chain cost. This leads to a chain reaction in the economy, increasing inflation rate and making the poor even poorer (Dresner, 2008; Portney, 2015; Thiele, 2016). The increased global consumption of fossil fuels also increases global warming, causing many environmental and health issues, which also leading to extinction of animal species, air pollution and climate changes (Pappis, 2010; Gunady et al., 2012). This example demonstrates how unsustainable consumption linked to disruption in economic, social and environmental dimensions as well as how they are associated. Consequently, it is very important for the development of cleaner, more fuel efficient and affordable energy technologies as well as renewable energy technologies to combat unsustainable consumption of fossil fuels in today’s supply chain (An et al., 2011; Niakolas et al., 2016).

This section details the concept of sustainability and how it plays a role in supply chain and how it is incorporated into logistics and supply chains in achieving SDGs.

2.5 Impact of Excelling in Circularity on Sustainability

Many studies have specified the general aim of conducting the CE is to achieve sustainability, for instance, “*…the concept has its roots in sustainable development… The overall aim is to manage all natural resources efficiently and, above all, sustainably*. (European Environment Agency, 2016)”, “*…implementation of CE approaches can be applied as a “toolbox” for achieving a sizeable number of sustainable development targets…* (Schroeder et al., 2018)”, “*…CE paradigm is being extensively explored by institutions as a possible path to increase the sustainability of our economic system…* (Elia et al., 2017)”, “*…the ultimate goal of a CE is a sustainable development…* (Linder et al., 2017)”. “*…circularity/closed-loop systems are seen as the main solution for a transformation to a sustainable system…* (Geissdoerfer et al., 2017; Ellen MacArthur Foundation, 2013)”. This notion has been supported and frequently exhibited in various research and reports.

Nevertheless, it is discovered that CE and sustainability have distinctive differences in terms of goals, prioritisation, motivation, interests and agency (Nakajima, 2000; Geissdoerfer et al., 2017; Murray et al., 2017). The goals of sustainability are open-ended with a multitude of goals depending on the stakeholders, while goals of CE is clearly aiming at eliminating all resources input and leakage out of the closed loop system (Geissdoerfer et al., 2017). Sustainability also prioritises development following triple bottom line approach, where a minimum performance is to be achieved in the environmental, economic and social dimensions while the development of CE focuses on benefitting the economy, with have priority over environment while repeatedly overlook social dimensions (See Geissdoerfer et al., 2017 for further information on motivation, interests and agency). One of the causes of the differences is the different origins of the terms, whereby sustainability is originated from environmental movements, non-profit and intergovernmental agencies, NGOS and cooperative systems while circularity is originated from different schools of thoughts like cradle-to-cradle, regulatory implementation by governments and lobbying by NGOs such as Ellen MacArthur Foundation, thus driving the differences as aforementioned. Besides the differences, it is also argued that circularity represents a necessary condition but not sufficient for a sustainable system (Nakajima, 2000).

Besides scrutinising the differences in CE and sustainability, some research studies have also provided proof that supports the trade-off relationship between CE and sustainability. For example, it is claimed that CE brings about economical sustainability, by imposing cost savings (Ellen MacArthur Foundation, 2013; Ellen MacArthur Foundation, 2015) and annual net benefits (Lawton et al., 2014; European Environment Agency, 2016). It is estimated that the material cost of USD 340–630 billion per year, which is roughly 12–23 % of current material input costs (Ellen MacArthur Foundation, 2013), as well as USD 700 billion per year, roughly 20% of the material input costs (Ellen MacArthur Foundation, 2013), can be saved in the manufacture of complex durable goods with medium lifespans and consumer goods such as beverages, foods, packaging and textiles respectively after the implementation of CE approaches. Similar estimation is performed on food, built environment systems and mobility, revealing a reduction in externality costs of up to EUR 500 million by 2030 because of the transition to CE (Ellen MacArthur Foundation, 2015). Businesses in EU-27 would also enjoy an annual net benefit around EUR 245 billion -EUR 604 billion, roughly 3–8 % of annual turnover after the implementation of CE measures (Lawton et al., 2014). Circular economy practices such as the recovery of materials, waste prevention, re-design of products range as well as changing procurement practices n sourcing for recycled and recyclable materials bring about cost savings and amplify the competitiveness of various Europe's industry (Lawton et al., 2014; European Environment Agency, 2016).

Nevertheless, some research argued that the economical sustainability is jeopardised while practicing CE. For example, it is discovered that the sourcing cost for materials in CE is too high for a very narrow profit margin (Andersen, 2007; Genovese et al., 2017; Duin and Best, 2018). The forward supply chains are often required to purchase EOL products or recycled materials from far away supplier as the sources available in the local are very limited (Genovese et al., 2017), thus incurring higher transportation cost for materials sourcing compared to virgin materials that have higher availability locally (Duin and Best, 2018). Also, the incentives to source materials recovered from EOL products are supported by government, which also possess a risk of subsidy reduction that could further heighten the sourcing costs (Genovese et al., 2017). Reverse supply chains that collected and processed the EOL products are also facing reduced profit margin, as they are forced to supply their EOL products or materials at lowered prices to nearby plants that are willing to accept them. As prospect markets that make the business feasible are limited and located at some distance away, this causes CE approach of selling EOL products and materials become impractical (Andersen, 2007). Further, recycling activities, which is one of the core activities in CE, also face financial difficulties as it is very difficult to compete with virgin materials in terms of cost and quality, making CE practice not as feasible as expected (Bellmann and Khare, 2000).

In terms of environmental sustainability, it is claimed that CE is able to minimise environmental pressures by cutting greenhouse gases (GHG) emissions (Lawton et al., 2014; Ellen MacArthur Foundation, 2015; European Environment Agency, 2016) and imposing energy and material savings (Horbach et al., 2015; Genovese et al., 2017). For example, Lawton et al. (2014) estimated that around 100–200 million tonnes of GHG emissions can be avoided annually by practicing CE measures in the food and drink, food services, hospitality and fabricated metals sectors. This figure is estimated to achieve 424–617 million tonnes over the years from 2015–2035, when more elaborated CE targets such as improved recycling of packaging and municipal waste, as well as diminishing landfill are practiced. Within food, built environment systems and mobility sectors, a prospective reduction in GHG emissions of 48 % by 2030 and 83 % by 2050 can be attained, compared with 2012 level, after practicing CE strategy, such as keeping materials in the loop (Ellen MacArthur Foundation, 2015). A positive energy and material savings can also be noticed as a result of moving towards a CE when a meta-study reviewing 65 studies on CE and employment was performed (Horbach et al., 2015). A similar estimation in reduction of GHG emissions and energy requirement can also be noticed when linear supply chain is transition into circular supply chain in ferrous Sulphate and biodiesel manufactured from waste (Genovese et al., 2017).

However, some studies disputed the findings and discovered that CE activities are more energy intensive and would be causing more material losses in the process (Allwood, 2014; Cullen, 2017; Smits and Woltjer, 2018). Some specific sectors such as paper recycling would even emit more greenhouse gases as compared to the linear economy counterpart (Allwood, 2014). A more energy intensive in CE activities has been proven in sectors such as concrete recycling (Cullen, 2017), cement production (Allwood, 2014) and fertilisers' production from manure waste (Smits and Woltjer, 2018). The extra energy required to process a lower quality of input materials in CE also offsets resource savings in concrete recycling industry, in which the effects are not compensated by the benefits it could provide. Extra minerals are also required in some sectors as utilisation of recycled waste in the production requires more chemical (Cullen, 2017; Smits and Woltjer, 2018). These findings suggest that recycling, the core activity related to CE, does not necessarily lead to environmental sustainability.

With regard to societal sustainability, it is advocated that performing CE activities are able to provide new direct jobs (European Commission, 2015; Horbach et al., 2015; Morgan and

Mitchell, 2015) and improve human health and safety (European Environment Agency, 2016). For instance, it has been projected that 500,000 jobs opportunity will be generated by practicing CE strategy, since preparation and sorting of materials for reuse or recycling as well as reverse logistics are very labour-intensive (Hansen et al., 2014; Morgan and Mitchell, 2015). This is supported by Horbach et al. (2015) who discovered a positive employment effects as a result of moving towards a CE, when carrying a meta-study reviewing 65 studies on the CE and employment. Human health and safety can also be attained when social innovation associated with CE practices such as eco-design, sharing, recycling, reuse and other developments are being exercised (European Environment Agency, 2016).

Still, some studies contested the above findings discovered that the employment effects due to transitioning to CE business is limited due to the high automation level of the CE business (Smits and Woltjer, 2018). Some theoretical findings also demonstrated that CE focuses predominantly on economic prosperity and followed by environmental quality, where social equity is being largely neglected. Overall, only 18% out of 144 definitions in the literature being analysed supported that CE brings about social benefits (Kirchherr et al., 2017). It is also being disclosed that impacts of CE on social equity remain largely unknown (Sauvé et al., 2016; Geissdoerfer et al., 2017; Murray et al., 2017). Some research even surprisingly argued that CE brings social inequalities (Frenken and Schor, 2017).

Evidently, the literature shows that the impact of the CE on sustainability is equivocal. It is discovered that transitioning to CE can be challenging from certain economic, environmental and social sustainability point of view. Overall, these findings contested the common perception towards CE. The contradicting findings as aforementioned is a result of different set of data (i.e., criteria used) and methodologies being employed in the research (European Environment Agency, 2016). The premise that suggested circularity bring about sustainability, is also argued to be contextually bounded, where it is claimed that the CE transition processes might not be beneficial to every business, since certain businesses, industrial sectors, societal groups or regions might lose while others gain the benefits (European Environment Agency, 2016; Ghisellini et al., 2016). For example, jobs in industries producing low-quality consumer goods or virgin materials, often outside Europe, might not be beneficial through the transition (European Environment Agency, 2016; Ghisellini et al., 2016).

The disputes arisen are causing the status quo of CE as well as the applicability of CE 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. The contradicting results in the literature exhibit a huge gap which motivated this research to investigate the effect of adopting circular economy strategies has on sustainability, as well as the magnitude of impact due to the transition.

The discovery of the actual relationship between circularity and sustainability and filling of this gap is utmost important because the common perception of people towards circularity having positive effect on sustainability has caused the activities pertaining to CE to be heavily promoted and adopted in the vision of realising sustainability. For example, Stewart and Niero

(2018) discovered 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) reported 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.

As a summary, the quest to discover the relationship between circularity and sustainability will refine the understanding of the effect on sustainability while practising CE agendas, stimulating additional theory-building and conceptual development. It will eventually facilitate the proper usage of CE related activities and shape the sustainable supply chain strategy in the future.

2.6 Sustainability Indicators

2.6.1 Dimension Involved in Sustainability

As aforementioned, the use of CE indicators in hoping to attain sustainability is inappropriate as it has been shown that CE does not necessarily lead to sustainability. To ensure that the recycling alternative chosen is not only circular but also sustainable, a sustainability indicator must be used in conjunction with circularity indicator in achieving the desired goal.

Unlike circularity, sustainability indicators are well studied in the literature (Neumayer, 2004; Dahl, 2012; Thirupathi and Vinodh, 2021). Some commonly used sustainability indicators were proposed by WBCSD (2000), IChemE (2002), Balkema et al. (2002), Amindoust et al. (2012) and Iacovidou et al. (2017). The commonly used sustainability indicators are shown in Table 2.8. From the table, 3 generally accepted dimensions which are common to the indicators, are S_1-economic, S_2-environmental and S_3-societal sustainability as defined in TBL in Section 2.4 (Carter and Rogers, 2008).

Table 2.8: Commonly used sustainability indicators (Source: Author).

Sustainability measurements	S_1	S_2	S_3
(WBCSD, 2000)	✔		
(IChemE, 2002)	✔	✔	✔
(Balkema et al., 2002)	✔	✔	✔
(Schwarz et al., 2002)		✔	
(Kranjnc and Glavic, 2003)		✔	
(Azapagic et al., 2003)		✔	
(Labuschagne et al., 2005)	✔	✔	✔
(Cameron et al., 2008)			✔
(UNEP and SETAC, 2009)			✔
(Kikuchi and Gerardo, 2009)			✔
(Wang et al., 2009)	✔	✔	✔
(Perkouslidis et al., 2010)		✔	
(Bernstad and la Cour Jansen, 2012)		✔	

(Amindoust et al., 2012)	✔	✔	✔
(Seuring, 2013)		✔	
(Govindan et al., 2013)	✔	✔	✔
(Wu et al., 2014)			✔
(Fang et al., 2015)		✔	
(Chong et al., 2016)	✔		
(Iacovidou et al., 2017)	✔	✔	✔
This research	✔	✔	✔

Economic sustainability is the dimension associated with the elements that reflect the ability of an institution, business or practice to produce operational profit to continue its operation. This dimension thus measures the profitability of the operation in the supply chain. Economic sustainability is crucial in not only ensuring financial viability and feasibility of the institution, business or practice, but also fulfilling broader economic objectives at the aggregated societal level. Only with a strong economic base, the institution, business or practice will possess the capability to create infrastructure and more opportunities for individuals or families to pursue prosperity. Also, with sturdy economic stability, the institution, business or practice may then able to help those who cannot meet their own needs, contributing to bridging the gap between disparities of wealth. Further, the concern for environment and social issues will also be sufficiently addressed when they have a robust economic performance (Dresner, 2008; Portney, 2015; Thiele, 2016). Nevertheless, it is not easy for a business to be profitable in this competitive economy. It is discovered that more than one third of new businesses will fail within two years, and more than half of all businesses will fail within four years. Those that can make a profit could hardly stay profitable for more than a few years (Knaup, 2005; Thiele, 2016). Conclusively, economic sustainability first starts with the concern for an institution to stay in business and approaches the issue from the inside. Because only when it can continue its operation by producing operational profit, then it can use its wealth to create a lasting effect to societies at large, extending the effect to the stakeholders beyond the institution. A society with economically sustainable businesses within it will result in workforce with sufficient incomes, thus creating continued supply of customers that can afford the living expenses within the society, ultimately producing a productive and healthy community to continue to do business, imparting a long-term effect affecting current and future generation (Doane and MacGillivray, 2001). The profitability sought by this dimension differs from traditional accounting definitions of profit. Within a sustainability framework, the "profit" aspect needs to be seen as the real economic benefit enjoyed by the host society, symbolising the real economic impact the organisation has on its economic environment.

Environmental sustainability is the dimension associated with the conservation of resources and ecosystems as well as the preservation of pollution-free land, atmosphere and water (Schwarz et al., 2002). This dimension measures the extent of resources consumption resources like energy, water and material in the supply chain operation as well as the associated pollution and impact on our environments (i.e., oceans, freshwater systems, land and atmosphere). Comprehending the environmental sustainability and impact of activities within the institution, business or practice like production and logistics is important to ensure sound environmental wellbeing. Ecologically destructive practices, such as overfishing or other endangering depletion of resources, are avoided by TBL companies. Energy, one of the key resources being consumed, is obtained primarily via burning of fossil fuels since industrial revolution. This, however, will produce a high level of air pollution that exceeds the assimilative capacity of the environment, negatively affecting our environment if it is over-consumed. Water, another key resource being consumed, has had its consumption intensified as high as four times as compared to the last decade, consuming almost half of globally available freshwater (Pisani, 2006; Portney, 2015; Thiele, 2016). This is the result of the advancement in science and technological development that increased the establishment of irrigated land, industrial area, power sector, and dam construction. Furthermore, as high as 35% of the water used is drawing on diminishing aquifers and rivers, which is projected to increase because of the population rise and the water supplies becoming polluted and unsanitary. This consumption style altered the global water cycle of water system (such as lakes and rivers), affecting their quality as well as natural habitat for aquatic animals (Shiklamov, 1998; Clarke and King, 2004; Duraiappah et al., 2005). Materials, including minerals, ores, fossil fuels and biomass, is another key resource being consumed. It is projected that as much as three times the current number of materials are required to be consumed in 2050 as compared to today. Furthermore, synthetic chemical production including fertilizers, pesticides, herbicides and domestic chemicals has also escalated tremendously since last decade. Besides emitting greenhouse gas into the atmosphere, the chemicals would gradually accumulate in the body of organisms faster than it could be eliminated, residing in the food chain and impacting our health (Emden and Peakall, 1996; Bournay et al., 2006). The over consumption of key resources causes burden to the environment by different extent. Atmosphere is polluted by released chemicals, accompanied by over-consumption of resources, such as sulfur oxides, nitrogen oxides, volatile organic compounds, airborne particulate matter, chlorofluorocarbons, which will produce photochemical smog, acid rain, greenhouse effect and ozone layer depletion. Fresh water and oceans are affected by over-consumption of freshwater, which will alter the circulation patterns of ocean currents, affecting the ocean's food supply and impacting the climate. The fresh water and oceans are also polluted by the industry effluents and urbanisation residual, making part of the population in the world do not have access to clean or safe water. Land is affected by the over-consumption of woods and extensive deforestation to produce land for agriculture and development, which result in habitat loss, in turn leading to loss of biodiversity and ultimately triggering a full or almost full extinction of humanity (Bologna and Aquino, 2020).

Societal sustainability is the dimension associated with the ability to create wellbeing of society at all levels, from individual to organisation, community and country (Dresner, 2008; Portney, 2015; Thiele, 2016). This dimension measures the impact of the supply chain operation on the quality of people's lives at all levels of society, over the entire life cycle of products and components that is circulating in the supply chain (Thiele, 2016). Wellbeing includes equity, which is the most known representatives of wellbeing within the sustainability literature (Jabareen, 2008; Eizenberg and Jabareen, 2017). Equity demands that the community provides equitable opportunities and outcomes for all the people within the diverse community, reducing the alienation of people from their living spaces, particularly the most vulnerable and poorest. Wellbeing also includes enhancement in quality of life, ensuring the basic needs of the diverse members within the community are met, including protection and security in situations of vulnerability, regardless of gender, health, age, and race (Jabareen, 2008; Eizenberg and Jabareen, 2017). For example, the businesses aligned to TBL will ensure their staff safety in the workplace and eliminate repetitive or alienating work to reduce workplace stress. They will not use child labour and will monitor all contracted companies and supply chain members for child labour exploitation. They will pay fair salaries to their workers and maintain tolerable working hours, without exploiting the community and their labour force (Hutchins and Sutherland, 2008; Vallance et al., 2011; Eizenberg and Jabareen, 2017). In the wider societal level, the businesses will consider customer safety while using their products and services. They will also consider employment impact when deciding the supply chain operation's location or outsourcing decision. They will never exploit developing country suppliers to maximise their own interest (Dempsey et al., 2011; Missimer et al., 2017). The businesses that are dedicated to the TBL will provide benefits to many constituencies and not to exploit or endanger any group of them, such as "up streaming" a portion of profit from the marketing of finished goods back to the original producer of raw materials like the farmers, via a fair trade agricultural practice (Magis, 2010). The TBL businesses would also seeks to "give back" by contributing to the strength and growth of its community with health care and education (Polese and Stren, 2000). The practice of TBL is likely to lead to improvement in workers' productivity and company loyalty, thus decreasing the likelihood of turnover and workdays lost.

2.6.2 Items Involved in Sustainability

Similar to Section 2.3.2, there are several items that are used in sustainability indicator to measure sustainability. The items can be clustered under different dimensions. as described in previous section, based on their similarity (Su et al., 2013). Like circularity, an iterative process known as emergent coding or inductive content analysis, is used to identify the sustainability items commonly used in sustainability indicator found in the literature, particularly in the context of recycling industry. However, unlike circularity, the iterative process in this section is to identify and refine the description of items so that it is more suitable to be used in this research context (Miyake, 1986). Each time an item is identified, additional sources of item definitions are taken into account to create a refined understanding of the item. Once the items are fully identified, they are categorised into the 3 dimensions as described in the previous section, namely S_1-economic, S_2-environment and S_3-societal.

The main search terms for this literature review are 'sustainability' and 'indicators'. The synonym of indicators in the search string, such as "performance", "indicators", "measuring", "metric", "assessment", "tool", "indices", "index" and "evaluation" is used to ensure richer output (Elia et al., 2017; Saidani et al., 2019; Parchomenko et al., 2019). The final search strings {sustainability} AND ({performance} OR {evaluation} OR {assessment} OR {measure} OR {measurement} OR {indicator} OR {indicators} OR {indices} OR {index} OR {metric} OR {metrics} OR {dimensions}) AND {recycling} are used in the database search, under title and abstract. The review is based on both peer-reviewed journal articles and conference proceedings in English. The databases used for the search include Science Direct, SAGE, Springer, Taylor and Francis, Wiley, Emerald and JSTOR. The publication years of the included papers ranged from year 2000 to June 2019. The included subject areas are environment, economics, social science, engineering, business and management, material, decision, and multidisciplinary science. The search identified 20 commonly used sustainability indicators that are relevant to this research context. These 20 indicators are used for emergent coding (inductive content analysis) to identfy the sustainability items used to construct the sustainability indicator. Overall, there are 12 items served as building blocks to construct the sustainability indicator. The definitions of items are described below and summarised in Table 2.9.

Dimension S_1-economic, involves items pertaining to cost and profit (IChemE, 2002; Labuschagne et al., 2005; Iacovidou et al., 2017). As mentioned in the section above, profit and cost need to be measured to reveal the real economic benefit and the impact an organisation has on its economic environment (Portney, 2015; Thiele, 2016). Eventhough there is some degree of similarity between sustainability dimension S_1-economic and circularity dimension C_1-monetary, the latter is very specific and granular in targeting CE related elements only (i.e., cost or profit related to recyclable materials or repairable products). In contrast, the items within dimension S_1-economic include more terms within it and are wider in context (Chong et al., 2016; Iacovidou et al., 2017). In sustainability, cost is generally divided into operational cost and capital cost. Operational cost (S_{1a}) is thus the first item within this dimension (WBCSD, 2000; IChemE, 2002; Labuschagne et al., 2005). It is the variable cost that is incurred periodically (i.e., monthly, annually, biannually) to sustain daily operations, including the cost of raw materials and intermediates, cost of operation, maintenance, energy, resources (material input, energy), equipment depreciation, repair, inspection, working hours, insurance, transportation, water, sewer and residual management (Balkema et al., 2002; Chong et al., 2016). Capital cost (S_{1b}) is the next item within this dimension (Wang et al., 2009; Amindoust et al., 2012; Chong et al., 2016). It is the cost that is incurred only once before the establishment of the business, including overhead cost that encompasses all the costs of planning, investment, land, equipment and setup (IChemE, 2002; Labuschagne et al., 2005). Net profit (S_{1c}) is the last item commonly used within this dimension (Labuschagne et al., 2005; Chong et al., 2016; Iacovidou et al., 2017). It represents the net value of sales deducting all expenses in administration, technology, R&D, income tax and taxation (energy, landfill, carbon) after considering all the subsidies and incentives received for planning, operation, renewable energy usage and carbon credit (Schwarz et al., 2002; Labuschagne et al., 2005). These items are the key components in the economical sustainability which must be closely monitored and excel, to ensure financial viability and feasibility of a business, to demonstrate the real economic impact of an organisation.

Dimension S_2-environment, involves items related to toxicity of emission, extent of recources consumption and renewable energy generation (IChemE, 2002; Schwarz et al., 2002; Amindoust et al., 2012). These items are commonly used under this dimension because supply chain activities mainly involve the consumption of raw materials to transform raw materials into products, emitting unwanted gaseous, water and solid waste in the process (Seuring, 2013;

Fang et al., 2015). The first item is gas emission (S_{2a}) (Wang et al., 2009; Amindoust et al., 2012; Govindan et al., 2013). Among many types of gas emission, the most widely reported gas emission is carbon emission, which is also known as global warming potential or carbon footprint (Christensen et al., 2009). Carbon emission measures the Greenhouse Gas (GHG) produced along the supply chain, which is collected in the atmosphere, subsequently containing the heat within our atmosphere that warming the globe. Global warming by every degree Celsius is estimated to cause different extent of animal extinction via various mechanisms (Root et al., 2003; Yanik and Aslan, 2018). Another frequently reported gas emission is ozone. Although ozone is important in the high atmosphere to protect against ultraviolet (UV) light, ozone at lower layer is hazardous and could damage crops and increase incidence of asthma and other respiratory problems (Azapagic et al., 2003). The next item is resources consumption (S_{2b}) (Kranjnc and Glavic, 2003; Labuschagne et al., 2005; Fang et al., 2015). It includes all the consumption of energy, water, material and land used in manufacturing products. It is frequently being employed to monitor supply chain activities and indicate sustainability. High resources consumption would imply over harvesting and could inhibit resources regeneration, causing resources to be fully depleted in the future and jeopardising the future generation to meet their own needs (Kranjnc and Glavic, 2003; Fang et al., 2015). The next commonly used item in this dimension is acidification and eutrophication potential (S_{2c}) (IChemE, 2002; Azapagic et al., 2003; Wang et al., 2009). It measures the extent of emission in the supply chain activities that would result in water acidification and eutrophication. Acidic water that leaks into the river or sea will destroy aquatic food chains as well as cause land infertility when it leaches into the soil, eventually reducing food supply (Azapagic et al., 2003). Wastewater emitted by supply chain activities especially in manufacturing could result in Eutrophication that causes algae blooming, disrupting the nature habitat of lake. This would increase the water biological oxygen demand, and cause extinction of aquatic animals in the affected lake (Balkema et al., 2002; Iacovidou et al., 2017). Like circularity, sustainability is interested in monitoring the renewable energy generation of the supply chain, as many supply chains today utilise energy generated from limited resources such as fossil fuel to sustain their daily activities. Thus, the next item within this dimension is renewable energy generation (S_{2d}) (Perkouslidis et al., 2010; Bernstad and la Cour Jansen, 2012; Iacovidou et al., 2017). However, unlike circularity, the primary motivation behind sustainability in reporting this item is to ensure that the limited supply of fossil fuels are preserved for the future generation usage, following the definition of sustainability in Section 2.4 (Wang et al., 2009; Perkouslidis et al., 2010).

Dimension S_3-societal, involves items associated with the wellbeing of workers within the company and the local citizens at a wider society level, such as working hours, working hourly wage, workers health and safety, child labour employment rate and job creation for the local community (Cameron et al., 2008). Some of these items are used internally within the organisation to indicate the wellbeing of the employees, while some are used to measure the social condition external to the business, such participation rate of external citizen. They complement each other in giving a full picture of the internal and external social condition of the stakeholders involved in the business. The first item within this dimension is job creation (C_{3a}) (IChemE, 2002; Labuschagne et al., 2005; Iacovidou et al., 2017). This item indicates the number of jobs created by the establishment of the system, measuring the wellbeing of the people at society level as a result of the company or its supply chain operation location (IChemE, 2002). Higher number of job creation will minimise unemployment rate, and consequently decreases unfavourable social conditions such as homelessness, robbery and high crime rate (Labuschagne et al., 2005; Iacovidou et al., 2017). The next item is working hours and wages (C_{3b}) (Amindoust et al., 2012; Wu et al., 2014; Iacovidou et al., 2017). It measures the ratio of average wage of the employees in the sector to their working hours (Amindoust et al., 2012). Higher value implies a good social condition, where the business maintains high pay with tolerable working hours, without exploiting the community and its labour force (Eizenberg and Jabareen, 2017). The following item concerns about the workers health and safety (C_{3c}) (Cameron et al., 2008; Govindan et al., 2013; Iacovidou et al., 2017). It uses the frequency of injuries or sick leaves taken by employees to reflect the health and safety standard in the working environment (Cameron et al., 2008). As aforementioned, the businesses aligned to TBL would ensure their staff safety in the workplace, thus maintaining low frequency of injuries and sick leaves (Hutchins and Sutherland, 2008). The next item is child labour (C_{3d}) (Wu et al., 2014; Iacovidou et al., 2017). It includes forced labour and debt bondage (to pay off debts incurred by parents) (Wu et al., 2014). Employing child labour can reduce cost significantly, which enticed many companies for such action (Banerjee et al., 2006). Nevertheless, this action is dangerous and harmful to the child and violates the child's freedom and human rights. A socially sustainable business should decouple from the unethical practice of employing child labour in return for reducing operating cost (Edmond and Pavcnik, 2005). The last item in this dimension is local citizen participation (C_{3e}) (Kikuchi and Gerardo, 2009; Chong et al., 2016; Iacovidou et al., 2017). It indicates the involvement and support of local citizen in the business' projects, such as community-led projects. A business that cares for its community will receive reciprocated care from their community (Jones, 2010), thus it can be used as a proxy measurement of business engagement towards caring their community .

Table 2.9: The common sustainability items (Source: Author).

Criteria	sustainability Sub-criteria	Description
Economy (S1)	S_{1a}: Operational cost	This item indicates the money spent to sustain daily operations, such as cost to purchase raw material, energy, water, logistics and maintenance. Operational cost, as one of the key components in economical sustainability, must be considered along with environmental and societal aspects to ensure financial viability and feasibility of a business.
	S_{1b}: Capital cost	This item indicates the overhead cost spent on equipment, land and setup of company or plant. Capital cost, as one of the key components in economical sustainability, must be considered along with environmental and societal aspects to ensure financial viability and feasibility of a business.
	S_{1c}: Net profit	This item indicates the profit made after considering the sales, subsidies deducting all the costs. Net profit, as one of the key components in economical sustainability, must be considered along with environmental and societal aspects to ensure financial viability and feasibility of a business.
Environment (S2)	S_{2a}: gas emission	This criterion indicates the gaseous waste such as greenhouse gas (GHG), ozone depletant and PM10. GHG includes carbon dioxide and methane, which cause global warming leading to extinction of animal species and climate changes. Ozone depletants such as chloro-fluro-carbon which damages the ozone layer and causes over-exposure of UV rays that would be detrimental to human health. Particulate matter (PM) less than 10 micron emitted along with gaseous waste will pollute the air and cause respiratory tract problems. Lower gaseous emission ensures sound human health and environment wellbeing.
	S_{2b}: resources consumption	This criterion indicates the resources such as water, energy, materials and land consumed by the business. Over-consumption of resources surpassing the regeneration rate causes scarcity of resources and supply risks, which leads to escalating price of commodities. Over-consumption of certain resources such as land may also cause land erosion, and over-consumption of energy, water and raw materials may worsen climate change and increase air pollution. Low resources consumption ensures sound human health and environment wellbeing.

	S_{2c}: acidification and eutrophication potential	This criterion indicates the extent of gaseous emission in the supply chain activities that would cause water, air and soil acidification, which will destroy aquatic food chains and cause land infertility, eventually reducing food supply. Eutrophication causes algae blooming, which disrupts the natural habitat of lake and causes extinction of aquatic animal in the affected lake. Low acidification and eutrophication potential ensure sound human health and environment wellbeing.
	S_{2d}: renewable energy generation	This criterion indicates a business moving away from utilising energy generated from limited resources such as fossil fuel which causes severe air pollution to using renewable energy generated from unlimited resources such as wind, water and solar with smaller environmental impact. Renewable energy generation served as an indicator demonstrating the potential of a company in supply chain to tackle environmental issue.
Social (S3)	S_{3a}: job creation	This criterion indicates the number of jobs created by the establishment of the system. Higher number of job creation will minimise unemployment rate, thus minimising unfavourable social conditions like homelessness, robbery and high crime rate.
	S_{3b}: working hours and wages	This criterion indicates the working hours required to sustain the business, considering the minimum wage in the country and average wage in the sector. Higher wages imply a good social condition.
	S_{3c}: workers health and safety	This criterion is measured using the frequency of injuries or sick leaves taken by employees to reflect the health and safety standard in working environment. Low frequency of injuries and sick leaves imply safe working environment.
	S_{3d}: child labour	This criterion includes forced labour and debt bondage (to pay off debts incurred by parents). Employing child labour can be dangerous and harmful to the child and violates the child's freedom and human rights. A socially sustainable business should decouple from the unethical practice of employing child labour.
	S_{3e}: local citizen participation	This criterion indicates the involvement and support of local citizen in the business' projects, such as attending town hall meetings and be involved with community-led projects. Ideally, the local citizens will understand and support the business and not obstruct the siting of the company based on perception of noise, hygiene, safety, handling, transport and land space requirements.

After indentifying the 12 key items that are commonly used in sustainability indicator construction via emergent coding (inductive content analysis), the number of items used in constructing each sustainability indicator is determined. This is performed by inspecting each sustainability indicator individually to determine how many items are involved. For example, 2 items are involved in the construction of WBCSD, namely S_{1a} and S_{1c}. The involvement of partcular item in the sustainability indicator is marked with the symbol "✔" and the results are shown in Table 2.10.

According to Table 2.10, some sustainability indicators consist of only 1 key item, such as Kranjnc and Glavic (2003), Azapagic et al. (2003), Cameron et al. (2008), Kikuchi and Gerardo (2009), Perkouslidis et al. (2010), Bernstad and la Cour Jansen (2012) and Seuring (2013). Nevertheless, the majority of sustainability indicators consist of 2 or more key items. The highest amount of key items involed in the sustainability indicator construction is 12. Evidently, only 1 out of 20 sustainability indicators includes all 12 key items to measure sustainability, which causes the measurement of most of other sustainability indicators in recycling industry to be biased, affecting the accurracy of measurement and signifying a gap in the literature. This research intends to overcome this limitation by including all key items in sustainability measurement, such that the sustainability of the research target can be accurately reflected.

Table 2.10: The items involved in sustainability indicators (Source: Author).

Literature	Items	Items											
		S_1			S_2				S_3				
		S_{1a}	S_{1b}	S_{1c}	S_{2a}	S_{2b}	S_{2c}	S_{2d}	S_{3a}	S_{3b}	S_{3c}	S_{3d}	S_{3e}
(WBCSD, 2000)	2	✓		✓									
(IChemE, 2002)	9	✓	✓	✓	✓	✓	✓		✓		✓		✓
(Balkema et al., 2002)	5	✓	✓		✓	✓	✓						✓
(Schwarz et al., 2002)	3				✓	✓	✓						
(Kranjnc and Glavic, 2003)	1					✓							
(Azapagic et al., 2003)	1						✓						
(Labuschagne et al., 2005)	7	✓	✓	✓		✓			✓		✓		✓
(Cameron et al., 2008)	1										✓		
(UNEP and SETAC, 2009)	2									✓			✓
(Kikuchi and Gerardo, 2009)	1												✓
(Wang et al., 2009)	6	✓	✓		✓		✓		✓		✓		
(Perkouslidis et al., 2010)	1							✓					
(Bernstad and la Cour Jansen, 2012)	1							✓					
(Amindoust et al., 2012)	8	✓	✓	✓	✓	✓	✓			✓	✓		
(Seuring, 2013)	1				✓								
(Govindan et al., 2013)	6	✓			✓	✓	✓				✓		✓
(Wu et al., 2014)	2									✓		✓	
(Fang et al., 2015)	3				✓	✓	✓						
(Chong et al., 2016)	4	✓	✓	✓									✓
(Iacovidou et al., 2017)	12	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
This research	12	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

2.7 Theoretical Underpinning of the Research

There are some theoretical and background works that have been conducted in the field, which became the basis and foundation that guide and underpin this research. Particularly, this research is built on transaction-cost theory (TCE), resources-based view theory (RBV), decision theories (DT) and knowledge-based view theory (KBV).

All the expenses incurred when buying or selling a goods or services as posited in TCE are considered in this research, such as operational costs, labour costs and logistical costs that are required to bring a goods or services to market, which give rise and facilitate exchanges in the industries (Grover and Malhotra, 2003; Horvath and Moller, 2004). Further, all the tangible and intangible resources that are responsible for providing competitive advantage in this resource deprived era, are also being pinpointed in this research. Some tangible resources that can provide competitive advantages following the Valuable, Rare, Inimitable and Organised (VRIO) framework in RBV are identified and included. This involves energy consumed, material supplies used for product manufacturing, labours and recycling equipment. On the other hand, intangible resources are the software used, knowledge and the culture of company. This research discovers how best to measure circularity and sustainability of the resources used in the ELT recycling context, such that the resources can be positioned to provide competitive advantage by being circular and sustainable (Barrutia and Echebarria, 2015; Khan et al., 2018).

In addition, decision theories guide and underpin this research to pursue for an optimal decision by studying the agent's choices (i.e. normative decision theory). This research aimed at finding tools and methodologies that can help people make better decisions in allocating resources among competing alternatives, derived from the decision theories. Uncertainty and complexity, being the crucial issue in the decision theories, is also being taken into account in shaping the research design, so as to enhance accuracy and rationality in decision-making (Alexander et al., 2014; Peterson, 2017).

Lastly, this research also built upon KBV theory by drawing the importance of knowledge in making a better and more informed decision. Partial conceptualisation of circularity and sustainability (see Sections 2.3, 2.6 and 3.2), as a result of the lack of knowledge resources, is limiting the capability of an organisation in making viable decisions. This research draws insights from KBV theory to create knowledge context and integrates it with decision theories, as a mean of sustained competitive advantage of the organisation (Grant, 2002; Gupta, 2006).

3 End of Life Tyre's Circular Supply Chain

This section focuses on reviewing the type of recycling alternatives that utilise end-of-life tyre (ELT) to manufacture new products. The reviews of all the currently available recycling alternatives in the market will be presented in Section 3.1. In the same section, the commonly used recycling alternatives in the EU will also be presented. Next, all the previous research studies that focused on the alternatives are reviewed, whereby the circularity and sustainability dimensions and items used in the research are investigated in Section 3.2. The key supply chain actors involved in the circular supply chain (CSC) are discussed in Section 3.3 as they will be involved in data collection for supply chain performance measurement.

3.1 End of Life Tyre's Recycling Alternatives

An outlook on the recycling alternative preference of ELT in EU-27 are synthesised from Pourriahi (2016) and Bermejo (2019) and is illustrated in Figure 3.1. There are 8 recycling alternatives that can retrieve the ELT and manufacture new products using the recycled materials obtained from the ELT. Among them, artificial turf represents the biggest market, which is 29% of the total recycled ELT. The retrieved ELT may also enter another supply chain that manufactures moulded objects and sports surface, where each of them represents 23% of the market share. Cement is the next major recycling alternative that is able to make use of the ELT, representing 17% of market share. Civil engineering projects also retrieve the ELT as replacement for sand and gravels, and only represent 5% of the market share. Albeit low, foundries, asphalt and pyrolysis also make use of the materials from ELT, and each of them only represents 1% of the market share.

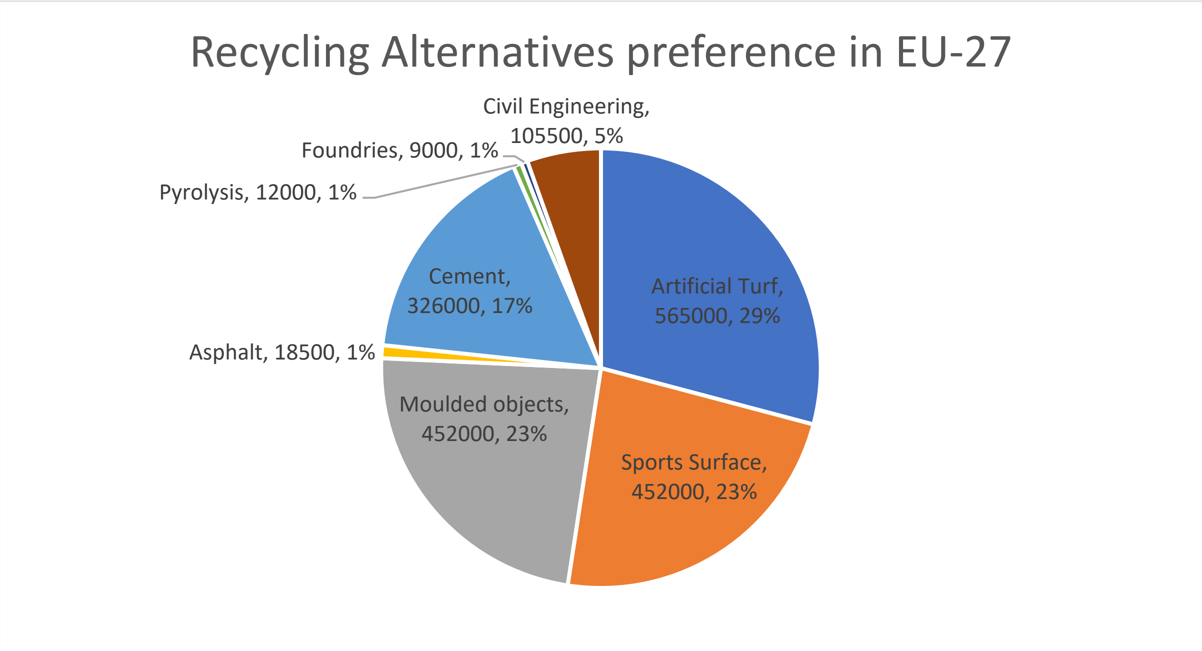

Figure 3.1: Recycling Alternatives preference in EU-27 (adapted from Pourriahi, 2016 and Bermejo, 2019).

As seen from Figure 3.1, artificial turf is the mostly used recycling alternative for ELT among the 8 alternatives, followed by moulded objects, sports surface, cement and civil engineering application, while asphalt, pyrolysis and foundries represents the least used recycling alternative. This section provides an overview of the recycling alternatives for ELT and how the recyclate of recycled ELT is used to manufacture new products, as well as their performances as compared to the products manufactured using virgin materials.

Artificial turf represents the major market that uses the recyclate of ELT. In the process of making artificial turf, the ELT is shattered into granules of 2 to 3 mm, subsequently being used as infills that fill the space between the grass-like fibres (US Environment Protection Agency, 2010; Jastifer et al., 2019). Comparing to natural grass, the artificial turf uses ELT granules as infills to replace sand are high in elasticity, providing extraordinary cushioning for the users, as well as more durable and possess high resistance towards weathering than natural grass, thus allowing it to be used in most weather conditions. Consequently, it has a longer lifetime (i.e., around 3-10 times) than the lifetime of natural grass pitches (US Environment Protection Agency, 2010; Ecopneus, 2020).

Sports surface represents the second largest market for ELT. In this process, the molten ground rubber granules reyclate of size 3-10mm is mixed with binder (e.g., polyurethane resins) to create a single surface. A coloured acrylic resin is subsequently applied above the rubber layer to increase grip (Ecopneus, 2020). Sports surfaces manufactured using ELT are resilient, flexible and durable cushioning material, compared to the wood chips, sand and gravel that are normally used to make the surfaces. Besides its ability to absorb impact, the smooth surface also makes manoeuvring on the sports surface easier compared to wood chips, sand and gravel (Shulman, 2004).

Moulded product, like sports surface, signifies the second largest market for ELT. In the making of moulded products (e.g., garden hoses, traffic cones or dustbins), the ground rubber is mixed with binder and additives in different ratio to create a semi-viscous homogeneous raw material to allow them to easily flow into a mould. The ratio differs according to the size of ground rubber, larger piece (i.e., 5 mm) would require less binder compared to finer rubber (i.e., 0.42mm to 2mm), where it is cheaper and could retain most of the characteristics of rubber, but with coarser surface texture and less bonding strength as compared to the latter or virgin rubber (US Environment Protection Agency, 2010). In the mould, the mixture is cured and cooled within a specified time and pressure, solidified into a solid product that meets defined design, shape and specifications.

Cement is the fourth largest market for ELT. In the cement manufacturing, ELT are fed continuously into kiln where 25% of the total weight of the ELT (i.e., rubber, carbon-black, sulphur, and steel) are incorporated into cement, while the rest are combusted to provide energy for the reaction (Khatib and Bayomy, 1999; Rodrigues and Joekes, 2011; Nakomcic-Smaragdakis et al., 2016).

Civil engineering application represents the fifth biggest outlet for ELT. For this application, the ELTs are shredded into small pieces (25 to 300mm), which is commonly known as tyre derived aggregates (TDA) and being used as replacement for sand and gravels in civil engineering works (e.g., foundation for roads and railways). This saves cost and provides higher safety factor than the use of sand and gravels, because of its lightweight, good thermal insulation property, high shear strength, good vibration absorption property, high permeability and it produces only half the lateral pressures on walls as compared to sand (Cecich et al., 1996; Archilleos et al., 2011; Da Silva et al., 2015). It is thus more capable to prevent the structure from sinking into the ground (Zornberg et al., 2014) and allow rain water that is collected on the structure to be drained off (Shirule and Hussain, 2015) and reduce off-site vibrations and curbing sound pollution (Li et al., 2019; Saberian and Cameron, 2019).

Foundries is a minor but increasingly more important market for ELT. In the process, ELT, which consists of 70% carbon, is used as a reducing agent that reduces metal ores to produce pure metal (US Environment Protection Agency, 2010). Nevertheless, unlike other recycling where the shredded tyre does not undergo chemical changes (also known as mechanical recycling), the ELT used in foundries undergoes chemical changes (thus known as chemical recycling), where it loses its original properties and its form, turning into irreversible carbon dioxide gas (Sahajwalla et al., 2011).

Asphalts is another minor market for ELT (Presti and Airey, 2013; Leng et al., 2018). In making asphalts, the ELT recyclates are mixed with regular asphalt concrete to produce rubberised asphalts, which is used as pavement material in road surfacing because of its high durability and ability to reduce road noise (Farina et al., 2017; Brasileiro et al., 2019).

Pyrolysis is also a small but promising market for ELT. In pyrolysis, the ELT undergoes thermal decomposition in an oxygen-limited environment, generating gas, oil, and char products with different ratio (i.e., 20-35%: 35-50%: 25-40%) depending on the temperature, pressure, and residence time of the pyrolysis process (Islam et al., 2013; Czajczyńska et al, 2017). The gas produced is used to fuel the pyrolysis process (Sathiskumar and Karthikeyan, 2019), while the oil is being sold as fuel oil or lower-value oil blend stock (Ślusarczyk et al., 2016). The carbon enriched char is sold at a higher value as solid fuel or adsorbent (Xu et al., 2020).

The 8 recycling alternatives represent all the mature recycling alternatives that are currently being commercially used in the ELT recycling industry. These alternatives retrieve ELT and manufacture different products using the recycled materials obtained from ELT. The overview above demonstrates that the different products manufactured using ELT are generally better in performance in comparison to the products manufactured using virgin materials (for examples, artificial turf, sports surface, civil engineering application, asphalts), if not then cheaper in some like moulded object, cement, and foundries. They can be used more intensively, for instance, artificial turf and civil engineering application drain rapidly, allowing quick subsequent use and thus more frequent usage during their lifetime.

Nevertheless, the discussion above concentrated on the intra-class comparison between the product manufactured using the recycled material and the product manufactured using virgin material. Still, inter-class comparison between different products manufactured using the ELT is as important but has gained limited attention in the literature. Inter-class comparison is crucial to identify the best alternative. This is more important than ever when resources are depleted to a point where the supply is less than the demand. Only the most circular alternative will be able to win the competition for resources by being more circular and sustainable.

This research is interested in comparing five recycling alternatives, where four of them (i.e., artificial turf, sports surface, moulded objects and cement) represent the largest ELT market in the EU, as shown in Figure 3.1 (Bermejo, 2019; Pourriahi, 2016). Foundry is also included in this research because it has an important emerging and promising market (Clauzade et al., 2010; Torretta et al., 2015; Jeswani et al., 2021). This is because there is an increases in demand for the advanced processors used in computers, smartphones, robotics, self-driving vehicles and artificial intelligence, which is forecasted to boost total foundry sales by 23% in 2021, as compared to the previous year (Jeswani et al., 2021). Together with the need to be more circular and sustainable, foundry industry has shifted to increase the use of more ELT in the manufacturing process, which justifies the need to include foundry in the unit of analysis.

In total, the five alternatives being studied in this research represent 93% of the market that recycled ELT to manufacture new products.

3.2 Discrepancy in Recycling Alternatives Comparison

There are very few research studies that are devoted to compare the inter-class recycling alternatives for the ELT. Nevertheless, not all alternatives are included in the studies for comparison, for instance, Schmidt et al. (2009) compared artificial turf and asphalt to cement, Kløverpris et al. (2009) compared artificial turf and asphalt with civil engineering application, Clauzade et al. (2010) and Feraldi et al. (2013) compared artificial turf, asphalt, foundries, civil engineering application and cement, Corbetta (2013) compared artificial turf, sports surface, moulded objects and asphalt to cement, Hallberg and Kärrman (2007) compared artificial turf, asphalt, cement and civil engineering application, Oostenrijk and Duuren (2011) compared artificial turf, sports surface, moulded objects, asphalt to cement, Neri et al. (2018) compared artificial turf, sports surface, moulded objects and asphalt to cement and pyrolysis, Fiksel et al. (2011) compared artificial turf, moulded objects and asphalt to cement, and finally, Ortiz-Rodrìguez et al. (2017) compared sports surface and asphalt to cement. The alternatives included in each study are summarised in Table 3.1.

Table 3.1: Alternatives included in each comparison study (Source: Author).

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	Market	Methods	Weight	Allocation model
Schmidt et al., 2009	✔			✔	✔				47%	Naïve	Equal	N/A
Kløverpris et al., 2009	✔			✔				✔	35%	Naïve	Equal	N/A
Feraldi et al., 2013	✔		✔		✔		✔	✔	75%	Naïve	Equal	N/A
Corbetta, 2013	✔	✔	✔	✔	✔				81%	Naïve	Equal	N/A
Clauzade et al., 2010	✔		✔		✔		✔	✔	75%	Naïve	Equal	N/A
Hallberg and Kärrman, 2007	✔			✔	✔			✔	52%	Naïve	Equal	N/A
Oostenrijk and Duuren, 2011	✔	✔	✔	✔	✔				81%	Naïve	Equal	N/A
Neri et al., 2018	✔	✔	✔	✔	✔	✔			82%	Naïve	Equal	N/A
Fiksel et al., 2011	✔		✔	✔	✔			✔	75%	Naïve	Equal	N/A
Ortiz-Rodrìguez et al., 2017		✔		✔	✔				41%	Naïve	Equal	N/A
This research	✔	✔	✔		✔		✔		93%	MCDM	Not equal	Yes

[1] Artificial Turf [2] Sports Surface [3] Moulded objects [4] Asphalt [5] Cement [6] Pyrolysis [7] Foundries [8] Civil Engineering

As mentioned in Section 3.1, some recycling alternatives are crucial in the recycling industry with a large market share (i.e., artificial turf, sports surface and moulded objects), while some represents a smaller market for ELT (i.e., asphalts, pyrolysis and foundries). Ideally, it is best to compare all 8 alternatives, but this is difficult as it is challenging to find a case study company that involved in all 8 alternatives and provides data for the study. However, it is important to focus on comparing the recycling alternatives that are important in the current market to ensure major recycling alternatives are being analysed. For that reason, the total market share for all recycling alternatives that are included in each study is calculated and tabulated under the column "Market" in Table 3.1. For example, Schmidt et al. (2009) compared artificial turf, asphalts and cement in their work, which cover 47% of ELT market. From Table 3.1, it can be seen that some research focuses on trivial alternatives, such as Kløverpris et al. (2009) where the alternatives being studied only cover 35% market share. The highest market covered in the research are 82% by Neri et al. (2018). This research includes artificial turf, sports surface, moulded objects, cement and foundries, which represent 93% market share for ELT, symbolising the highest market share and the most important recycling alternatives compared to the literature.

Further, in the literature, some alternatives such as artificial turf, sports surface, moulded objects and asphalt are being bundled together and considered as one alternative during the comparison, such as in Schmidt et al. (2009), Kløverpris et al. (2009) and Feraldi et al. (2013). Even though the bundling effect could include many alternatives simultaneously in a study, but it is unable to shed light on how specific alternative is better than the other alternative within the bundle, thus limiting the effectiveness of the studies. However, there are a few studies that compared the alternatives separately and individually, such as Feraldi et al. (2013), Fiksel et al. (2011) and Ortiz-Rodrìguez et al. (2017), which is more effective compared to the other studies. Separating the alternatives is important as each of them represents distinctive manufacturing processes with different supply chain that would have totally different circularity or sustainability when it comes to performance assessment. Therefore, separating them will help practitioners to visualise which alternative among the options is more circular or sustainable, making decision making more effective.

Generally, the studies mostly included artificial turf in the comparison discovered that it is the best alternative compared to other alternatives. This is because the use of recycled rubber as infill of artificial turf pitches could provide the highest environmental gains as compared to other recycling alternatives (Clauzade et al., 2010; US Environment Protection Agency, 2010; Corbetta, 2013). As a general rule of thumb, the artificial turf is found to be better than sports surface, followed by moulded objects, asphalt, pyrolysis, cement, foundries and civil engineering application. However, there are contradicting studies that find cement and civil engineering application are better than asphalt (Hallberg and Kärrman, 2007; Fiksel et al., 2011; Ortiz-Rodrìguez et al., 2017), and the cement is better than moulded products (Fiksel et al., 2011). The ranking given to each alternative is also different in each study, causes divergence of opinions in the literature and deviation from the general rule of thumb.

The discrepancy in the studies is due to two reasons. Firstly, the literature mostly relies on naïve judgement in ranking the alternatives, as shown under the column "method" in Table 3.1. The naïve judgemental method uses data obtained across multiple dimensions and items without the use of a rigorous method to analyse the data, which added another layer of uncertainty to the results. The naïve judgemental method is quick in providing result, but it is proven to be ineffective as it lacks a robust scientific approach towards analysing the data (Chen et al., 2003). This research thus intends to introduce rigorous Multi-criteria decision-making methods to analyse the data and provides a more accurate answer towards the quest to compare the recycling alternatives.

Secondly, even though circularity and sustainability dimensions and items are mainly used to compare recycling alternatives, the conceptualisation of the circularity and sustainability within the studies are fragmented, resulting in different dimensions and items to be used in the literature. The dimensions and items used within each study is tabulated in Tables 3.2 and 3.3. It is discovered that within circularity, most of the studies concentrated on the use of items from C_2-energy and environment dimension while other items from other dimensions are rarely used. Within C_2-energy and environment dimension, C_{2d}-total greenhouse gas produced is the most frequently used item, which is used in all studies, followed by C_{2e}-total energy consumed which is used sparingly in Schmidt et al. (2009), Kløverpris et al. (2009) and Hallberg and Kärrman (2007). Only one study uses the item from C_3-material dimension, namely C_{3d}-total weight of unrecoverable waste in Fiksel et al. (2011) and only one study uses the item from C_5-efficiency dimension, which is C_{5c}-recyclability of product in Oostenrijk and Duuren (2011). The reason why C_2, particularly C_{2d}, is receiving vast attention, is because it is an indicator that has many calculators or software tools that are commercially available (Clauzade et al., 2010). This allows quick set- up and implementation, ensuring that data can be collected and analysed within a short time span, guaranteeing fast research outputs. The commercially available guidelines or frameworks, also ensuring the analysis using C_{2d}, are acceptable for wide audience range. In contrast, other dimensions or items are not being used widely, thus no commercial calculators or softwares were designed for them. Consequently, they are overlooked by most of the researchers.

Within sustainability, most of the studies concentrated on the use of items from S_2-environmental dimension while other items from the other dimensions are rarely being considered. Within S_2-environmental sustainability, S_{2a}-gas emission is most predominantly used, including the emissions of Photochemical, ozone, smog, carcinogen, PM 10 and carbon dioxide. S_{2b}-resources consumption, including iron ore and water consumption, is the next mostly used item within environmental sustainability, which can be found in Schmidt et al. (2009), Kløverpris et al. (2009), Feraldi et al. (2013), Corbetta (2013) and Neri et al. (2018). S_{2c}-acidification and eutrophication has also have similar frequency of usage in the studies, as shown in Schmidt et al. (2009), Kløverpris et al. (2009), Feraldi et al. (2013), Fiksel et al. (2011) and Ortiz-Rodrìguez et al. (2017). Only one study uses the item from S_1-economy sustainability, which is C_{1a}-operational cost in Oostenrijk and Duuren (2011), and one study uses the item from S_3-social sustainability, namely S_{3a}-job creation in Corbetta (2013). The same reason for why C_{2d} is receiving immense interest as previously mentioned in circularity, is applicable here for sustainability. They are many calculators or software that are commercially available for the indicator S_2, particularly S_{2a} (Clauzade et al., 2010). This drives the use of S_2, particularly S_{2a} within sustainability. Besides, some items that involved cost and profit, such as S_{1a}, S_{1b}, S_{1c} and S_{3b} are usually very sensitive and thus not being widely used (Opriel et al., 2021). Certain items are also not usually being recorded in businesses, such as S_{2c}, S_{3a} and S_{3d}, which have rendered their uses in research.

It can be seen that there is an unbalance and partial use of items within circularity and sustainability. Most of the studies consider only a single domain of circularity or sustainability in their study. Within circularity, the studies generally tend to use items from energy and environment dimension compared to other dimensions such as monetary, material, temporal and efficiency. Within sustainability, items from economy and social sustainability are found to be underutilised as compared to environmental sustainability. The reason of why there is an exceptionally unbalance and partial use of items in ELT recycling alternatives comparison is because of the difficulty in obtaining data across the whole supply chain and whole product life cycle, which is also a great hindrance shown in many research (Arbulu et al., 2013; Elrod et al., 2013). Further, some data such as monetary or economical metrics are very sensitive, where company are usually reluctant to share (Opriel et al., 2021). Besides, the research studies that are dedicated to comparing recycling alternatives are also very limited and are usually offering a slight improvement that benchmarks against the previous research, which are also explaining the slight increment of items used within circularity and sustainability criteria over time.

This illustrates a research gap in the literature, where the unbalance and partial use of items within circularity and sustainability could render the fairness of comparison among alternatives. Apparently, conflicting results are produced when this partial approach is employed, which will ultimately mislead decision-makers or policymakers. Furthermore, the actual circularity and sustainability of each alternative will also not be reflected, which will obscure the uptake of circularity and sustainability practices within the industry.

Hence, this research intends to challenge such partial approaches to assess the alternatives once again by incorporating all key circularity and sustainability dimensions and items obtained via literature review, by using a more rigorous multi-criteria decision-making methods to analyse the data. Further, to enable the inclusion of all possible circularity and sustainability dimensions and items in this research, it is proposed that qualitative data should be used as a substitute to the actual numerical data (e.g., very high, high, very low, low), which not only reduces data collection time, but also ensures that the data that is not currently being reported in the company or data that are too sensitive to be revealed to the public can be sufficiently estimated and shared. Furthermore, some data are not qualitative in nature and not possible to be quantified, can also be captured when qualitative data is used.

Table 3.2: The sustainability dimensions and items used in comparing the alternatives (Source: Author).

Source	Sustainability											
	S_1			S_2				S_3				
	S_{1a}	S_{1b}	S_{1c}	S_{2a}	S_{2b}	S_{2c}	S_{2d}	S_{3a}	S_{3b}	S_{3c}	S_{3d}	S_{3e}
Schmidt et al., 2009				✓	✓	✓						
Kløverpris et al., 2009				✓	✓	✓						
Feraldi et al., 2013				✓	✓	✓						
Corbetta, 2013				✓	✓			✓				
Clauzade et al., 2010				✓								
Hallberg and Kärrman, 2007				✓								
Oostenrijk and Duuren, 2011	✓			✓								
Neri et al., 2018				✓	✓							
Fiksel et al., 2011				✓		✓						
Ortiz-Rodrìguez et al., 2017				✓		✓						
This research	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 3.3: The circularity dimensions and items used in comparing the alternatives (Source: Author).

Source	Circularity																						
	C_1						C_2						C_3				C_4		C_5				
	C_{1a}	C_{1b}	C_{1c}	C_{1d}	C_{1e}	C_{1f}	C_{2a}	C_{2b}	C_{2c}	C_{2d}	C_{2e}	C_{2f}	C_{3a}	C_{3b}	C_{3c}	C_{3d}	C_{4a}	C_{4b}	C_{5a}	C_{5b}	C_{5c}	C_{5d}	C_{5e}
Schmidt et al., 2009										✓	✓												
Kløverpris et al., 2009										✓	✓												
Feraldi et al., 2013										✓													
Corbetta, 2013										✓													
Clauzade et al., 2010										✓													
Hallberg and Kärrman, 2007										✓	✓												
Oostenrijk and Duuren, 2011										✓													
Neri et al., 2018										✓													
Fiksel et al., 2011										✓						✓							
Ortiz-Rodrìguez et al., 2017										✓											✓		
This research	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Besides, Table 3.1 also shows that weight (i.e., the relative importance of each dimension and item) is assumed to be equal in the studies, which would lead to infeasible suggestion and inaccurate decision-making. It has been strongly suggested against using dimensions and items with equal weight in the decision-making process, as it would render the accuracy of the decision-making (Saaty, 2008; Peterson, 2017). This represents another gap in the literature which this research intends to address.

In addition, Table 3.1 also shows that there is no resources allocation being modelled in the studies. These studies proposed some "best recycling alternative" for the ELT without considering the actual demand for resources and its constraint (Kløverpris et al., 2009; Fiksel et al., 2011; Feraldi et al., 2013). It is also being strongly advised against the proposal of decision-making model that does not consider demand and constraint because of its existence in reality (Kornai, 1979; Fawcett and Pearson, 1991). This represents another gap in the literature which this research intends to address by investigating how best to allocate the ELT among the several contending recycling alternatives to maximise circularity and sustainability, considering various demand for resources and its constraint.

3.3 Key Supply Chain Actors in CSC

Lately, CSC has received a lot of attention. CSC highly involved CE thinking in all core activities (De Angelis et al, 2018; Mishra et al., 2018; Farooque, 2019). To accurately assess a CSC's circularity, all the main actors' performance, both in the forward supply chain and reverse supply chain should be evaluated (Jain et al., 2018; Moraga et al., 2019). The main actors in a CSC are manufacturers, users, collectors and recyclers who contribute mostly to the material recycling and reuse as well as waste reduction (Farooque, 2019). Since logistics is involved in all stages of CSC and carried out individually by each CSC actor, it is not considered as a main actor but a function encompassed in each actor. Sales channel such as retailer or distributor are not being considered as a main actor in CSC as their contribution towards the circularity is very limited from perspective of resources productivity (Jain et al., 2018).

The main actors in forward supply chain of the CSC are manufacturers and users. The manufacturers involve in the planning, sourcing and making of products that fit circular vision (Jain et al., 2018). They must ensure the products being manufactured are designed for disposal, such that its constituent materials are recyclables (design for recycling) and easy to dissemble (design for disassembly), to warrant substantial recovery of resources from the post-consumer products (Holt and Barnes, 2010). The manufacturers also have the most intense use of resources and waste generation in the supply chain. By committed to CE strategies, the manufacturers will contribute tremendously to the overall circularity of the CSC.

Users are also one of the most important CSC actors that contributes to the success in transition towards CE (Lofthouse and Prendeville, 2017; Wastling et al., 2018; Selvefors et al., 2019). The users' behaviour towards accepting CE products as well as adopting CE practices (e.g.:

minimise waste and prolong the usage of products by sharing, repairing, maintaining and refurbishing) will significantly improve the circularity of CSC via resources retention. This is being exhibited in many research studies, including Webster (2017) who emphasises the power of users via inner circle mechanism: '*tighter loops, those closest to the original product serve best value … while outer loops … provide less value*'. To date, the inclusion of users in performance measurement in a CSC is made possible via digital technologies such as the Internet of Things. Some measurement items that can be used on users are C_{2d}- GHG produced per kg product, since the GHG produced, is different from user to user depending on the consumption pattern (e.g., driving style affecting GHG produced by cars (Webster, 2017)). Similarly, C_{4a}- lifetime of product and C_{5e}- rental-ability are also greatly influenced by the consumption pattern of the users. Users that are more vigilant when using a product, would significantly extend the lifetime of the product and its ability to be rented.

The reverse supply chain of CSC consists of collectors and recyclers. The post-consumers waste from forward supply chain will be recovered and reintroduced into the supply chain by a collector. Consequently, the collectors play a very important role in CSC as they are the initial point of the reverse logistic cycle (Gou et al., 2008; Isernia, 2019). They play a decisive role in deciding the flow of collected waste, affecting the value of the waste (Nasr and Thurston 2006; Özceylan, 2016). Their efficiency also directly influences the final amount of the post-consumers waste that could be successfully reintroduced into the supply chain (Ellen MacArthur Foundation, 2015). The post-consumer waste recovered by the collector will then be recycled into components, before being used by the manufacturer.

The recycler forms the heart of the CE system, which has the potential to reduce the amount of material going to the landfill and displace primary production (Van Schaik and Reuter, 2016; Zink and Geyer, 2019). Since no raw materials will be harvested from the Earth in a mature CSC, the recycler will displace the supplier and plays the role of supplying the raw materials to the forward supply chain (i.e., manufacturers and users) using recycled post-consumer products. This is especially important in the future when the finite natural resources are being fully consumed and materials are ought to be recovered from EOL products. Thus, the traditional role of supplier will disappear and be replaced by recyclers.

It is shown that each individual actor has its own goals, performance indicators and optimisation criteria (Chan et al., 2003; Aramyan et al., 2007; Jain et al., 2018). By focusing on measuring and improving performance of one core actor and neglect others will compromise the overall performance of the SC (Van Hoek, 1998). In addition, certain items used in circularity measurement are also specifically applied to certain manufacturers (Parchomenko et al., 2019) or recyclers (Van Schaik and Reuter, 2016). Evidently, Sassanelli et al. (2019) reviewed 45 CE-indicators and discovered that almost half of them do not target all supply chain actors. Nevertheless, the literature has shown that these phenomena are indeed exhibited in the existing supply chain, where attentions are concentrated on the core actors such as manufacturers while other SC actors are unintentionally omitted, which is strongly being advised against due to the some compromises and disadvantages (Jain et al., 2018). This also justifies the necessity of using all circularity and sustainability dimensions and items for this research, as different dimensions and items are used to measure the performance of different supply chain actors. The use of all circularity and sustainability dimensions and items will involve all the supply chain actors in measurement, thus effectively avoiding and circumventing the pitfall of over focusing on certain supply chain actors such as those in the literature shown in Section 3.2.

4 Research Method and Methodology

This research follows the common procedure of research paradigm according to Patterson and Williams (1998), Saunders (2012) and Bell et al. (2018) in designing the research. The research philosophical stance will first be established and followed by the selection of research strategy and its corresponding research approach. The identification of research philosophical stance, facilitated by ontological, epistemological and axiological assumptions, before research is conducted is important, as it determines the eventual choice of the research design (i.e., research strategy, research approach and methods of data collection and data analysis) (Bell et al., 2018).

4.1 Research Paradigm

4.1.1 Research Philosophical Stance

Research philosophy refers to "*a system of beliefs and assumptions about the development of knowledge*" (Saunders, 2012). There are four major research philosophical stances related to business studies, namely pragmatism, positivism, critical realism, and interpretivism (Saunders, 2012; Bell et al., 2018). The four research philosophical stances differ from each other based on ontological, epistemological and axiological assumptions (Bell et al., 2018). The set of assumptions will constitute a credible research philosophy, which underpin researchers' methodological choice, research strategy and data collection techniques and analysis procedures, and essentially, these assumptions shape all their research projects. Nevertheless, there is no single 'best' research philosophical stance to be used in business and management research as each philosophical stance contributes to a unique and valuable way of seeing the organisational world (Saunders, 2012; Bell et al., 2018).

Since all research philosophical stances make three major types of assumption (i.e., ontological, epistemological and axiological assumption), this section gives an introduction on the possible ontological, epistemological and axiological assumptions before describing the four research philosophical stances in details.

Ontology can be defined as "the science or study of being", which concerns with the assumptions about the nature of reality. The ontological assumption will determine the researcher's view of the nature of reality or being since different research is founded based on different belief about what the truth is. The perception towards reality is thus shaping the potential of one to know about reality and their subsequent action studying it, as well as how the research object or phenomenon is being approached (Thomas and Hardy, 2011). There are two very important ontological positions, namely objectivism and subjectivism/ constructivism (Bell et al., 2018). Objectivism is an ontological position indicating that social phenomena (and subsequently their meanings) have an existence which is independent of all social actors, as well as their beliefs, theories, behaviours and is context free. Objectivists believe one truth exists and will not change, and it continues to exist even it is not yet known. Reality is thus free from any context and can be generalised, and it can be transferred to all available contexts (Saunders, 2012;; Bell et al., 2018). Subjectivism, on the contrary, portrays the ontological position opposites to the objectivist. A subjectivist claims that social phenomena (and their meanings) are highly dependent on social actors and are continually being accomplished by the social actors depending on their unique perceptions and actions. The subjectivist thus believes in multiple versions of reality and truth, depending on the meaning and experience one undergoes, because reality is only created by how social phenomena are perceived, which may evolve and change depending on experiences. Reality is thus context bound and cannot be generalised, where it can only be transferred to another similar context.

Epistemology, on the other hand, deals with the study of knowledge, and concerns with the assumption of what constitutes valid and acceptable knowledge (Bell et al., 2018). The concern lies on the sources, nature and limitations of knowledge in the field of study. The legitimate types of knowledge that are mostly used include numerical data, visual data, textual data, facts, interpretations, narratives, stories and even fictional accounts (Saunders, 2012). The epistemological assumptions being made will then determine the different contribution to knowledge one's research can make. There are three very important epistemological positions, namely positivism, realism and interpretivism (Bell et al., 2018). Positivism is an epistemological position which is informed by an objectivist ontological position. Since the objectivist believes that the truth can be discovered via objective measurements through observable mediums and measurable facts, as a result, facts and numbers are considered as good quality data and acceptable knowledge, mimicking that of experimental research in physical sciences. Ultimately, law-like generalisations about the social reality are usually made and contributed to the body of knowledge. Realism is another epistemological position that shares two features with positivism, believing that one truth exists and same approach to data collection for natural science should be applied to social science. Interpretivism is a contrasting epistemological position to positivism, which is underpinned by a social subjectivism ontological stance. Interpretivism focuses on the subjective meaning of social actions because of the different perceptions between social actors. Consequently, opinions and narratives that are collected via social phenomena are considered as acceptable knowledge, where subjective meanings are being harvested, as well as all the fine details of a situation and the motivation behind it. As a result, individual or context bounded conclusions are usually being made and contributed to the body of knowledge (Saunders, 2012; Bell et al., 2018).

Axiology refers to the role of values and ethics within the research process, concerning the values created by the research. Particularly, it concerns with the value created for both the researcher and the research participants (Patterson and Williams,1998; Saunders, 2012). There are also two important axiological positions, namely positivism and interpretivism (Patterson and Williams,1998). Positivism is an axiological position that commits to value via explaining and predicting social phenomena. On the contrary, interpretivism is an axiological position that commits to value by communicating, interpreting and understanding social phenomena (Patterson and Williams,1998; Saunders, 2012).

The following section discusses how the four research philosophical stances made different ontological, epistemological and axiological assumptions (Niglas, 2010).

Positivism is a philosophical stance that involves working with quantifiable and observable social reality to produce law-like generalisations, and its ontological assumption is leaning towards objectivism. The research methods are designed to produce pure facts and data (rather than impressions) that are uninfluenced by human bias or interpretation, shaping its epistemological assumption towards positivism, and to focus on discovering measurable and observable facts and regularities. A positivist often posits that meaningful and credible data can only be obtained from phenomena that are observable and measurable. The positivist will remain detached and neutral from the research and data to avoid interfering and distorting the findings (Bell et al., 2018). Unlike interviews, where the researchers usually use their own judgement to alter interview questions to collect rich and valuable respondent-led responses, a highly structured questionnaire will usually be administered to the respondents in a positivism research method. This is because the answers given by the respondents in questionnaire will not be influenced by the researcher. As a result from this philosophical stance, positivist researchers are likely to use a highly structured methodology to avoid disturbance in data collection, and to facilitate replication (Gill and Johnson, 2010). Further, quantifiable observations will be emphasised, leading to the use of a range of statistical analysis.

Interpretivism, on the contrary, is a philosophical stance that views humans differently from the physical phenomena, as human can create meanings, which are the subject interested by an interpretivist. Humans are viewed differently than physical phenomena because social experiences and meanings are constantly being made by different people from different cultural backgrounds, under different time and circumstances. Therefore, interpretivists condemned a formulation of universal laws or law-like generalisations of truth that apply to everybody. Rather, they believe that multiple realities exist due to the complexity that arise in different contexts, thus its ontological assumption is coined as subjectivism. Interpretivist research aimed at creating richer and new understanding of social world in different contexts, from the perspectives of different groups of people, such as organisational roles, gender of employees or customers, ethnic, geographical location and cultural backgrounds. Interpretivists believe that these different groups of people may experience services, workplaces or events in different ways, where law-like generalisation of these experiences is impossible. The epistemological assumption is leaning towards interpretivism, where an interpretivist would favour personal experiences associated with feelings, observations and senses rather than data, to explore the fine details of a situation and the motivation action and reality behind it (Bell et al., 2018).

Realism, which is the philosophical stance between the two extremes, focuses on exposing the reality that shapes observable events, and explaining what is experienced throughout the events. The ontological assumption is leaning towards objectivism, where realists see reality as independent and external to social actors, but it is not directly accessible through our observation and knowledge of it. Unlike in positivism epistemological assumption, where a reality can be directly measured and tested, the reality as viewed by a realist can only be attained after “reasoning backwards” from the experiences underwent by the social actors

(Reed, 2005). Thus, a critical realist research focuses on explaining the events being studied by inspecting the mechanism and reasons via an in-depth historical analysis of social structures. The epistemological assumption is leaning towards realism, where the knowledge gathered is historical situated and generated specifically in the past, where social accounts are required to re-construct the social facts (Bhaskar, 2010). This indicates that the causality cannot be examined via a quantitative method or a statistical correlation.

Pragmatism, on the other hand, recognises different ways of interpretation of the world phenomena, where no single philosophical stance alone can give a real picture of the investigated phenomena. A pragmatist views adoption of one philosophical position as unhelpful, where its ontological assumption can change as they might be one, or potentially multiple realities in the world. The research problem and the research question will then be the most important determinant for the research design and strategy, where no specific ontological or epistemological stance will be employed. Any research design and strategy will be chosen depending on practical outcomes, disregard of the ontological or epistemological stance (Nastasi et al., 2010). At such, the pragmatist uses one or mixture of methods to enable reliable, credible and relevant data to be collected that advance the research (Kelemen and Rumens, 2008).

As a summary, the research philosophies, taking the view from three different research assumptions (i.e., ontology, epistemology and axiology) are summarised as shown in Table 4.1.

Table 4.1: Research philosophy, taking the view from ontological, epistemological, and axiological assumptions (Source: Author).

	Research Philosophy			
	Positivism	Interpretivism	Realism	Pragmatism
Ontology	External fact, Singular reality	Socially constructed, Multiple realities	Independence of human thoughts	Complex, Singular and multiple realities
Epistemology	Scientific method, Measurable fact, Casual relationship, Law-like results	Details of the situation, Subjective understanding of actions	Observable phenomena can provide credible data, Continually research	Practicality, Problem solving
Axiology	Explain/Predict social entities	Communicate/Understand social entities	Interpret/Understand social entities	All
Research strategy	Quantitative research	Qualitative research	Quantitative or qualitative research	Quantitative and qualitative research
Predominant data collection technique	Rigorously structured questions: large sample size survey, structured questionnaire	Interactive and non-standardised: small sample size interview	Mixed	Mixed
Predominant data analysis procedure	Graph/Statistics	Categorising data/coding	Mixed	Mixed
Research approach	Deductive	Inductive	Deductive or Inductive	Deductive or Inductive depending on research questions.

4.1.2 Research Strategy

In general, there are three research strategies, namely quantitative research, qualitative research and mixed methods research. Quantitative research emphasises on data collection technique or data analysis procedure that generates or uses numerical data, which is generally associated with positivism research philosophical stance. In contrast, qualitative method emphasises on data collection technique or data analysis procedure that generates or uses non-numerical data such as words, images or video clips, which is generally associated with interpretivism research philosophical stance. Mixed methods combine both quantitative and qualitative research in different combination to arrive at a richer research output. The approach to research strategy underpinned by different philosophical stances is shown in Table 4.1.

Quantitative research is generally associated with positivism philosophical stance, where a highly structured and predetermined data collection techniques are often employed. Quantitative research may also be used within the realist or pragmatist research philosophy when deemed suitable. It usually uses a deductive theory development approach, focusing on using data to test a proposed theory that is developed from reading of the academic literature, by verifying or falsifying it. In the deductive approach, the causal relationships between concepts and variables are sought and explained. A highly structured methodology is usually employed to facilitate replication and ensure reliability. The concept is thus operationalised to enable facts to be measured, often quantitatively (Bell et al., 2018). However, in rare circumstances, inductive approach would also be used (see details in qualitative research below), where data are employed to develop a theory. Quantitative research measures variable numerically and analyses them using various statistical techniques to reveal relationship between the measured variables. Due to the nature of epistemological assumption, quantitative research often employs probability sampling on vast amount of research target (or respondents) to produce generalisable results. As a result, questions are often expressed in such a way that are understood in the same way by each participant. Surveys and experiments are usually used in quantitative research. The former is normally conducted using questionnaires or structured interviews (or structured observation). The strength of quantitative research design lies in the abilities to produce a generalisation that represents the whole population without the need to study whole population, and is generally less time consuming. However, its limitation includes the risk of missing out important phenomena that are occurring.

Qualitative research, on the other hand, is associated with interpretivism philosophical stance (Denzin and Lincoln, 2011). Like quantitative research, qualitative research can also be incorporated within realist or pragmatist philosophical stance when deemed suitable. Qualitative research is associated with subjectivism ontological assumptions that assume different multiple versions of reality exist, where researchers are required to understand the phenomenon being studied and the meaning constructed through the social study subjectively. Inductive approach to theory development is usually being used in qualitative research, where emergent research design is employed to generate theory (conceptual framework) or contribute a richer theoretical perspective to the current body of knowledge, by exploring a phenomenon. In the inductive approach, research will start by interviewing a group of the respondents and followed by the formulation of theory after analysing the interview data. In social study, it is argued that human should not be treated as an object that responds in a mechanistic way, but rather, they respond differently depending on the social experience they have. It is thus viewed that new theory may emerge using inductive approach, when studying the respondents under different context and different social experience, which are often impeded by the limits set by the highly structured research design in deductive theory development (Bell et al., 2018). Nevertheless, some deductive approach will still be used in some qualitative research strategies in rare circumstances to test an existing theory using qualitative procedures (Yin, 2009). Qualitative research uses various data collection techniques and analytical methods to study meanings and responses put forward by the participants and the relationships between the responses. Unlike quantitative method which employs rigorously structured questions in data collection, qualitative research employs an interactive and non-standardised data collection method. The questions and procedures are usually altered or emerged during the research process, so that richer and more complete responses could be sought. The strength of qualitative research design lies in its ability to produce an in-depth study on case study in response to specific context. However, its limitation is on its ability to produce a generalisation that is applicable to describe the whole population, and its low credibility due to the biasness that might be introduced to the research caused by the intervention of researcher.

Mixed research is a research strategy that combines the use of qualitative and quantitative research, resulting in a mixture of data collection techniques and analytical procedures. Mixed research strategy is usually incorporated in realism and pragmatism research philosophical stances, where both qualitative and quantitative research are valued equally. Both deductive and inductive theoretical approaches may be used in mixed methods research, sequentially following one another. This approach is known as abductive theory development, in which research would start by theory generation in a conceptual framework from data collected, and the theory is subsequently tested through additional data collection (Suddaby, 2006; Bell et al., 2018). Nevertheless, this method will take longer to complete. It is also relatively riskier as there may not be any useful data or theory that would emerge. In mixed research, different combination of qualitative and quantitative research, as well as the extent of combination are allowed. The research can be conducted either concurrently or sequentially. The differences in the combination, timing of data collection phases and priority given to research methodology (i.e., either quantitative or qualitative) will thus give rise to a number of mixed methods research (Creswell and Plano Clark, 2011; Nastasi et al., 2010). The variations emerged due to the different combination are known as concurrent, sequential exploratory, sequential explanatory, and sequential multiphase mixed methods research design. Concurrent mixed methods research uses both qualitative and quantitative methods in the same phase of data collection and analysis, interpreting the results and concurrently producing a more comprehensive answer to the research question, as compared to the use of single method design. Sequential exploratory research design, sequential explanatory research design and Sequential multiphase research design involve more than one phase of data collection and analysis, and therefore will take a longer timescale for research in comparison to concurrent mixed methods research. Sequential exploratory research design is used to test qualitative exploratory findings, prioritising the qualitative method in phase 1 exploratory approach, and complemented by quantitative method in phase 2. Sequential explanatory, on the contrary, is used to explain quantitative results, where priority is given to quantitative method in phase 1, complemented by qualitative method in phase 2. Sequential multiphase involve more than two phases, using different combination of research design to further elaborate or expand on the initial findings (Nastasi et al., 2010; Bell et al., 2018). Occasionally, one methodology can be embedded within the other during data collection (for example, some quantitative questions are included in an interview, or some qualitative response questions are included within a questionnaire), and it is known as embedded mixed methods research. For instance, in the concurrent mixed methods research, both qualitative and quantitative methods are concurrently used in the same phase but collected separately. However in an concurrent embedded mixed methods research, both qualitative and quantitative methods are concurrently used in the same phase and embedded into each other (Creswell and Plano Clark, 2017).

4.1.3 Research Design of this Study

The methodology is associated with each of the research question of this research is rather complex, where different research philosophical stance and research design are used in each research question to generate the best possible outcome.

Overall, this research employs a pragmatism research philosophical stance and mixed research strategy because it is deemed that exclusive adoption of one research methodology is unhelpful to arrive at a richer research output for this research. This research employs a mix of quantitative method and qualitative method in sequence, forming a sequential multiphase research design (as shown in Figure 4.1) to elaborate and further expand on the initial findings.

To facilitate the subsequent discussion, the research questions will be segmented into different phases where each phase is associated with a dedicated research philosophy and methodology. Different ontological and epistemological assumptions are employed in different phases of the research to accommodate the different needs. This research stands that the most appropriate methodological choice should be driven by the nature of the research question and its context, where both quantitative and qualitative research are equally valued in this research and are used tentatively to produce a rich research output (Nastasi et al., 2010).

Phase 1 is associated with research questions (1) and (2), which investigates the suitability and influential of dimensions and items within circularity and sustainability criteria required to compare recycling alternatives, and how important are them in decisions making.

This phase will be approached using a positivism research philosophical stance that is associated with objectivism ontological assumption and positivism epistemological assumption. Objectivism ontological assumption is made in this phase because it is assumed that there is one set of suitable dimensions and items within circularity and sustainability criteria that can be used to compare the ELT recycling alternatives, and with specific relative importance among them. Further, it is also expected that the respondents will have almost similar experience when exposed to the ELT recycling industry, which shapes their understanding towards producing almost similar results that would be independent of the respondents, and thus a law-like generalisation can be made. Positivism epistemological assumption is also being made in this phase. Since it is believed that truth can be discovered through an observable medium and measurable facts, it is then assumed that facts and numerical data are good and acceptable knowledge for this phase. The axiological assumption of this phase is to predict which dimensions and items are important in circularity and sustainability criteria and explain their relative importance for decision makers.

The approach to theory development is deductive. In this phase, the dimensions and items within circularity and sustainability criteria for ELT recycling alternative evaluation are pre-determined by an extensive literature review, which is subsequently presented to the Delphi panels to test their relevance for the ELT recycling industry. The research strategy employed in this phase is quantitative research. The relevance of each dimension and item within circularity and sustainability criteria as well as their relative importance are sought via the use of a highly structured self-completed internet questionnaire, forming a pre-determined and 'standardised' set of questions that are identical for all respondents.

Survey will be used where the respondents are comprised of the subject experts in the field, such as professors in CE and supply chain managers in the ELT recycling industry, collectively forming a Delphi panel. Prior to the survey, a pilot study will be performed, where the dimensions and items within circularity and sustainability criteria that are collected from the literature are presented to some of the members in the Delphi panel to test their relevance. This method is frequently being employed in the literature as a valid source of knowledge input to determine the inclusion and exclusion of necessary data for the research (Landeta, 2006; Azevedo et al., 2017). After the pilot study, all the Delphi members will be invited to rank the relative importance of the dimensions and items. The responses will be analysed via the use of Multi Criteria Decision Making (MCDM) method to reveal the degree of importance of each dimension and item within circularity and sustainability criteria by integrating responses from all Delphi members. In this study, the MCDM method chosen to be used is fuzzy Analytical Hierarchy Process (FAHP), which is a structured technique that uses mathematics and psychology to analyse and organise complex decisions (Saaty, 2008) and is frequently used in business and management research to determine the degree of importance of each item within supplier selection criteria (Ghodsypour and O'Brien, 1998; Chan et al., 2008) or supply chain selection criteria (Wang et al., 2004).

Phase 2 is associated with the rating of recycling alternatives. Even though this phase does not answer any research question, it still represents a very important phase to identify the case study company and collect certain information from the company (i.e., data of recycling alternatives supply chain) to answer the remaining research questions.

The philosophical stance for this phase is positivism, which consists of objectivism ontological assumption and positivism epistemological assumption. Since this phase is pertaining to the rating of recycling alternatives, it is assumed that one truth exists and is independent of social actors, thus the objectivism ontological assumption. It is believed that the rating of a particular recycling alternative will always yield the same result regardless of respondents, because the basis of rating is guided by hard evidence and data in the industry instead of personal judgement. Consequently, the positivism epistemological assumption is also being made, which assumes that only facts and numerical data will constitute a good quality data and knowledge to obtain unbiased responses pertaining to performance of each recycling alternative. Consequently, the research strategy for this phase will be quantitative research, which uses numerical data in the data collection technique and data analysis procedure. Particularly, TOPSIS is used to analyse the data.

Like phase 1, survey will be used in this phase. Prior to the survey, a suitable case study company involving in ELT collection in the EU that fits a set of selection criteria will be identified and invited to participate in this research. Several managers from the case study company will be selected and invited to provide data via the use of structured self-completed internet mediated questionnaire. Ideally, the respondents should provide actual data regarding the performance of each alternative under each dimension and item. Nevertheless, owing to confidentiality and difficulties in accessing the supply chain data, the respondents are instead being invited to rate each alternative using a 7-point Likert scale, under the circularity and sustainability criteria as previously defined through phase 1. The responses will be analysed using the TOPSIS approach. A score for each recycling alternative will be obtained by aggregating all the rating from the managers, which will be used as an input in the next phase.

Phase 3 is associated with research question (3) that examines how to allocate the ELT among recycling alternatives in supply networks to maximise the circularity and sustainability.

The philosophical stance for this phase is positivism. It is assumed that there exists one resources allocation pattern among the recycling alternatives that can maximise the circularity and sustainability which is independent of social actors, representing objectivism ontological assumption of this phase. This phase also assumed that only facts and numerical data will constitute a good knowledge and good quality data, thus the positivism epistemological assumption. Consequently, the research strategy for this phase will be quantitative research, which uses numerical data in both the data collection technique and data analysis procedure.

In this phase, the resources to be allocated to each recycling alternative will act as explanatory variables while both the circularity and sustainability will act as response variables. The explanatory variables are randomised and tested using a heuristic method with the goal of maximising the response variables. This phase is thus resembling an experiment, by testing the explanatory variables until a maximum value of the response variables is attained. The result obtained from phases 1 and 2 will be incorporated into this experiment in constructing a Multi Objective Linear Programming (MOLP) model for ELT allocation. The result in phase 2 will be used as coefficient in the objective function, guiding the optimisation of ELT allocation among the alternatives. To complete the experiment, the MOLP will be solved using an advanced heuristic method, namely NSGA-II as it is faster and more accurate time (Deb et al., 2000; Cao et al., 2011). The justification for the use of NSGA-II is provided in Section 4.5.1.

Phase 4 is associated with research question (4). Upon revealing the result (i.e., discrepancy of ELT allocation between the modelling result and the actual business scenario) to the managers, this research takes the opportunities to interview the managers. This interview divulges the reasons for maintaining the current ELT allocation, rather than shifting to employ the allocation suggested by the model. This sheds light on the barriers that hinder the decision towards the uptake of circular and sustainable practices in the ELT recycling industry. Similarly, enablers that would ease and improve the situation are also being sought in the interview.

The philosophical stance for this phase is interpretivism. Subjectivism ontological assumption is made in this phase as it is assumed that there exists multiple reasons that could potentially obstruct the attempt towards achieving the optimum result shown in the modelling as well as multiple enablers that can improve the situation. It is dependent on social actors and will behave like a product of social construct. Interpretivism epistemological assumption is made in this phase, which stands that opinions and narrative will be a valid source of knowledge. The theory is inductively generated in this phase, to explain the discrepancies of ELT allocation between the actual and modelling results.

Qualitative research strategy will be used in this phase together with interviews. The managers from the case study company who participated in phase 2 of the research will be invited for interview via an internet-mediated group interview to understand and explain the discrepancy of ELT allocation between the actual and modelling results, as well as possible hidden connection between the actual business condition and the results suggested by the model. The interviews will be transcribed and analysed thematically by close reading and manual coding. The managers are elected by the senior management to participate in this research as they fit the respondents' criteria. Further, they represent the most qualified respondents as they have knowledge of their supply chain partners and can provide an accurate estimation of their performance.

The managers from the case study company who participated in phase 2 of the research also represent the most suitable interviewees for the interview in phase 4. This is because the managers are the respondents that rate the recycling alternatives, which in turn shape the allocation strategy proposed by the model. Since the managers are heavily involved in several phases, thus they will be more immersed in the research context and will provide a richer response, when the modelling solution is revealed to them. Furthermore, they also possess industry-specific knowledge in answering questions such as why an innovative solution will be accepted or why certain alternative is favoured, especially in ELT recycling sector. This will provide a more contextual contribution to the research community when analysing the barriers or enablers for a niche sector.

Phase 5 is related to research question (5) which investigates the impact on sustainability while achieving the circularity in the ELT recycling industry.

This phase will be approached using a positivism research philosophical stance, where objectivism ontological assumption and positivism epistemological assumption are made. It is assumed that one true relationship between circularity and sustainability exists and is independent of social actors. Positivism epistemological assumption is made in this phase in view that only facts and numerical data will constitute a good knowledge and data to create a credible result that is not subjected to biasness. The impact on sustainability while achieving the circularity should not be answered by relying on personal judgement via interview because the answer to this question could be very subjective and susceptible to biasness.

Quantitative research is thus being used in this phase, which uses numerical data in the data collection technique and data analysis procedure. This phase utilises the output from phase 3 to answer this research question. The paired value of sustainability of the supply network under different value of circularity will be captured and used for a scatter plot to reveal the relationship between circularity and sustainability.

As a summary, phase 1 associates with dimensions and items' weight determination for circularity and sustainability criteria. Phase 2 associates with alternatives ranking under different dimensions and items within circularity and sustainability criteria. Phase 3 associates with the optimisation of ELT allocated to the recycling alternatives, subjected to problem constraints, in maximising both circularity and sustainability. Phase 4 involves the explanation of discrepancy between the model output and the actual resource allocation. Phase 5 reveals the relationship between circularity and sustainability. The philosophical stance, research strategy and research plans are summarised in Table 4.2.

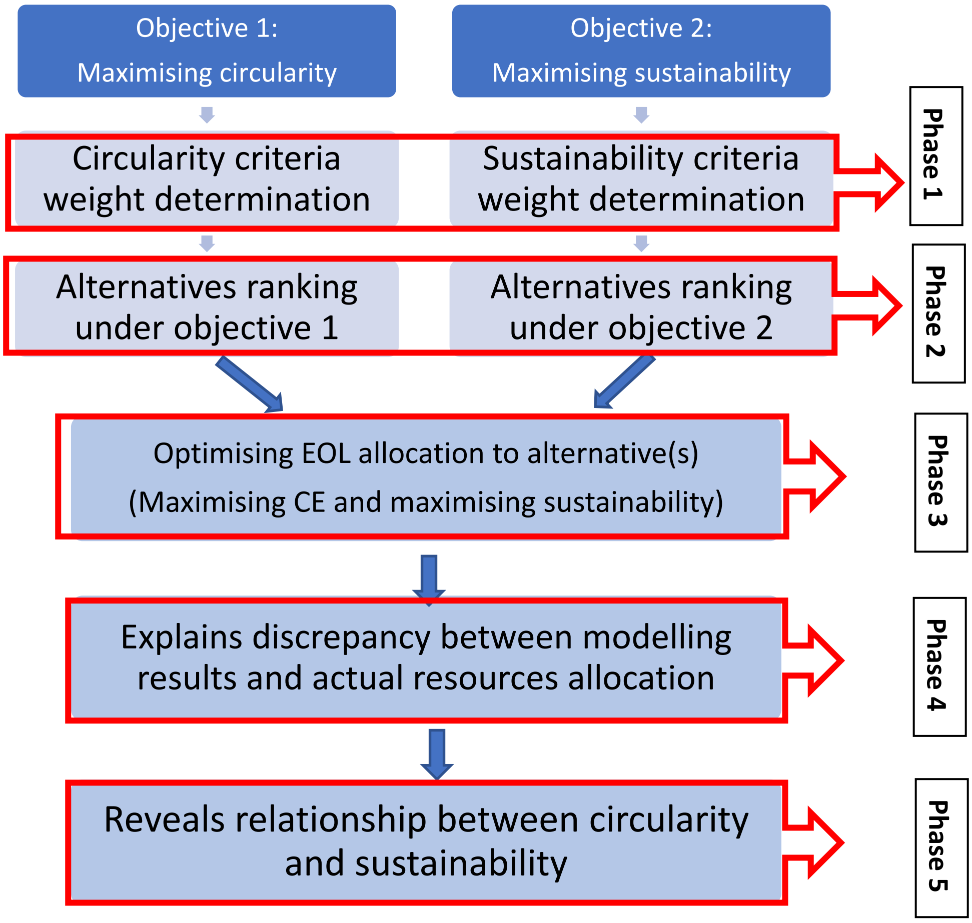

Figure 4.1: The five phases of the research (Source: Author).

Table 4.2: Philosophical stance, research strategy and research plan for this research (Source: Author).

Phase	Philosophical Stance	Research Strategy
1	Positivism	Quantitative
2	Positivism	Quantitative
3	Positivism	Quantitative
4	Interpretivism	Qualitative
5	Positivism	Quantitative
Overall	Pragmatism	Quantitative and Quantitative

4.2 Methods in Solving Decision-making Problems

4.2.1 Methods Used in Solving ELT Recycling Alternative Selection

Decision-making can be defined as an intentional and reflective choice in satisfying a need. It includes identification of the problem, determination of alternative among the potential solutions and their assessment (Kleindorfer et al., 1993). In this research, phases 1, 2 and 3 require decision-making. In phase 1, a decision is made to determine weight or relative importance of each of the dimensions and items that is required for recycling alternative ranking. In phase 2, a decision is made to rank the recycling alternative based on the dimensions and items previously defined in phase 1. In phase 3, a decision is made to select the best resources allocation such that circularity and sustainability can be maximised.

As shown in Section 3.2, the research in the literature assumed that the dimensions and items used for recycling alternatives ranking carries equal weight or relative importance. They rank the recycling alternatives using mostly the Naïve judgemental method, which is proven to be fast but inaccurate (Chen et al., 2003). To arrive at a more accurate result for the ranking of recycling alternatives, more rigorous methods to analyse the data should be used. Particularly in this study, the Multi-criteria decision-making (MCDM) method is used because of the involvement of multiple criteria, dimensions, and items as well as inputs from multiple respondents. For example, this can be seen in the weight determination in phase 1, ranking of recycling alternatives in phase 2 as well as resources allocation modelling in phase 3.

The MCDM method is widely used in various research area (Gebre et al., 2021). It is a generic term used to represent all methods that are useful to solve complex problems that involved multiple quantitative and qualitative evaluation factors. MCDM application has been an active operational research area for many years and is very effective in solving complex as well as conflicting decision problems (Sitorus and Cilliers, 2019). MCDM methods can be classified into two broad classes, namely the multi-attribute decision-making (MADM) and multiple-objective decision-making (MODM) (Malczewski, 1999; Zimmermann, 2013) as shown in Figure 4.2.

Figure 4.2: MCDM methods (Source: Gebre et al., 2021).

MADM and MODM are suitable to be used when different number of alternatives are present (i.e., discrete or continuous). In MCDM, alternatives are the different preferences or choices available for decision-makers (Gebre et al., 2021). MADM is suitable to be used when there is a limited number of alternatives (i.e., discrete decision space) while MODM is suitable when the number of alternatives is infinite (i.e., continuous decision space). In MADM, the discrete number of pre-determined alternatives are screened, prioritised and ranked according to the criteria decisions (i.e., weighted attributes) (Chai et al., 2013). In MODM, the alternatives are not pre-determined, and all the alternatives will be evaluated using a set of objective functions subjected to a set of constraints. Optimisation will then be used to search for the optimal value of an objective function (maximum or minimum), to determine the best alternative among the infinite alternatives.

There are different types of MADM methods, i.e., value/utility function (e.g., multi-attribute value theory (MAVT), multi-attribute utility theory (MAUT), simple additive weighting (SAW)) (Churchman, 1954; Pohekar and Ramachandran, 2004); pairwise comparison (e.g., analytic hierarchy process (AHP), analytic network process (ANP)) (Saaty, 1988; Strantzali and Aravossis, 2016); distance-based (e.g., technique for order of preference by similarity to ideal solution (TOPSIS)) (Tzeng and Huang, 2011) as well as outranking (e.g., preference ranking organization method for enrichment evaluation (PROMETHEE), elimination and choice expressing reality (ELECTREE), VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR)) (Duckstein and Opricovic, 1980; Brans and Vincke, 1985; De Boer, 1998).

The MODM are further classified into mathematical programming models and heuristic algorithms. Mathematical programming models include linear programming (LP), non-linear programming (NLP), mixed integer linear programming (MILP), goal programming (GP), compromise programming (CP), and dynamic programming (DP) (Meyer et al., 2014).

Heuristic algorithms are referring to simulating annealing (SA), genetic algorithm (GA), tabu search (TS), Max-Min operator (MMO) and Outer algorithm (OA) (Mitchell, 1998; Belton and Stewart, 2002; Castillo-Villar, 2014). The working principle for all the listed MCDM methods is introduced in Table 4.3.

Table 4.3: MCDM methods (Source: Author).

Methods	Working Principle
Multi-Attribute Value Theory (MAVT)	A method that uses one or more different attributes or criteria to measure the performance of the alternatives in relation to that objective (Keeney and Raiffa, 1993).
Multi-Attribute Utility Theory (MAUT)	A method that attains a conjoint measure of the attractiveness (utility) of each outcome of a set of alternatives by weighing all the attributes, and scales the attributes by importance to the DMs (Hastie and Dawes, 2009).
Simple Additive Weighting (SAW)	A method that is also known as weighted linear combination or scoring method. It is a best known and simplest method for evaluating a number of alternatives. It is performed by ranking the alternatives using the sum of the product of each criterion weight to the performance value of each alternative (Afshari et al., 2010).
Analytic Hierarchy Process (AHP)	A structured technique that compares the items (criteria or alternatives) in pairs, based on individual expert's experience and judgement in estimating the relative magnitude of factors through pair-wise comparisons, where the priorities of items are derived (Saaty, 2008).
Analytic Network Process (ANP)	A generalisation form of AHP, where the decision problem is structured into a network instead of a hierarchy as in AHP. Unlike AHP, where each element in the hierarchy is considered to be independent of all the others, the elements in the ANP network are interrelated with each other. DEMATEL is a methodology sometimes used with AHP by revealing the interrelationship between items using impact-relations map or cause-effect chain using a survey (Saaty, 2005).
Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)	A method that chooses an alternative that is closest to the ideal solution, by selecting alternative based on two "reference" points (i.e., has a minimum distance from the positive ideal solution and a maximum distance from the negative ideal solution). Unlike ELECTRE and PROMETHEE, threshold is not required to eliminate alternatives (Hwang and Yoon, 1981).
Preference Ranking Organization Method for	A method to determine an outranking relation between a set of alternatives. PROMETHEE uses preference functions and

Enrichment Evaluation (PROMETHEE)	a threshold as justification of outranking relationship (Brans et al., 1985)
Elimination and Choice Expressing Reality (ELECTRE)	A method to determine an outranking relation between a set of alternatives (i.e. alternative A outranks alternative B if sufficient justification exists to decide A at least as good as B). ELECTRE uses concordance and discordance and their respective threshold as justification of outranking relationship. This method is usually used to discard some alternatives to the problem which are unacceptable (Boer, 1998).
VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR)	A method that chooses an alternative that is closest to the ideal solution, by selecting the alternative based on particular measure of "closeness" to the ideal solution. Unlike TOPSIS, linear normalisation is used in VIKOR to eliminate the units of criterion functions, as opposed to vector normalisation that is used in the former (Duckstein and Opricovic, 1980).
Linear Programming (LP)	Optimisation methods for solving problems where all model functions (objectives and constraints) are linear.
Non-Linear Programming (NLP)	Optimisation methods for solving problems where the objective functions are non-linear.
Mixed Integer Linear Programming (MILP)	Optimisation methods designed for problems where some of the solutions (decision variables) must be integer.
Goal Programming (GP)	The most popular method in handling MILP, by converting the model into a single objective, yielding an efficient solution that might not be optimum with respect to all conflicting objectives. When all the goals are at roughly comparable importance, the GP is known as non-preemptive GP. Similarly, when there is a hierarchy of priority levels for the goals, the GP is known as preemptive GP (Schniederjans, 2012).
Compromise Programming (CP)	A method that identifies an ideal or utopian solution using a distance function as a proxy measure for human preferences (Parra et al., 2005).
Dynamic Programming (DP)	A method that breaks a problem into sub-problems and then recursively finds optimal solutions to the sub-problems (Bellman, 1966).
Simulating Annealing (SA)	A metaheuristic method that approximates global optimisation of a given function in a large search space. This method can obtain an approximate global optimum in a short amount of time while avoiding local optimum, which is particularly useful when solving time is a concern in an optimisation problem (Aarts and Korst, 1989).

Genetic Algorithm (GA)	A metaheuristic inspired by the process of natural selection used to generate high quality solutions to optimisation problems, relying on bio-inspired operators such as mutation, crossover and selection. A set of alternatives are evaluated using analogy chromosome and the fit chromosomes are selected to produce offspring, until the stopping criteria are satisfied (Mitchell, 1998).
Tabu Search (TS)	A metaheuristic method that takes a potential solution to a problem and checks its immediate neighbours (slight variation to the solution) in hoping of finding an improved solution (Glover and Laguna, 1998).
Max-Min Operator (MMO)	A method to solve LP by converting it to a single objective problem. By solving each objective separately to obtain upper limit and lower limit of the solution, which are necessary to form a membership function in the solving process (Zimmerman, 1987).
Outer Algorithm (OA)	A basic approach for solving MINLP using a guess value (Duran, 1986).

There is no method that is one-size-fits-all for all decision-making problems (Gebre et al., 2021). Each of the method and technique possesses unrivalled strengths and weaknesses and their applicability is highly dependent on the condition of the problem being studied as well as the aim of the application. Since this research is carried out in multiple phases with different aims, the most appropriate methods and techniques will be used in different phases to manipulate the strength of each, so as to harvest the best results. Consequently, a hybrid of methods and techniques are employed in this research.

4.2.2 Methods Used in Solving Decision-making Problem in the Literature

A literature review is performed to examine the methods that are commonly used in solving the MCDM problems in SCM and logistics, particularly, using circularity or sustainability criteria. The literature review is performed using search strings: {MCDM} and {supply chain} and ({circularity} OR {Circular Economy}) and {sustainability}.

The review is based on both peer-reviewed journal articles and conference proceedings in English. The databases used for the search are Science Direct, SAGE, Springer, Taylor and Francis, Wiley, Emerald and JSTOR, which cover most of the literature available (Ghisellini et al., 2016; Merli et al., 2018). The publication years of the included papers ranged from year 2000 to June 2019. The included subject areas are environment, economics, social science, engineering, business and management, material, decision, and multi-disciplinary science. In addition, articles obtained in the bibliographic cross-referencing of the search are also being added. Overall, 29 papers were identified.

The MCDM methods used in the literature are scrutinised and examined in 3 categories, namely:

a) MADM methods to determine the relative importance of discrete alternatives (i.e., as in phase 1 of this research)
b) MADM methods to rank the discrete alternatives (i.e., as in phase 2)
c) MODM methods to determine optimum resources allocation among the infinite alternatives (i.e., as in phase 3).

The methods used in the research are marked with symbol "✔" and the result is tabulated in Table 4.4.

Table 4.4: Review of MCDM methods employed in SCM and logistics area (Source: Author).

Author	MADM (as in phase 1)									MADM (as in phase 2)									MODM (as in phase 3)										
	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F	G	H	I	J	K
(Chen et al, 2006)															✓														
(Sarkis, 2003)					✓									✓															
(Chan and Kumar, 2007)				✓																									
(Boran et al., 2009)			✓												✓														
(Büyüközkan, 2012)					✓										✓														
(Chaabane et al., 2012)																					✓								
(Agarwal et al., 2006)					✓									✓															
(Wang et al., 2004)				✓																		✓							
(Altiparmak et al., 2006)																										✓			
(Chan, 2008)				✓									✓																
(Gupta and Maranas, 2003)																													✓
(Liu et al., 2000)												✓																	

(Kumar et al., 2004)																						✓							
(Amid et al., 2006)																												✓	
(Liu and Hai, 2005)				✓																									
(Kuo et al., 2010)					✓																								
(Kulak and Kahraman, 2005)				✓									✓																
(Sanayei et al., 2010)																		✓											
(Hugo and Pistikopoulos, 2005)																					✓								
(Chan, 2003)				✓																									
(Pishvaee and Torabi, 2010)																							✓						
(Kannan et al., 2013)				✓											✓													✓	
(Chen and Lee, 2004)																												✓	
(Kannan et al., 2014)			✓												✓														

(Büyüközkan and Çifçi, 2011)					✔									✔															
(Krikke et al., 2003)																					✔								
(Li et al., 2007)			✔																										
(Chou et al., 2008)			✔									✔																	
(Deng et al, 2014)				✔																									
This research				✔											✔											✔			

Symbol:
MADM: 1= MAVT, 2= MAUT, 3= SAW, 4= AHP, 5= ANP, 6= TOPSIS, 7= PROMETHEE, 8= ELECTRE, 9 = VIKOR
MODM: A= LP, B= NLP, C= MILP, D= GP, E= CP, F= DP, G=SA, H= GA, I= TS, J= MMO, K= OA

The most common topics that utilise MCDM in SCM and logistics research are related to supplier ranking, selection or resources allocation (e.g., Chen et al, 2006; Boran et al., 2009; Kannan et al., 2014), location ranking, selection or resources allocation (e.g., Krikke et al., 2003; Altiparmak et al., 2006; Pishvaee and Torabi, 2010) and strategy ranking and selection (e.g., Hugo and Pistikopoulos, 2005; Agarwal et al., 2006; Chaabane et al., 2012). The research topic as in this research is rarely being discussed in the literature (e.g., Krikke et al., 2003), representing a new area for application of MCDM that deserves more exploration.

As seen in Table 4.4, 17 among the 29 studies used MADM methods to determine relative importance of discrete alternatives (as in phase 1 of the research). Among them, methods like AHP and ANP prevail, while SAW is used sparingly. Particularly, 8 out of the 17 research studies have used AHP. The vast usage of AHP coincides with findings of Vaidya (2006) and Chen (2011), who discovered that AHP is widely used in decision-making. The utilisation of AHP in weight determination also transcends in many fields, for example software selection in Lai et al., (2002), advanced technology selection in Kengpol and O'Brien (2001), project management constructor selection in Al Harbi (2001), conventional store selection in Kuo et al. (1999), warehouse site selection in Korpela and Tuominen (1996), project delivery method in Al Khalil (2002), car selection in Byun (2001), telecommunication vendor selection in Tam and Tummala (2001) and quality-based program in Noci and Toletti (2000). The use of AHP still persists in present days and transcends across more fields, as it can be seen in aquifer selection in Kaur et al. (2020), construction project selection in Kalan and Ozbek (2020), power grid construction strategy selection in Pu et al. (2020), supplier selection in Ozkan and Aydin (2020), industrial robot selection in Kutlu and Kahraman (2020), clean energy technology selection in Karasan et al. (2019), etc. ANP on the other hand is the second most abundantly used method as shown in Table 4.4, where 5 among 17 studies have used it in determining the relative importance of discrete alternatives. ANP is more complex than AHP because it assumes interdependency among dimensions, items and alternatives. It can only be used when interrelationships between dimensions, items and alternatives are assumed to be present and the goal in revealing the interrelationships is part of the research aims (Saaty, 2005). Within value/ utility function class, SAW is used more frequently than its predecessor MAVT or MAUT as the latter are dated. Methods in outranking class are not used for this purpose as they will eliminate alternatives from the procedure from time to time, which defeats the purpose for this phase (i.e., to obtain relative importance for all the dimensions and items without eliminating any of them). Even though distance-based methods like TOPSIS do not eliminate alternatives, it is also not suitable to be used to determine the relative importance of discrete alternatives because it does not take relative viewpoints into consideration unlike pair-wise comparison methods (Hwang and Yoon, 1981).

By referring to Table 4.4, TOPSIS is the most frequently used method (5 out of 13 research) to rank the discrete alternatives (i.e., as in phase 2 of this research), preceding ANP, AHP, SAW and VIKOR with 3, 2, 2 and 1 uses respectively. This result coincides with the finding of Behzadian et al., (2012), who conducted a thorough state-of-the-art survey of TOPSIS application and discovered that majority of papers that involved in ranking of discrete alternatives from 103 journals have utilised TOPSIS since the year 2000 to 2012. Particularly, supply chain management and logistics research are the most prominent area of research in utilising TOPSIS for alternatives ranking that serves different purpose, such as supplier selection, and outsourcing decision and location selection. Similar to the previous section, SAW is used more frequently than its dated predecessor MAVT or MAUT within the value/utility function class. However, unlike previous section, TOPSIS is used more regularly than AHP or ANP because the relative viewpoint is not important in ranking the discrete alternatives, where pairwise comparison is not necessary. As a result, TOPSIS with generally shorter questionnaire is more commonly used (Hwang and Yoon, 1981). Still, methods from the out-ranking class, as shown in Figure 4.2, are used sparingly as they are generally faster. Nevertheless, these methods ignore out-ranked alternatives (i.e., alternatives with lower rank) and are only useful for the research that does not concern about the ranking for alternatives with lower rank (Duckstein and Opricovic, 1980).

Among the MODM methods used to determine optimum resources allocation in the infinite alternatives (i.e., as in phase 3 of this research), methods such as mixed-integer linear programming (MILP), max-min operator (MMO), goal programming (GP), genetic algorithm (GA), compromise programming (CP), and outer algorithm (OA) are commonly used (i.e., 3 used MILP, 3 used MMO, 2 used GP, 1 used GA, 1 used CP and 1 used OA, among 11 research studies that utilise MODM methods). MILP, one of the methods within mathematical model cluster, is mostly used as some commercial software such as Lindo (Chaabane et al., 2012) or CPlex (Krikke et al., 2003) can solve it automatically without losing much of the computational time. MMO and GP, which are the methods within meta heuristic cluster, are also commonly used due to its simplicity and can easily be computed. Albeit fast, these methods are limited as there is a possibility that the solution will be trapped in the local minimum or maximum.

From Table 4.4, some research involves the use of more than one MCDM method. This section examines the studies that involve more than one MCDM method by analysing them in a Venn diagram as shown in Figure 4.3. The number of research studies that utilise MCDM methods to determine the relative importance of discrete alternatives (as in phase 1 of this research) is recorded in subset A. The number of studies that utilise MCDM methods to determine the ranking of alternatives (as in phase 2 of this research) is recorded in subset B while the number of studies that uses MCDM methods to determine optimum resources allocation in the infinite alternatives (i.e., as in phase 3 of this research) is recorded in subset C.

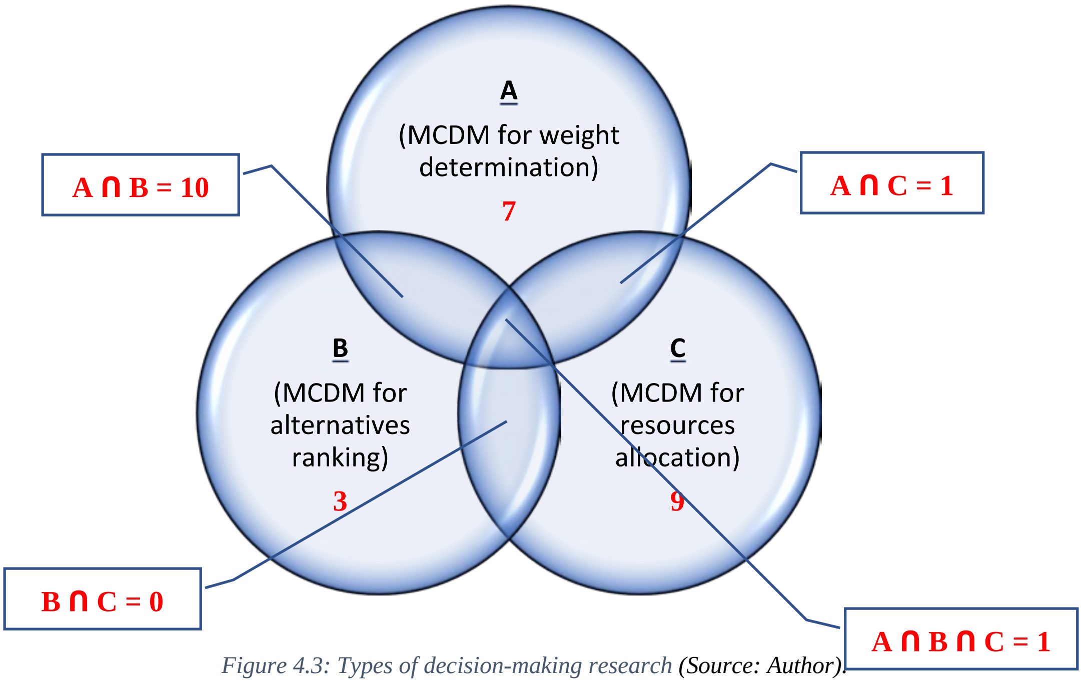

Figure 4.3: Types of decision-making research (Source: Author).

From Figure 4.3, some studies are exclusively using a single MCDM method to determine the relative importance of discrete alternatives, serving as a framework that guides future decision-making (i.e., 7 research studies which are the relative complement of B ∪ C in A). Some studies use a single MCDM method to determine the ranking of alternatives, by assuming equal weight among the criteria (i.e., 3 studies which are the relative complement of A ∪ C in B). Some studies use a single MCDM method to determine optimum resources allocation among the infinite alternatives, by assuming equal weight among criteria (i.e., 9 research which are the relative complement of A ∪ B in C).

It can also be seen that some studies use hybrid of MCDM methods in solving their research problems. 10 studies use a combination of MCDM methods (i.e., two MADM methods) to determine the relative importance of discrete alternatives and rank the discrete alternatives (i.e., A ∩ B). Nevertheless, hybrid of MCDM methods (i.e., MADM and MODM methods) which determine relative importance of discrete alternatives and optimisation of resources allocation (i.e., A ∩ C) or rank alternatives and optimise resources allocation among the alternatives (B ∩ C), received less attention in the literature.

It can be noticed that MODM methods are usually being used separately without involving the use of MADM methods. Only 2 among the 11 studies performed MODM by involving the use of MADM (i.e., A ∩ C) to provide a richer output (e.g., Wang et al., 2004; Kannan et al., 2013). A hybrid of 2 MADM and MODM (i.e., A ∩ B ∩ C) is even more rare (i.e., Kannan et al., 2013). These research studies employ the MADM and MODM methods in sequence, which determine the relative weight of dimensions and items affecting the alternatives ranking (as in phase 1 of this research), then rank the alternatives (as in phase 2 of this research) before proceeding to research allocation (as in phase 3 of this research). This can be seen as a strength because the research that uses MODM methods alone without MADM usually made an assumption that the dimensions and items affecting the resources allocation would carry an equal weight, which is not true and will compromise the results (Wang et al., 2004; Kannan et al., 2013).

Inspired by Kannan et al. (2013), this research combines different MCDM methods (i.e., 2 MADM and MODM) to determine the relative weight of dimensions and items, alternatives ranking and resources optimisation (A ∩ B ∩ C). Particularly, the combination of methods is not used before in the literature, which also demonstrated the uniqueness in methodological approach to the research problem in this study.

It is also noteworthy that among the 29 research as shown in Table 4.4, more than half of them (i.e., 17 studies) use fuzzy theory to resolve the uncertainty that is commonly arise in the decision-making process, signifying the importance of incorporating fuzzy theory in the solution. By combining fuzzy theory which is commonly employed in the literature, this contributes to a highly exclusive hybrid of MADM methods in a new area that is increasingly more popular.

4.3 Phase 1: Weight determination

4.3.1 Inclusion of Dimension and Item in Sustainability and Circularity

A content analysis is first performed to examine the appropriateness of the dimensions and items in each criterion to be used for the rating and comparing the recycling alternatives. Further, the description of the dimensions and items are also being validated in the content analysis. A pilot test that involves 5 subject-matter-experts that are specialised in supply chain management, sustainability and circularity is conducted for the content analysis. The subject-matter-experts are also a subset of the Delphi panels. A pilot study is a small study designed to gather information before a larger study, serving to improve the quality of that final study. The pilot study can reveal deficiency in the design of a proposed research proposal (Antonisamy, 2017). The pilot study survey can be seen in Appendix A.

In the pilot study, the face validity as well as the description of the dimensions and items in both criteria are examined. Face validity refers to the ability of an item to measure the construct that it intends to measure, on its face value (Nunnally, 1967, p. 99; 1978, p. 111). A measurement item within a construct can only be appropriate indicator for its corresponding construct as well as be internally consistent with other measurement items when the measurement item has a high face validity value.

In this study, the subject-matter-experts are required to evaluate the face value (appropriateness of the items in measuring the constructs) using 7-point Likert scale (i.e., “1” indicates barely adequate and “7” indicates almost perfect) (Rungtusanatham et al., 1999). A mean score of 3 is required to justify the adequacy of the constructs and its’ items. The standard deviation of the feedbacks from examiners are also calculated to inspect the degree of convergence of the examiners' feedbacks. A low standard deviation indicates that the values tend to be close to the mean of the set, implying a high convergence in the responses. Conversely, a high standard deviation indicates that the values are spread out over a wider range, indicating a potential of disagreement between each examiner. The standard deviation that is lower than or equal to 1 implying that the items are accepted for construct measurement (Rungtusanatham et al., 1999). Refer Section 5.1.1 for results for pilot study survey.

A written feedback is requested after the pilot study to assess the suitability of the description for all of the items and constructs. The feedback is crucial in identifying the possibilities of poor clarification, lengthiness or discomfort within the description (Antonisamy, 2017). The written feedback from the examiners have improved the descriptions by scrutinising on the clarification and lengthiness of the descriptions.

4.3.2 Selection of Data Analysis Method and Technique

Like in many decision-making problems, a decision maker (DM) may incline toward a certain item as opposed to another item when making a decision, based on his/her personal preference (Saaty, 1990). As a result, certain item may carry a weight that is relatively higher than another item in the decision-making process. Thus, phase 1 of this research intends to determine the relative weight (relative importance) of each dimension and item, which will be imperative in ranking the alternatives in phase 2.

There are many MCDM methods that can be used to determine the relative importance of each dimension and item. As aforementioned in Section 4.2.2, AHP and ANP are the most widely employed methods for this purpose. AHP is used in phase 1 of this research as oppose to ANP because the goal to reveal the interrelationship between the dimensions, items and alternatives are not a part of the research aims. The absence of interrelationship between the dimensions and items have been constantly exemplified in various research. For example, Menzel (2010) discovers that there is no significant relationship between energy consumption and GHG emission with profit (in this case, energy consumption is equivalent to C_{2e} and GHG emission is equivalent to C_{2d}, which are found to have no correlation with profit, which is equivalent to C_{1f}), coincides with the findings of Carson et al. (1997) and Ozturk and Acaravci (2010). Similarly, Aras et al. (2010) also discover that excels in social sustainability (equivalent to S_3) do not significantly affect financial performance of a corporate (equivalent to S_1). Since there are no evidence proving the interdependence among the dimensions and items within circularity and sustainability, AHP that assume no interrelationship between them is chosen over ANP.

However, there is a drawback of AHP where it fails to consider for the uncertainty present in decision-making, which is associated to human thinking and reasoning. In AHP, uncertainty always arise when DMs are required to rank the relative importance of each item under pair-wise comparison using linguistic variables. This is because the object being judged is naturally subjective and ambiguous, and cannot be estimated exactly using any numerical scale (Mehrjerdi, 2012).

As a remedy, Fuzzy set theory which is conceived by Zadeh (1965, 1976) is therefore incorporated into AHP, which is designed to help DMs to solve the vague nature in decision-making (Ku et al., 2010). The incorporation of fuzzy theory into AHP can also be seen in various highly cited articles such as Kulak and Kahraman (2005), Chan and Kumar (2007), Chan et al. (2008), Kannan et al. (2013) and Deng et al (2014), signifying the importance of incorporating fuzzy theory (or D-theory) in the problem. Fuzzy set theory allows partial set membership to be used in the analysis, rather than crisp set membership of exact numerical number used in AHP. In Fuzzy AHP (FAHP), data collected from AHP is processed using advance mathematics to resolve the uncertainties arise from pairwise comparisons, which is proven to be able to strengthen the reasonableness and comprehensiveness of the decision-making process (Chen, 2000; Chen et al., 2006). The applications of fuzzy theories has been presented in decision making processes by Bellman and Zadeh (1970), and has been incubated in the fuzzy MCDM methodology ever since.

Triangular fuzzy numbers are used in this study to assess the preferences because it is relatively easy to be used by the DMs and to be calculated, as compared to Gaussian and trapezoidal fuzzy numbers. A triangular fuzzy number is defined as (l, m, u) where l ≤ m ≤ u. The parameters l, m, and u represent the smallest possible value, the most promising value, and the largest possible value respectively. A fuzzy subset M in X, where X is universe set of items with its elements denoted by x, is represented by a membership function $\mu_M(x)$. The membership function is associated with every element x in subset M and possesses a real number between 0 and 1. A fuzzy set is defined by its membership function as shown in Equation (1) and depicted in Figure 4.4. The basic definitions of fuzzy method were introduced in Zadeh (1965, 1976) and Zimmermann (2001).

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

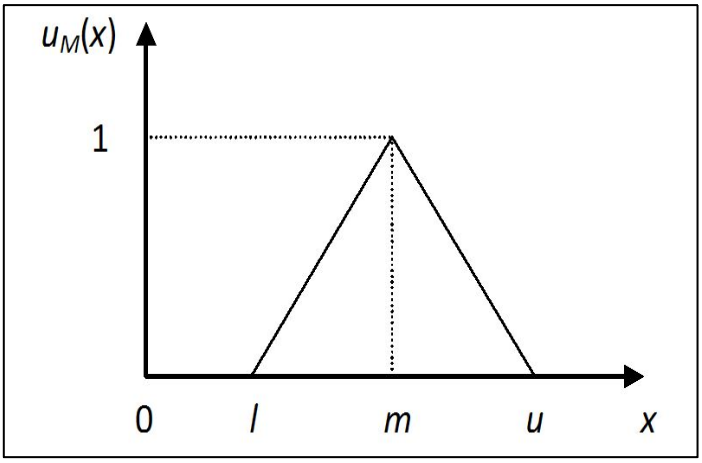

Figure 4.4: Membership function of triangular fuzzy number M (Source: Author).

The procedures of FAHP method in Buckley (1985) is utilised in this paper to determine the relative importance of each dimension and item within circularity and sustainability, followed by de-fuzzification method proposed by Chou and Chang (2008) as well as consistency ratio (CR) calculation in subsequent steps. The steps are described below.

Step 1: The DMs are required to compare dimension and item within circularity and sustainability via linguistic terms shown in Table 4.5.

Table 4.5: linguistic terms and the corresponding triangular fuzzy numbers (Source: Author).

Saaty scale	Definition	Fuzzy triangular scale
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)

The pair wise contribution matrix is shown in Equation (2), where $\tilde{d}_{ij}^{k}$ indicates the kth DM's preference of ith criterion over jth criterion under pair-wise comparison, in the equivalent fuzzy triangular numbers.

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

Step 2: The opinions of DMs are aggregated and the judgements are synthesised using a geometric mean method as shown in Equation (3), yielding a set of overall priorities as shown in Equation (4). Each of the element $\tilde{d}_{ij}$ in the matrix in Equation (4) is the geometric mean of all the element ijth provided by the DMs.

$$\tilde{d}_{ij} = \left(\prod_{k=1}^{K} \tilde{d}_{ij}^{k}\right)^{\frac{1}{k}}, where\ i = 1,2,\ldots,n\ and\ j = 1,2,\ldots,n \text{------------------------------ (3)}$$

$$\tilde{A} = \begin{bmatrix} \tilde{d}_{11} & \tilde{d}_{12} & \cdots & \tilde{d}_{1n} \\ \tilde{d}_{21} & \tilde{d}_{22} & & \tilde{d}_{2n} \\ \vdots & & \ddots & \vdots \\ \tilde{d}_{n1} & \tilde{d}_{n2} & \cdots & \tilde{d}_{nn} \end{bmatrix}, \tilde{d}_{ij} = \left(l_{ij}, m_{ij}, u_{ij}\right),\ \tilde{d}_{ji} = \frac{1}{\tilde{d}_{ij}} = \left(\frac{1}{u_{ij}}, \frac{1}{m_{ij}}, \frac{1}{l_{ij}}\right) \text{ ---------- (4)}$$

Step 3: The fuzzy geometric mean value, $\tilde{r}_i$ (i.e., the row geometric mean) is calculated using Equation (5).

$$\tilde{r}_i = \left(\prod_{j=1}^{n} \tilde{d}_{ij}\right)^{\frac{1}{n}} where\ i = 1,2,\ldots,n \text{-- (5)}$$

Step 4: The fuzzy weights of each criterion ith is obtained by multiplying each $\tilde{r}_i$ with the inverse power of vector summation of $\tilde{r}_i$ (i.e., column summation), as shown in Equation (6).

$$\widetilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \ldots \oplus \tilde{r}_n)^{-1} \text{ -- (6)}$$

Step 5: Centre of area method is used for De-fuzzification of fuzzy weight $\widetilde{w}_i$, by averaging the three components (l, m, u) of the fuzzy weight as shown in Equation (7). Normalisation is performed subsequently to determine the weight of each criterion N_i .

$M_i = (l_i + m_i + u_i)/3$-- (7)

Step 6: Consistency Ratio (CR) is used to calculate the final consistency of the judgments, in ensuring that no conflicting ratings or mistakes are made by the DMs. CR is calculated by taking the ratio of Consistency Index (CI) to Random Index (RI) depending on the size of the matrix (Al-Harbi, 2001). Generally, RI is bigger as the size of the matrix increases, as shown in Table 4.6. The CI is calculated using Equation (8), where n is the size of the matrix and λ_{max} is the Eigen value of the aggregated matrix. The Eigen value λ_{max} is calculated by taking the ratio of matrix multiplication between aggregated matrix and weight matrix, to the weight matrix. A CR that is less than 0.1 implies that the judgments are acceptable (Saaty, 1990).

$CI = \frac{\lambda_{max} - n}{n-1}, \lambda_{max} = \frac{[A][N]}{[N]}$ --- (8)

Table 4.6: Random Consistency (RI) for CR calculation (Source: Saaty, 1990).

4.3.3 Data Collection and Questionnaire Construction

This section shows the questionnaire construction and data collection method. A questionnaire with 26 questions is created to collect data for phase 1 of the research. The questionnaire is split into two part. Part 1 of the questionnaire consists of 3 questions that are related to respondents' profile and part 2 consists of 16 questions that are related to circularity and 7 questions that are associated to sustainability. The questionnaire is attached in Appendix B.

In part 1, the respondents are required to select the sector they worked in (i.e., educational or non-educational) and their position in the organisation. Optionally, the respondents are encouraged to provide the name of their institute or company.

In part 2, the respondents are required to pairwise compare the dimensions and items within circularity and sustainability criteria, against one another. For example, pairwise comparing C_1–monetary dimension with C_2–energy and environment using Saaty scale (See Table 4.5). Similar procedure is repeated for all the dimensions and items within circularity and sustainability, until each item has been pairwise compared against one another.

A total of 332 pairwise comparisons are required in this inquiry. The description of each dimension and item (as in Section 2.3) is given in the questionnaire to ensure agreement of understanding among the respondents. This questionnaire takes around 60 minutes to finish. The respondents are given the option to save and continue with the questionnaire at different time, to ensure they engage and finish the survey. A consistency ratio as shown in Equation (8) is used to confirm that the respondents have attempted the survey with no conflicting ratings or mistakes being made.

A panel of experts is invited to participate in this research to assess the relative importance of the dimensions and items within the proposed criteria, by providing responses in the pairwise comparison survey. A panel of experts is defined as a group of people who are skilful in the scope of a study area (Davis, 1992). They are selected based on leading position in supply chain management with significant practical knowledge in their field of practice. In this study, the inclusion criteria for the experts were supply chain related specialisation, familiarity with sustainability and circularity, authority in the field, and the number of years of experience. Each chosen expert is either an academic or a practitioner that fulfils the following criteria:

1. A supply chain manager or a member from the senior management team (i.e., the highest level of management in an organization, immediately below the board of directors) or an academic (i.e., professors, associate professors or assistant professors) in the supply chain related field that has published articles related to supply chain management,
2. Has previously worked or experienced in sustainability or circularity related job,
3. Has a minimum of five years of experience in the related field of supply chain management,
4. Has knowledge of ELT recycling.

Online forum that brings together supply chain experts from all over the world are used in this research for recruitment of respondents. Linkedin, an online network of more than 30 million experienced professionals from 150 industries, is used to achieve this agenda. The prospect respondents are searched using Linkedin search engine according to the aforementioned criteria and filtered according to their years of experience in the related field.

This sampling method falls into non-probable purposive sampling category. As opposed to probability sampling that is aimed at selecting sample randomly from the target population to represent and produce a generalisation about the target populations, this research uses non-probable sampling technique, where elements of subjective judgement will be included in selecting the respondents. Particularly, this non-probable sampling technique is inclined towards homogeneous purposive sampling because a stringent selection criterion has been applied for respondent's selection. Eventually, one particular sub-group which consists of similar sample members can be obtained, which allow the research questions to be explored in-depth.

A total of 18 experts were recruited as the panel of experts via this non-probable, purposive sampling method. The number is considered viable according to the suggestions which required 10 to 50 experts (Jones and Twiss, 1978). Less amount of experts is required, i.e., 10 to 15, if they are homogenous experts (Adler and Ziglio, 1996; Skulmosk et al., 2007; Saunders, 2012: 297). The panels are experts from various parts of the EU, consisting of 9 supply chain managers or CEO from companies around the EU and 9 academics including professors, assistant professors and associate professors from universities around the EU. The panels were contacted by the researcher via LinkedIn or emails to introduce the research and obtain their informed consent to participate.

The questionnaire was distributed to each expert via emails or LinkedIn, attaching the link to the survey created using Bristol online survey (BOS) between March and June 2019. They were instructed to pairwise compare the dimensions and items on the self-completed internet mediated questionnaire. Upon successful completion, each answer sheet is delivered to primary researcher through BOS.

4.4 Phase 2: Alternative Ranking

4.4.1 Selection of Data Analysis Method and Technique

There are several methods and techniques that can be used for alternative ranking, for example MAUT, MAVT, SAW, AHP, ANP, TOPSIS, PROMETHEE, ELECTRE and VIKOR (see Section 4.2). As aforementioned, TOPSIS is the most abundantly used method for alternative ranking, preceding AHP, ANP, SAW and other methods.

Some research compared the performance for MCDM methods that perform various alternative rankings and discovered the superior accomplishment of TOPSIS. For example, TOPSIS is found to be more accurate than other methods such as AHP, PROMETHEE, ELECTRE, VIKOR and SAW in the context of employee ranking (Widianta et al., 2018), off-shore wind turbine ranking and selection (Jozaghi, 2018), pipe ranking and selection (Anojkumar et al., 2014). TOPSIS is also easier to compute and consume less computational time as compared to other methods (Kahraman et al., 2009; Anojkumar et al., 2014). TOPSIS effectively reduces the length of questionnaire by negating the need for pairwise comparison and increase response rate significantly (Roszkowska and Wachowicz, 2015; Efe, 2016). Besides quantitative data, TOPSIS also works well with qualitative data and still provides meaningful output. In addition, TOPSIS could accept conversion of numerical data into qualitative data (i.e., good, very good, poor, and very poor) as input, given if the data is limited or sensitive (Awasthi et al., 2011; Chen, 2006). Because of this ability, TOPSIS significantly increases the choices of parameters or criteria involved in the analysis for a more fruitful comparison (Caterino et al., 2009). TOPSIS is also a compensatory method, which uses aggregation of scores to rank alternatives. In TOPSIS, an alternative that obtained a lower score in a certain item can be compensated by high scores on another item, which proved to be more appropriate, compared to compensatory method that selects alternative using non-compensatory decision models.

Furthermore, TOPSIS is also often used in combination with AHP (or FAHP) in selecting alternatives. This hybrid method uses AHP to determine the weight for criteria that will be taken into account in TOPSIS calculation. This hybrid method can also be seen in various research studies, such as Tsaur et al. (2002) in airline service provider ranking and selection, Tzeng et al., (2005) in fuel mode ranking and selection for transportation, Işıklar and Büyüközkan (2007) in mobile phone ranking and selection, Ertugral and Karakasoglu (2008) in facility location ranking and selection. Consequently, TOPSIS is chosen as data analysis for phase 2. The differences between TOPSIS and other methods as well as the justification of using TOPSIS is summarised in Table 4.7.

Table 4.7: Justification of using TOPSIS for phase 2 of the research (Source: Author).

TOPSIS	MAVT, MAUT, SAW, AHP, ANP, ELECTRE, PROMETHEE and VIKOR
Most frequently used alternative ranking method in supply chain management and logistics research.	Less frequently used alternative ranking method in supply chain management and logistics research.
Most accurate in ranking the alternatives	Not as accurate in ranking the alternatives
Easy and fast to compute	Difficult and slow to compute
Reduces the effort on pairwise comparison and thus shorter length of questionnaire	Some require pairwise comparison and lengthy of questionnaire
Works well with both qualitative and quantitative criteria, as opposed to mathematical programming	Some only work with quantitative criteria and objective data
A compensatory method which uses the score of an alternative on a particular criterion (i.e., a particularly worst criterion can be compensated by high scores on other criteria)	Some are non-compensatory methods, which might exclude alternative solutions based on hard cut-offs.
Used frequently in combination with other MADM methods such as AHP for weight for criteria determination that will be included in TOPSIS calculation	Not vastly use together with other MADM methods for criteria weight determination.

TOPSIS was first developed by Hwang & Yoon (1981). In this technique, the best alternative is situated closest to the positive ideal solution (PIS) and farthest away from the negative ideal solution (NIS) (Ertugrul & Karakasoglu, 2009). PIS is a solution composes of all best values attainable from the criteria by maximising the benefit criteria and minimising the cost criteria. NIS solution, on the other hand, consists of all worst values attainable from the criteria by maximising the cost criteria and minimising the benefit criteria (Wang & Elhag, 2006). Like other MCDM methods, vagueness and uncertainty always present in a decision-making process, thus fuzzy theory will also be incorporated in TOPSIS method to resolve the vagueness and uncertainties in the reasoning process. The fuzzy TOPSIS method consists of the following steps (Kannan et al., 2013):

Step 1: The decision matrix for the ranking is established as shown in Equation (9). The triangular fuzzy numbers $\tilde{x}_{ij}$ indicates the performance score of each alternative A_i with respect to each criterion C_j. The a_{ij} of the element $\tilde{x}_{ij}$ is the lowest value of all a_{ij} provided by all DMs, the b_{ij} of the element $\tilde{x}_{ij}$ is the mean value of all b_{ij} provided by all DMs while the c_{ij} of the element $\tilde{x}_{ij}$ is the maximum value of all c_{ij} provided by all DMs.

$$\widetilde{D} = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_i \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{ccccccc} C_1 & C_2 & \cdots & C_j & \cdots & C_n \end{array} \\ \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1j} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2j} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ \tilde{x}_{i1} & \tilde{x}_{i2} & \cdots & \tilde{x}_{ij} & \cdots & \tilde{x}_{in} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mj} & \cdots & \tilde{x}_{mn} \end{bmatrix} \end{array}, \tilde{x}_{ij} = (a_{ij}, b_{ij}, c_{ij}),\ \tilde{x}_{ji} = \frac{1}{\tilde{x}_{ij}} = \frac{1}{c_{ij}}, \frac{1}{b_{ij}}, \frac{1}{a_{ij}} \text{---}(9)$$

where
A_i represents alternative i and i = 1,2, … ,m
C_j represents j^th attribute or criterion and 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 Equations (10) and (11), where B and C are the sets of benefit and cost criteria respectively, following the linear normalisation method (Shih et al., 2007). Maximum c_{ij} value in each column j for j^{th} benefit criteria and minimum a_{ij} value in each column j for j^{th} cost criteria will be used in the calculation of this part.

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), j \in B,\ c_j^* = \max_i c_{ij}\ \ if\ j \in B \text{ --------------------------------------- } (10)$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right), j \in C, a_j^- = \min_i a_{ij}\ \ if\ j \in C \text{--------------------------------------- } (11)$$

Step 3: The weighted normalized decision matrix is obtained by multiplying the normalised decision matrix by its associated weights, $\widetilde{w}_j$ obtained from FAHP. The weighted normalized value v_{ij} is calculated using Equation (12).

$v_{ij} = \widetilde{w}_j \times \tilde{r}_{ij}$ where i = 1,2, … ,m and j = 1, 2, … , n ---------------------------------- (12)

Step 4: Fuzzy positive ideal solution (FPIS or A^*) and Fuzzy negative ideal solution (FNIS or A^-) are determined using Equations (13) and (14). A^* is the biggest c_{ij} value in the j^{th} column, while A^- is the smallest a_{ij} value in the j^{th} column.

FPIS: $A^* = \{\tilde{v}_1{}^*, \tilde{v}_2{}^*, \cdots, \tilde{v}_n{}^*\} = \left\{\left(\max_i v_{ij} \middle| j \in J\right), \left(\min_i v_{ij} \middle| j \in J'\right)\right\}$ --------------- (13)

FNIS: $A^- = \{\tilde{v}_1{}^-, \tilde{v}_2{}^-, \cdots, \tilde{v}_n{}^-\} = \left\{\left(\min_i v_{ij} \middle| j \in J\right), \left(\max_i v_{ij} \middle| j \in J'\right)\right\}$ ------------ (14)

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 Equations (15) and (16) respectively. D_i^* in Equation (15) is the summation of the FPIS distance in the i^{th} row for each alternative i and D_i^- in Equation (16) is the summation of the FNIS distance in the i^{th} row for each alternative i. The distance of fuzzy number is calculated using Equation (17) by taking the mean square value of all fuzzy elements.

$D_i{}^* = \sum_{j=1}^{n} d_v(v_{ij}, v_j{}^*)\ , for\ i = 1,2, \dots, m$ --- (15)

$D_i{}^- = \sum_{j=1}^{n} d_v(v_{ij}, v_j{}^-)\ , for\ i = 1,2, \dots, m$ -- (16)

$D(\tilde{x}, \tilde{y}) = \sqrt{\frac{1}{3}[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2]}$ ------------------------------- (17)

Step 6: The relative closeness to the ideal solution, or closeness coefficient $\overline{C_i}$ is calculated using Equation (18). The alternatives are ranked in descending order of the closeness coefficient $\bar{C}_i$. The value of closeness coefficient $\bar{C}_i$ ranges from 0 to 1. The closer an alternative A_i relative to FPIS, the larger the value of closeness coefficient $\bar{C}_i$.

$\bar{C}_i = \frac{D_i{}^-}{D_i{}^- + D_i{}^*}\ for\ i = 1,2, \dots, m$ -- (18)

4.4.2 Data Collection and Questionnaire Construction

This section shows the questionnaire construction and data collection method for phase 2. A questionnaire with 39 questions was created to collect data for phase 2 of the research. This questionnaire is split into two parts. In part 1, there are 4 questions related to respondents' company profile. In part 2, there are 23 questions related to rating of ELT recycling alternatives under circularity and 12 questions are related to rating of ELT recycling alternatives under sustainability. The questionnaire can be found in Appendix C.

In part 1, the respondents are required to select and provide the information pertaining to the size of company, annual gross sales or turnover, monthly output of ELT and the ELT recycling alternatives applicable to the company.
In part 2, the respondents are required to rate the relevant recycling alternatives under each circularity and sustainability item. The rating is performed using linguistic variables (i.e., Very High, High, Medium High, Medium, Medium Low, Low and Very Low). In this phase, linguistics data is collected as opposed to numerical data due to several reasons. Firstly, the data is too sensitive and is prohibited to be revealed to the public. Secondly, some data is not currently being reported in the company, where subjective assessment is required to judge the current status in the industry. Thirdly, some criteria cannot be measured using numerical numbers and can only be assessed using qualitative assessment.

A non-probable, critical case purposive sampling will be used to select one case study company and its supply network to participate and provide data for this research. Critical case sampling is used in a research to make a point dramatically using a representative case (Saunders, 2012: 302). The focus of data collection is to apprehend what is happening in the critical case, so that logical generalisations can be made. The reason of using single case study is because a richer response can be obtained by focusing solely and more in-depth on one case. Furthermore, one case study is also sufficient to disprove a theory by the discovery of a single refuting case (i.e., circularity would not contribute to sustainability) (Saunders, 2012).

To find the most suitable research target, four selection criteria were formed. It must be an experienced (at least ten years of operating experience) and a major company that deals with collection and sales of ELT. It must also have the afore selected five recycling alternatives to manufacture new products (i.e., synthetic turf, sports surface, moulded objects, cement, and foundries). The company must not be owned by the manufacturer and possesses company vision related to circularity and sustainability. The critical case sample must fit and satisfy the criteria and case description, which is summarised in Table 4.8.

Table 4.8: Case description of Case Study Company (Source: Author).

Case study Company
An ELT collection company that has a minimum of ten years of operating experience.
A company that supplies the collected ELT to 5 recycling alternatives to manufacture new products, namely synthetic turf, sports surface, moulded objects,

cement, and foundries.
A decentralised company (not owned by the manufacturer, so that it possesses free will to distribute the product to any recycling alternative).
Possesses company vision related to circularity and sustainability

LinkedIn that brings together supply chain experts from all over the world are used in this research for recruitment of respondents. Similar to the previous section, the prospect companies are searched using Linkedin search engine according to the criteria listed and filtered according to their years of experience in the related field.

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 sale of USD 69 million. Not only that there are very few recycling companies worldwide that would fit the criteria (i.e., supplying ELT to the 5 specific recycling alternatives), the French company also represents one of the biggest companies who is keen to participate in this research, which many smaller companies usually benchmark against.

The company person in charge was contacted by the researcher via LinkedIn and an email to brief the research and obtain their informed consent. Three sets of questionnaires were distributed to the case company person in charge via an email, attaching the link to the survey created using Qualtrics. The three-set questionnaires were completed by three different managers in the company to obtain results with high precision and accuracy through the triangulation method. The use of three DMs and triangulation of results are widely used to increase reliability of data (Boran et al., 2009; Kannan et al., 2014). Upon successful completion, the answer sheets were delivered to the researcher through Qualtrics.

4.5 Phase 3: Optimising Product Allocation to Alternative(S)

4.5.1 Selection of Data Analysis Method and Technique

As exemplified in Section 2.4, unequivocal relationship between circularity and sustainability cannot be attained due to the conflicting results in different research studies (Geissdoerfer, 2018). Even though vast majority of the research presented a positive relationship between circularity and sustainability, the minor proclaim of the negative relationship is not circumvented.

Consequently, circularity and sustainability are treated as different objectives that are contradicting, making this research problem to be modelled as a multi-objective problem. Furthermore, since the desired output of decision variable from solving this problem is the weight of ELT, which is allowed to be a non-integer value with decimal, this research problem is thus not an Integer Programming. Meanwhile, all the objectives' functions and the constraints in this study are linear, thus this research problem is formulated as linear programming. As a result, a Multi Objective Linear Programming (MOLP) is formed.

The use of MOLP is beneficial because the information about the real world resources limitations can be sufficiently addressed in this study (Emrouznejad and Marra, 2017). The integration of FTOPSIS and MOLP is even more superior to the sole use of MOLP because more dimensions and items with different units can be simultaneously integrated in the analysis without affecting the computational time. Moreover, qualitative data can be included in this hybrid model as input. 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).

The formulation of objective functions and their constraints in the hybrid MOLP model is presented in the following section. Objective functions 1 and 2 are constructed using the output from FTOPSIS in phase 2 as coefficients in the objective functions, which are derived according to the normalised closeness coefficient. Nevertheless, there will always exist some constraints in the real world problems, such as production capacity, resources available, demands or quality. In order to closely resemble the actual case, and to maintain the reliability and accuracy 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 Equations (19) and (20):

$$Max\ (Circularity) = \sum_{i=1}^{N} w_{Circ,i} * X_i \text{ --- } (19)$$

$$Max\ (Sustainability) = \sum_{i=1}^{N} w_{sust,i} * X_i \text{ --- } (20)$$

where
X_i = the allocated amount of ELT for the ith recycling alternative.
$W_{CE,i}$ = The overall score (priority value) of ith recycling alternative under circularity criteria obtained from the FTOPSIS.
$W_{sust,i}$ = The overall score (priority value) of ith recycling alternative under sustainability criteria obtained from the FTOPSIS.
N = the number of recycling alternative.

The MOLP model is subjected to the following constraints:

$$f(X_i) = \begin{cases} X_i \leq D_i, & D_i \leq C \\ X_i \leq C, & D_i > C \end{cases} \text{--} (21)$$

$$\sum_{i=1}^{N} X_i = S \text{--} (22)$$

$$X_i \geq 0 \text{--} (23)$$

where
Di = The demand of i[th] recycling alternative for the planning period.
C = The capacity of the ELT collector company.
S = Total sales of previous year.
The amount of the ELT allocated to each recycling alternative must be equal or less than the demand of that alternative, under the condition that it is not exceeded the capacity of ELT collector company (Equation 21). The sum of ELT allocated to all the alternatives must be equal to the ELT sales of the collector company from the previous year (Equation 22). The decision variable, which is the weight of ELT assigned to the recycling alternatives, must satisfy the non-negativity restriction as shown in Equation (23).

In the multi-objective problems, optimisation means finding the set of solutions, comprised of a (or more) decision variable that is able to satisfy all the constraints and provides an acceptable value for the objective functions. In this research, the decision variable that is required to be optimised is the weight of ELT that should be allocated to the recycling alternatives, aiming to attain high values for both objectives, namely the circularity and sustainability.

Nevertheless, it is almost difficult to find one best solution that can satisfy all constraints and excel in all objectives simultaneously. However, it exists a set of solutions that can satisfy both objectives reasonably under specified constraints. This set of solutions is also known as feasible solutions (Rabbani et al., 2017). Among the feasible solutions, there will be some solutions that are known as non-dominated solutions, where the solutions are not dominated by any other solutions in the feasible area. The non-dominated solutions, are also called Pareto optimal solutions (Mitchell, 1998; Yilmaz and Tufekci, 2018).

Some methods that are commonly used to solve multi-objective problems and to acquire the Pareto optimal solutions, are GA, SA, GP, TS, MMO and OA (See Section 4.2). Among the methods, GA is better than other methods due to several reasons. The computational effort and time in using GA is much shorter compared to other methods, because several Pareto optimal set can be obtained in a single run using GA (Mitchell, 1998). Moreover, GA is less sensitive to the convexity of the Pareto front (Talbi, 2009), making it more effective than other methods whereby their applicability is highly susceptible to convexity of the problem and the result can potentially be trapped in a local minimum or maximum (Talbi, 2009). One of the derivatives of GA, known as NSGA-II, further outperforms other algorithms as well as its predecessor GA in terms of the number of Pareto solutions, spacing metrics, and diversifications (Rabbani et al., 2017). NSGA-II is also discovered to be highly appropriate for solving MOLP with two or three objectives (Adra and Fleming, 2011; Chow and Yuen, 2012). NSGA-II could yield a highly diverse set of solutions that are converging near the true Pareto optimal solution just by using a few iterations, further shortening the computational time (Deb et al., 2000; Cao et al., 2011; Masoomi et al, 2013). Moreover, it has now become the standard method for solving multi-objective problems (Talbi, 2009; Adra and Fleming, 2011; Chow and Yuen, 2012).

The differences between the abovementioned methods used for solving the MOLP are summarised in Table 4.9. By comparing and contrasting the different methods, GA specifically NSGA-II will be used in this study to solve the MOLP as opposed to SA, GP, TS, MMO and OA.

Table 4.9: Justification of the use of NSGA-II (Source: Author).

GA (NSGA-II)	SA, GP, TS, MMO and OA
One run of the algorithm produces a set of Pareto optimal solutions, which greatly reduces the computational time	The algorithm is repeated to produce one Pareto optimal solution in each run, which greatly increases the computational time
Becomes the standard approach to be used in solving multi-objectives problems	Not a standard approach to be used in solving multi-objectives problems
Highly suitable for optimisation problems having two or more objectives	High computational time is required to solve optimisation problems having multiple objectives
Outperformed other solution methods in term of the number of Pareto solutions, spacing metrics and diversification	The solution sets are not diverse and are located very closely to one another in the feasible region

NSGA-II involves several steps that require to be customised to solve the multi-objective problems (Deb et al., 2000), namely chromosome representation and encoding, initialisation of population, parent selection, cross-over and mutation.

<u>Step 1: Chromosome representation and encoding</u>

Like its predecessor, GA, the decision variables in a MOLP are required to be encoded into a chromosome (Zhang et al., 2017). A chromosome is an information carrier regarding a system, with several genes and each gene is carrying a part of the different information within it. In this research, the allocation of ELT to recycling alternatives is considered a chromosome, and the information regarding the allocation of ELT to different alternative is stored individually in different genes in the chromosome. An example is shown in Figure 4.5. In this example, gene 1 encodes the allocation of ELT to recycling alternative 1, which is 500 tonnes, gene 2 encodes the allocation of ELT to recycling alternative 2, which is 400 tonnes, and gene N encodes the allocation of ELT to recycling alternative N, which is R tonnes. The total number of genes in the chromosome is the total number of alternatives N in the study.

Genes	1	2	N
Real number encoding	500	400	R

Figure 4.5: Representation of chromosome (Source: Author).

There are many encoding types in GA, namely binary encoding, real number encoding, permutation encoding and tree encoding. Real number encoding is used due to the problem in this research involves real numbers (i.e., the weight of ELT allocated to alternatives) and the range involved is small (i.e., from 0 to D_i, the demand of each alternative).

Step 2: Population and population initialisation

In GA, initialisation of population is a highly important stage during the optimisation process. The initialisation of population defines the parent solution (P_t), which in turn cross-overs with one another in the mating process to generate offspring (Q_t), which represents a new solution to the MOLP. The ability to produce high varieties of offspring in short computational time, spreading across the whole feasible solutions region and not be trapped in the local optimum, is highly dependent on the initial population size. Usually, the whole population is randomly initialised through a process of randomisation to allow maximum variation of the chromosomes and genes. A good population size is about 20 to 30, even though 50-100 are also reported (Mitchell, 1998).

Step 3: Parent selection

They are a series of mating processes among the parents and produce offspring in the calculation. In this step, the first generation of offspring, which are produced by the mating of initial parents in previous step, will become parents that mate and produce second generation of offspring. This process is continued until the offspring carrying non-dominated solution set is produced.

In this step, there are various selection schemes in selecting the best offspring among the many offspring in each generation to become the new parents for mating and producing the next generation's offspring via the "survival of the fittest" method. The commonly used selection schemes are Roulette wheel selection with/without scaling, Stochastic (probability) or Deterministic Binary Tournament Selection, Remainder Stochastic Sampling with/without replacement and Elitism (Mitchell, 1998). In this study, the Binary

Tournament Selection is used for the selection scheme as it is faster and more accurate (Goldberg and Deb, 1991).

Before the Binary Tournament Selection process, each chromosome is evaluated by assessing the level of achievement of objective functions by providing the information in the genes of each chromosome into Equations (19) and (20). The value of objective functions will be used as fitness value to determine the superiority of the solution. The solutions are then plotted in a scatter plot and sorted into each front (F_1, F_2,… F_t), depending on the fitness value as shown in Figure 4.6. In the figure, solutions A, B, C, D, E have the best fitness value and are dominating the solutions F, G, H, I, J, K, L and M. Since solutions A, B, C, D, E do not dominate each other, there are situated together in the same front.

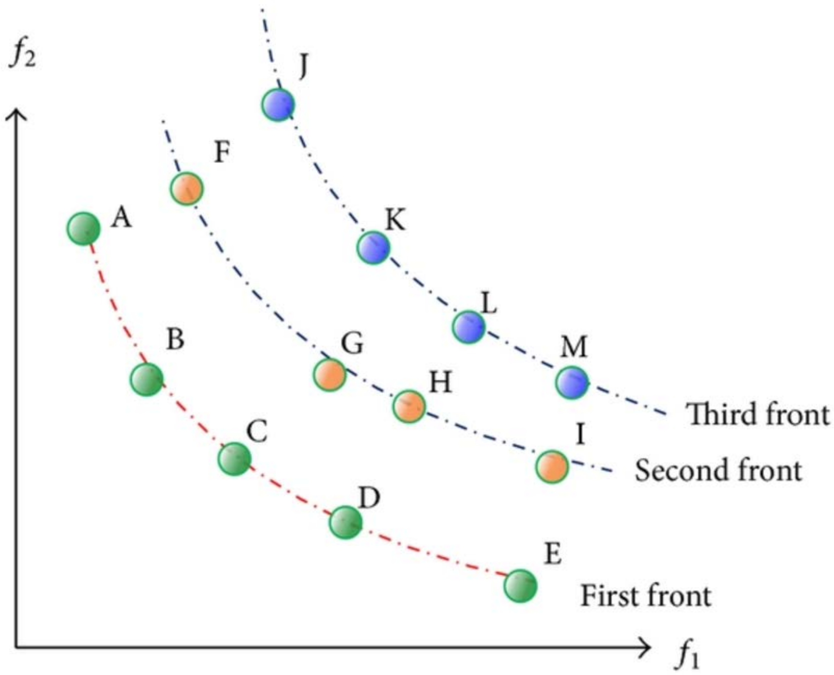

Figure 4.6: Diagram of non-dominated sorting (source: *Wang et al., 2015*).

A rank, known as non-domination rank, is assigned to every solution in each front depending on the front they are situated in. Rank of 1 is given to solutions in the first front while rank of 2 is given to solutions in the second front and so on. A better solution from each generation are the solutions with lower ranking value.

In the Binary Tournament Selection, two solutions with lower non-domination rank (i.e., 1st rank), are selected as new parents to mate in every iteration, in producing a new generation of offspring. If there are more than two solutions having the same rank (i.e., both solutions are situated in first front and have non-domination rank of 1), only two solutions with greater Crowding Distance (CD) is selected for mating, as shown in

Equations (24) and (25). CD is calculated for each i^{th} solution in the first front with non-domination rank of 1, using the fitness value (f) for each objective, m. For a bi-objective problem where m=2, the fitness value, f_m is thus f_1 and f_2.

$$CD_{im} = \frac{f_m(x_{i+1}) - f_m(x_{i-1})}{f_m(x_{max}) - f_m(x_{min})}, i = 1,2, \dots, (l-1) \tag{24}$$

$$CD_i = \sum_{m=1}^{M} CD_{im} \tag{25}$$

This section depicts how NSGA-II prevails its predecessor and other methods because of its fast-sorting ability while preserving elitism of chosen chromosomes to the next generation, as well as its ability to maintain the diversity of solution by maximising the Crowding Distance. The mating process of the two selected solutions to produce offspring is described in the following step using crossover and mutation operators.

Step 4: Crossover and mutation

Like reproduction process in the nature, crossover operation will produce near parent offspring with characteristics that are closely resembled to their parents (Mitchell, 1998; Deb et al., 2000). In this process, two offspring are produced from two parent solutions after the crossover process. Two points between a string are randomly selected for crossover operation as depicted in Figures 4.7 and 4.8. From Figure 4.7, the genes of the first parent are shown in white colour and the genes of the second parent are shaded in grey. Crossover points are randomly selected as depicted by bold line in Figure 4.8, where genes of the first and second parents will interchange, resulting in two new offspring with different genetic contents (i.e., child 1 and child 2).

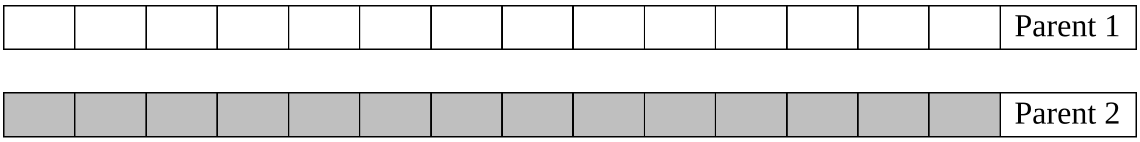

Figure 4.7: Genes of parent 1 and parent 2 before crossover (Source: Author).

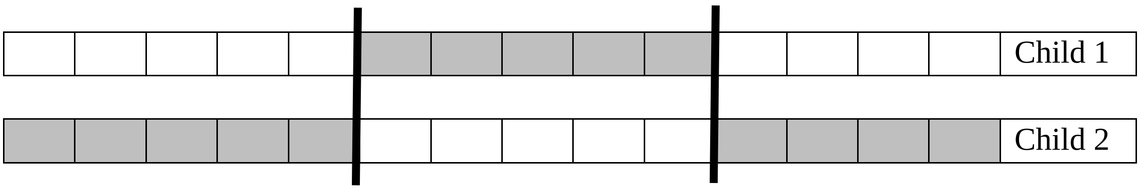

Figure 4.8: Genes of parent 1 and parent 2 after crossover (Source: Author).

Generally, crossover probability should be high, around 80%-95%, even though it could be as low as 60% in some cases. A random value will be generated for each chromosome to determine the occurrence of crossover. Crossover will only occur if the random value generated is higher than the probability pre-set (i.e., 80%-95%).

The parent solutions that do not crossover will be selected for the mutation operation. Every individual gene in the chromosome will have a chance to be mutated (i.e. modified) by randomly interchanging the information in the selected genes with a given probability p_m (Mitchell, 1998; Deb et al., 2000). After the mutation process, one parent solution will generate one offspring. The mutation rate is usually rather small with a general rule of thumb being 1/number of genes in a chromosome, ranging from 0.001 to 0.1.

Eventually, all the generated offspring from crossovers and mutations are to be ensured to fulfil some specified constraints. The offspring that fail to satisfy the constraints are removed from the new population. The whole process of NSGA-II to obtain the Pareto optimal solutions is described in pseudo code as shown in Figure 4.9 and a flow chart in Figure 4.10. A termination criterion of 150 iterations of the generated solutions is applied. The code used for this research is shown in Appendix D.

```
Procedure NSGA-II
  Input: N', g, f_k(X) ▷ N' members evolved g generations to solve f_k(X)
  Initialize Population ℙ';
  Generate random population - size N';
  Evaluate Objectives Values;
  Assign Rank (level) based on Pareto - sort;
  Generate Child Population;
     Binary Tournament Selection;
     Recombination and Mutation;
  for i = 1 to g do
      for each Parent and Child in Population do
          Assign Rank (level) based on Pareto - sort;
          Generate sets of nondominated solutions;
          Determine Crowding distance;
          Loop (inside) by adding solutions to next generation starting from
          the first front until N' individuals;
      end
      Select points on the lower front with high crowding distance;
      Create next generation;
         Binary Tournament Selection;
         Recombination and Mutation;
  end
```

Figure 4.9: Pseudo code for NSGA-II algorithm (source: Filho and Vergilio, 2016).

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Figure 4.10: Flowchart of NSGA-II process (source: Kumar and Yadav, 2017).

4.5.2 Data Collection and Questionnaire Construction

The only primary data required for this phase are data pertaining to demand and capacity (i.e., demand for each recycling alternative and the capacity of the ELT production of the company). These data are required to build constraints in the MOLP. The data are requested in the same questionnaire developed for phase 2, as shown in Section 4.4.2 and Appendix C.

4.6 Phase 4: Explaining Discrepancies Between Modelling Results and Actual Resources Allocation

An interview protocol was prepared based on the reviewed literature and the optimised results of the MOLP model to explore the discrepancy between the modelling results and actual business. The interview protocol is shown in Appendix E, consisting of opening script, rationale for interview questions and closing script. The interview questions and the rational are summarised in Table E1.

Particularly, this interview focusses on discovering the barriers that obstruct the company from the attempt towards achieving the optimum result shown in the modelling from phase 3. Further, the enablers that would improve this situation and promote circular and sustainable practices in the ELT recycling industry are learnt.

A semi-structured online interview was conducted on 3rd April 2020 with the three managers that participated in phase 2 of the research. The three managers are nominated by the company's person in charge; they fulfilled the set of criteria, which must be a senior manager with 5 years or above of working experience, with sufficient knowledge of the five recycling alternatives involved in the company.

A group interview is conducted, lasting for about one hour. The names of the managers were anonymised to encourage openness of responses, which would ensure a more fruitful information regarding the ELT recycling alternatives selection in the actual business. This will ultimately illuminate any possible hidden connection between the actual business condition and the result suggested by the model proposed in this study.

In semi-structured interviews, only a few pre-determined questions where prepared in advance while the rest of the questions are not, effectively combining both the structured and unstructured interview styles to offer the advantages of both (Bell et al., 2018), The area covered in the semi-structured interviews are listed in Appendix E.

All interviews were taped with permission granted. The audio recorded interviews were then transcribed and analysed thematically by close reading and manual coding using the themes identified in the literature and from the actual terms used by the interviewees. A pre-structured outline was employed, which served as a 'shell' for the gathered data (Miles and Huberman, 1994). The quotes from the interviewees which best explained a particular situation were chosen to illustrate the key points. The findings are summarised in a matrix to enable comparison of data as well as to reveal possible patterns that could emerge from the findings. The analysis was conducted iteratively through the course of data collection. Throughout the iterative and time-intensive data analysis process, the reoccurring words, concepts, and ideas are identified, and integrated into categories according to the emergent and common properties.

The information obtained during the interviews has been used to supplement the quantitative research strategy in the previous phase and is incorporated into the research analysis. The results obtained from these interviews can be served as a critical case study that represents most of the collectors companies in the industry, where government supports are limited.

4.7 Phase 5: Revealing Relationship Between Circularity and Sustainability

This phase utilises the output from phase 3 to answer the research question "What is the impact on sustainability while achieving the CE agenda in the ELT recycling industry?". The objective functions for both objectives (i.e., circularity and sustainability) are calculated using Equations (19) and (20) for every different set of solutions obtained in phase 3. The value of objective functions corresponding to each set of solution is used for a scatter plot to reveal the relationship between circularity and sustainability (Friendly and Denis, 2005). An example of scatter plot is shown as Figure 4.11.

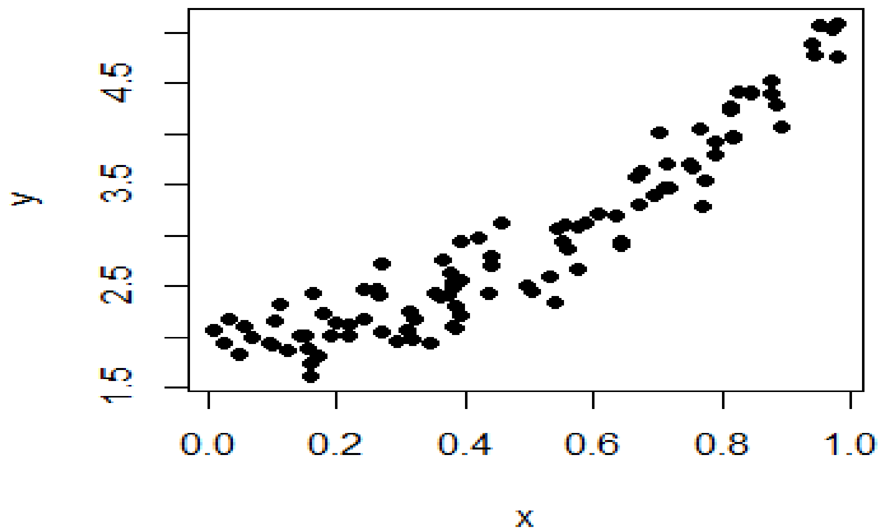

Figure 4.11: Example of scatter plot (Source: Author).

The scatter plot is a type of plot or mathematical diagram which uses Cartesian coordinates to display values for two variables in a set of data (Greenacre, 2017). The data are displayed as a collection of points in the scatter plot. In this process, one variable will determine the position of the point on the horizontal axis, while the value of the other variable will determine the position of the point on the vertical axis (i.e., circularity and sustainability) (Friendly and Denis, 2005).

Upon plotting the points on the scatter plot, it suggests various kinds of correlations between variables, such as positive (rising), negative (falling), or null (uncorrelated) correlation. Positive correlation arises when the points are generally distributed along the diagonal from lower left to upper right. On the contrary, a negative correlation will emerge when the points are distributed along the diagonal from upper left to lower right (Moon, 2016).

A line of best fit (also known as 'trendline') can be drawn to study the relationship between the variables. A best-fit procedure can be applied to determine an equation for the correlation between the variables. In this research, linear regression, which is the best-fit procedure for a linear correlation, will be applied to generate the trendline (Friendly and Denis, 2005; Greenacre, 2017).

5 Results and Discussion

5.1 The Results and Analysis of Phase 1: Weight Determination

5.1.1 The Result of Pilot Study

The face values of the items are obtained following the procedure shown in Section 4.3.1. Overall, five subject-matter-experts comprised of three academic and two practitioners were invited to give their feedbacks in this pilot study. The academic consists of one professor and two associate professors while the practitioners are both managers in their company. The subject-matter-experts are required to rate the questions pertaining to the appropriateness of each item in measuring the constructs using a 7-point Likert scale. For example, “How appropriateness is item C_{1a} in measuring construct C_1?”

The result is tabulated in Table 5.1. The mean score for all the items is well above 3, indicating that the items are appropriate in measuring its construct (i.e., dimension). The standard deviation is also calculated and tabulated under the column “SD”. All the standard deviations are below 1, implying a high convergence in the responses (Rungtusanatham et al., 1999). The decision to include an item within the study is tabulated under the column “Verdict”. All the items are accepted as valid items of measurement within this study.

Table 5.1: Pilot test result (Source: Author).

Dimension	Items	Respondents					Mean	SD	Verdict
		1	2	3	4	5			
C_1	C_{1a}	5	5	6	7	6	5.8	0.8367	Accepted
	C_{1b}	7	6	5	5	7	6	1.0000	Accepted
	C_{1c}	5	4	4	5	4	4.4	0.5477	Accepted
	C_{1d}	5	7	5	6	6	5.8	0.8367	Accepted
	C_{1e}	7	6	7	5	6	6.2	0.8367	Accepted
	C_{1f}	6	6	5	4	6	5.4	0.8944	Accepted
C_2	C_{2a}	6	7	5	6	7	6.2	0.8367	Accepted
	C_{2b}	6	4	6	4	5	5	1.0000	Accepted
	C_{2c}	6	6	6	4	5	5.4	0.8944	Accepted
	C_{2d}	7	7	6	6	7	6.6	0.5477	Accepted
	C_{2e}	7	6	5	7	5	6	1.0000	Accepted
	C_{2f}	7	7	5	6	7	6.4	0.8944	Accepted
C_3	C_{3a}	5	7	6	6	5	5.8	0.8367	Accepted
	C_{3b}	7	7	6	6	6	6.4	0.5477	Accepted
	C_{3c}	6	6	5	6	4	5.4	0.8944	Accepted
	C_{3d}	7	6	5	5	6	5.8	0.8367	Accepted
C_4	C_{4a}	6	5	7	6	7	6.2	0.8367	Accepted

	C_{4b}	6	6	6	5	7	6	0.7071	Accepted
C_5	C_{5a}	7	7	5	5	6	6	1.0000	Accepted
	C_{5b}	7	7	6	7	7	6.8	0.4472	Accepted
	C_{5c}	6	4	6	5	4	5	1.0000	Accepted
	C_{5d}	6	4	5	6	4	5	1.0000	Accepted
	C_{5e}	7	6	5	6	5	5.8	0.8367	Accepted
S_1	S_{1a}	7	5	5	6	6	5.8	0.8367	Accepted
	S_{1b}	7	7	5	6	6	6.2	0.8367	Accepted
	S_{1c}	4	6	5	5	5	5	0.7071	Accepted
S_2	S_{2a}	5	7	6	5	7	6	1.0000	Accepted
	S_{2b}	5	7	6	5	5	5.6	0.8944	Accepted
	S_{2c}	6	5	7	7	7	6.4	0.8944	Accepted
	S_{2d}	7	6	7	5	7	6.4	0.8944	Accepted
S_3	S_{3a}	7	6	5	5	5	5.6	0.8944	Accepted
	S_{3b}	7	5	5	6	5	5.6	0.8944	Accepted
	S_{3c}	7	6	7	7	6	6.6	0.5477	Accepted
	S_{3d}	7	7	7	6	7	6.8	0.4472	Accepted
	S_{3e}	5	5	5	4	5	4.8	0.4472	Accepted

Based on the result, the hierarchical structures of both circularity and sustainability criteria are shown in Figures 5.1 and 5.2, respectively. The hierarchical structures consist of three levels, where the objective is in the first level, the dimensions in the second level and items in the third level.

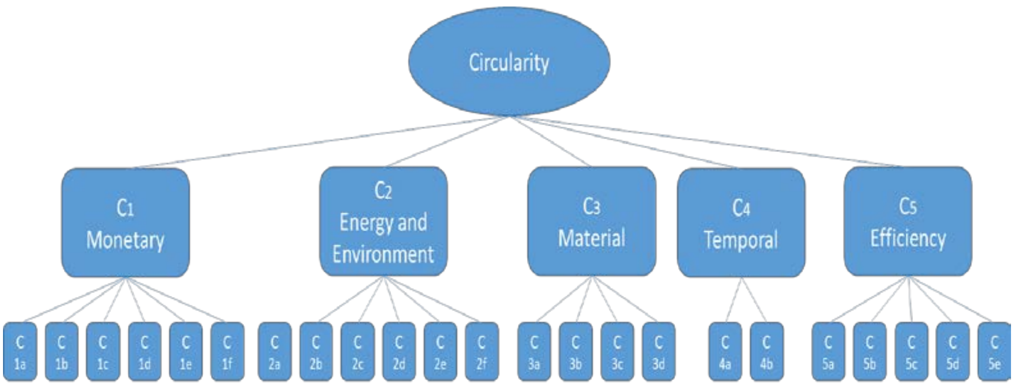

Figure 5.1: Hierarchy of the circularity criteria (Source: Author).

As shown in Figure 5.1, the first objective of this study is to measure the circularity of the recycling alternatives. There are five dimensions involved in the circularity measurement, namely C_1-monetary, C_2-energy and environment, C_3-material, C_4-temporal and C_5-efficiency. The items that are involved in dimension C_1 are pertaining to the cost and profit related to CE elements, namely C_{1a}, C_{1b}, C_{1c}, C_{1d}, C_{1e} and C_{1f}, with the description as discussed in Section 2.3. Dimension C_2 concerns about the pattern of energy consumption and environmental pollution related to it, measuring using items C_{2a},

C_{2b}, C_{2c}, C_{2d}, C_{2e} and C_{2f}. Dimension C_3 concerns with the source of materials input to the recycling alternatives as well as the handling of the undesired output materials, using four items namely C_{3a}, C_{3b}, C_{3c} and C_{3d}. Dimension C_4 concerns with items associated with time, i.e., C_{4a} and C_{4b}. Dimension C_5 intends to understand the efficiency or performance of the CE related processes, using items C_{5a}, C_{5b}, C_{5c}, C_{5d} and C_{5e}.

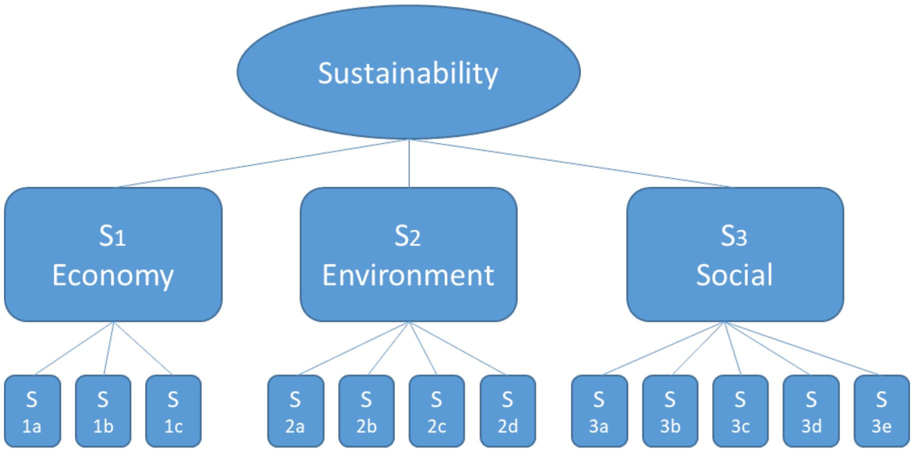

Figure 5.2: Hierarchy of the sustainability criteria (Source: Author).

Based on Figure 5.2, the second objective of this study is to measure the sustainability of the recycling alternatives. The dimensions involved are S_1-economy, S_2-environment and S_3-social. Dimension S_1 concerns with the items related to the economic performance and feasibility of the alternative to continue its operation, namely S_{1a}, S_{1b} and S_{1c}, as described in Section 2.5. Dimension S_2 is related to the consumption of key resources and the environmental pollution, measured using items S_{2a}, S_{2b}, S_{2c} and S_{2d}. Dimension S_3 intends to understand the social wellbeing of the stakeholders within and external to the recycling alternatives using items S_{3a}, S_{3b}, S_{3c}, S_{3d} and S_{3e}.

5.1.2 Analysis of Respondents' Responses

After the pilot study, the phase 1 of the research was conducted using the procedure as described in Sections 4.3.2 and 4.3.3. Overall, 18 experts that fulfilled the inclusion criteria were invited to provide inputs for this phase. The responses of all 18 respondents, pertaining to the relative importance of each dimension and item within circularity and sustainability are collected via Bristol online survey tool and recorded in the Appendices F, G, H and I. The responses are recorded according to the hierarchy level as shown in Table 5.2. The responses pertaining to the relative importance of each dimension (level 2) and item (level 3) within circularity are shown in Appendices F and G respectively. Similarly, the responses pertaining to the relative importance of each dimension (level 2) and item (level 3) within sustainability are included in Appendices H and I respectively.

Table 5.2: The responses pertaining to the relative importance of each dimension and item within circularity and sustainability (Source: Author).

Hierarchy Level	Attributes	
Level 1 (objectives)	Circularity	Sustainability
Level 2 (dimensions)	C_1, C_2, C_3, C_4, C_5 (Appendix F: Tables F1 -F18)	S_1, S_2, S_3 (Appendix H: Tables H1 -H18)
Level 3 (items)	C_{1a}, C_{1b}, C_{1c}, C_{1d}, C_{1e}, C_{1f}, C_{2a}, C_{2b}, C_{2c}, C_{2d}, C_{2e}, C_{2f}, C_{3a}, C_{3b}, C_{3c}, C_{3d}, C_{4a}, C_{4b}, C_{4c}, C_{4d}, C_{5a}, C_{5b}, C_{5c}, C_{5d}, C_{5e} (Appendix G: Tables G1 -G18)	S_{1a}, S_{1b}, S_{1c}, C_{1d}, S_{2a}, S_{2b}, S_{2c}, S_{2d}, S_{2e}, S_{3a}, S_{3b}, S_{3c}, S_{3d}, S_{3e} (Appendix I: Tables I1 -I18)

The profession of the 18 experts invited to provide input for phase 1 are academic and industrial practitioner. There are 9 respondents from each profession. In academic, there are 3 levels of seniority, namely the professors, associate professors and assistant professors, with 3, 4 and 2 experts from each seniority, representing 33%, 45% and 22% of the academics. All the 9 practitioners are of same seniority, namely managers. The breakdown is summarised in Figure 5.3.

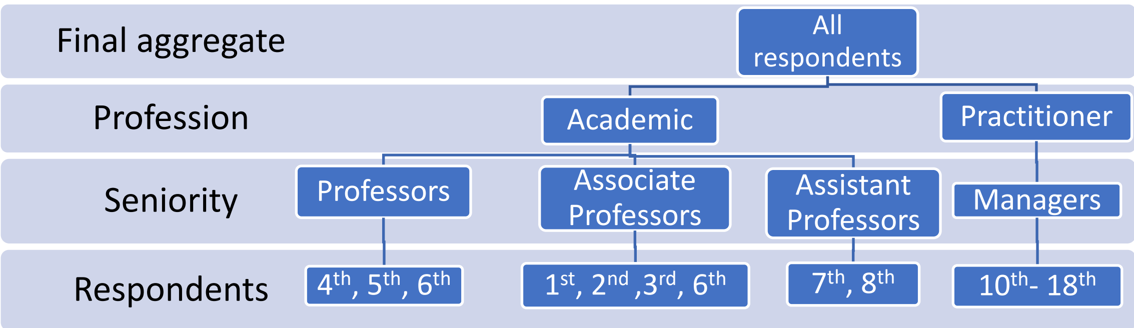

Figure 5.3: Profession, seniority of respondents (Source: Author).

This section determines the reliability of the results by comparing the results of each profession and seniority to the final aggregate result. To determine the reliability, the steps in FAHP calculation as shown in Section 4.3.2 are repeated by single out the respondents based on their profession or seniority. For example, the responses from 3 professors (i.e., respondents 4th, 5th and 6th as shown in Figure 5.3) are aggregated and the FAHP result obtained are compared with the final aggregate result from all 18 respondents. The error is calculated to determine how far the responses deviated from the final aggregate result. The error for each dimension and item for both circularity and sustainability is determined according to respondents' profession and seniority.

Ideally, the error is at its best if the value is close to zero. This will occur if the responses are the same as the final aggregate result. For example, the relative importance of dimension C_1 of professor is 25.71%, which is obtained by single out the professors from other respondents and aggregating their results using FAHP. The error, which is the difference between professors' response with the final aggregated result, is -3.36%. The example of error calculation is shown in Table 5.3. From the table, the error is calculated and tabulated in the last column by taking the difference between professors' response to the final aggregated result. The final aggregated result of all 18 experts can be seen in Section 5.1.3 (refer to Tables 5.10 and 5.12).

Table 5.3: Example of error calculation for professors' responses (Source: Author).

Dimension/ item		Final aggregate (18 respondents)	Professor (3 respondents)	Error, Δ (Professor –Final aggregate)
Circularity dimensions				
C_1		29.07%	25.71%	-3.36%
C_2		25.00%	24.30%	-0.70%
C_3		17.02%	17.31%	0.29%
Circularity items				
C_1	C_{1a}	3.07%	3.03%	-0.04%
	C_{1b}	3.52%	1.40%	-2.12%
C_2	C_{2a}	3.16%	2.35%	-0.81%
	C_{2b}	2.14%	1.04%	-1.10%
	C_{2c}	3.24%	2.83%	-0.41%
C_3	C_{3a}	3.78%	2.38%	-1.40%
	C_{3b}	5.67%	5.42%	-0.25%
	C_{3c}	3.76%	1.76%	-2.00%
C_4	C_{4a}	5.88%	6.35%	0.47%
	C_{4b}	2.43%	1.85%	-0.58%

In total, they are 5 dimensions and 23 items in circularity, yielding 28 errors for each profession and seniority (i.e., professor, associate professor, assistant professor, academic and practitioner or manager). Cumulatively, 140 errors can be obtained from circularity. Likewise, they are 3 dimensions and 12 items in sustainability, yielding 15 errors for each profession and seniority. In total, 75 errors can be obtained within sustainability. Overall, there are 215 errors in both circularity and sustainability.

The errors obtained are analysed using a statistical method to determine the reliability of the results. Mean (μ), also called the expected value, as well as Median are used to calculate the central tendency of the errors of each profession and seniority. The mean and median of errors close to 0 indicate that the responses are very close to the final aggregated result.

Standard deviation (σ) indicates the statistical dispersion of the data set. It is used to determine how the data spreads. A low standard deviation indicates that the values tend to be closer to the mean of the data set, while a high standard deviation indicates that the values are spread out over a wider range (Bland and Altman, 1996).

The distribution of errors is also analysed to ensure that the data obeys the probability theory, which stated that the errors distribution should incline towards a normal distribution. According to the three sigma rules, a data set that is normally distributed will have 68% of the data falling within 1 sigma away from mean (i.e., $\mu \pm \sigma$), 95% of the data falling within 2 sigma away from mean (i.e., $\mu \pm 2\sigma$) and 99.7% within 3 sigma away from mean (i.e., $\mu \pm 3\sigma$), only 0.3% of data will fall outside the range $\mu \pm 3\sigma$ (Pukelsheim, 1992).

Nevertheless, the distribution of an event will only resemble a normal distribution if the number of samples is sufficiently large, as postulated in the law of large number (Hsu and Robbins, 1947). Since the sample size of this research is small due to the nature of Delphi method, a normal distribution of errors is not necessarily attainable. The 140 errors obtained from the circularity and 75 errors obtained from the sustainability are compared against the normal distribution as shown in Figure 5.4. It is seen that the errors distribution is not symmetric and does not exactly follow normal distribution due to small sample size.

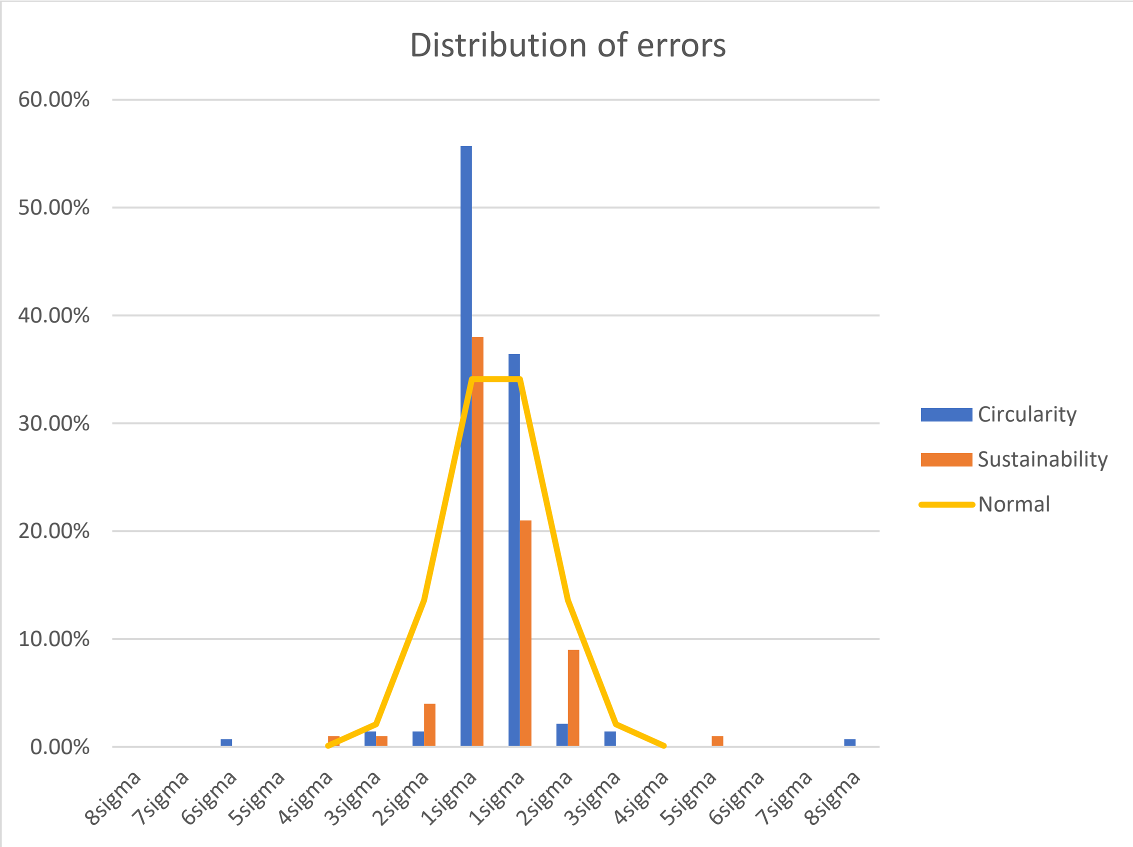

Figure 5.4: Distribution of errors in this research (Source: Author).

Chebyshev's inequality (also called the Bienaymé–Chebyshev inequality), can be used in this case where the distribution is not normally distributed (Heyde and Seneta, 2001; Evans, 2020). Chebyshev's inequality is applicable over a wider class of probability distribution to check whether it obeys probability theory by checking the fraction of values within or a certain distance away from the mean.

To ensure all data are acceptable and reliable, as well as no presence of outliers in the data that would distort the overall results, the errors must distribute in a way as described in Chebyshev's inequality, where no more than $1/k^2$ of the distribution's values can be k or more standard deviations away from the mean (or equivalently, over $1 - 1/k^2$ of the distribution's values are less than k standard deviations away from the mean). There is, therefore, a minimum and maximum threshold to obey in order to be statistically acceptable.

Overall, this section shows that by comparing the final aggregated response of all 18 respondents to the responses of different profession and seniority, a highly cohesive responses can be observed proving the accuracy, reliability and cohesiveness of the results using statistical methods such as the mean, median, SD as well as Chebyshev's inequality for both circularity and sustainability criteria.

5.1.2.1 Reliability of Responses Depending on Seniority and Profession of Respondents in Circularity

The mean, median, SD and Chebyshev's inequality analysis for the errors obtained within circularity criteria are presented in this section as shown in Table 5.4. The errors for each profession and seniority (i.e., professor, associate professor, assistant professor, academic and practitioner or manager) are obtained by comparing individual results to the final aggregate result.

Table 5.4: Analysis of errors in circularity according to profession and seniority (Source: Author).

Statistic Parameter	Academic				Practitioner
	Professor	Associate professor	Assistant professor	Total	Manager
Mean (μ)	0.0000%	0.0014%	-0.0011%	-0.0004%	0.0007%
Median	-0.73%	-0.15%	-0.17%	-0.09%	-0.24%
SD (σ)	2.83%	1.81%	7.62%	1.96%	2.21%

From this table, within the academic, the mean (μ) for professors is the lowest, which is 0.0000%, compared to the academics with lower seniority, which is 0.0014% for associate professors and -0.0011% for assistant professors. Overall, all the academic' means are very small, signifying that their responses are close to the final aggregate. Particularly, professors are having the smallest mean, implying that they are more knowledgeable among the academics, and making them more likely to provide a more accurate response. By aggregating the academics' responses, the mean of error is -0.0004%, which is slightly smaller than the practitioners' mean of 0.0007%. This is probably due to the slightly lack of circularity exposure in the industry, resulting in slightly bigger mean than the academics.

In terms of median, professors have a bigger median of -0.73%, compared to median of lower seniority, which is -0.15% and -0.17% respectively for associate professors and assistant professors; this indicates that professors could be more conservative and most of the data are lower than final aggregate result. By aggregating the academics' responses, the median of error is -0.09%, which is slightly smaller than practitioners' median (which is -0.24%). This suggests that practitioners are slightly more conservative than the academics and most of the data are lower than final aggregate result.

In terms of standard deviation (σ), assistant professors have a bigger standard deviation of 7.62%, as compared to professors and associate professors, which is 2.83% and 1.81% respectively. This shows that the responses for assistant professors are, to some extent, more widespread, probably due to less state-of-the-art knowledge and experience related to the field. Further, this also shows that professors with more knowledge and experience in the field do not necessarily have a smaller spread of errors. This suggests that a good mix of academic of seniority is necessary to be studied. By aggregating the academics' responses, the standard deviation of error is 1.96%, which is slightly smaller than practitioners' standard deviation of 2.21%. This implies that practitioners' opinions are slightly more widespread as compared to academics, probably due to different exposure to circularity in their respective company.

Subsequently, the errors for all professions and seniority are analysed using Chebyshev's inequality to check whether the data are acceptable and reliable, and no outlier greater than maximum allowance is present and distorts the overall results in the data. Overall, there are 140 errors for circularity (28 for each profession and seniority). The mean μ of the 140 errors is -0.0001% and the standard deviation σ is 3.9596%. The range of errors that falls within $\mu \pm k^*\sigma$ is shown in Table 5.5, and the ranges within and outside the $\mu \pm k^*\sigma$ are also checked against the minimum and maximum thresholds to ensure the data are reliable and no outlier is present.

Referring to Table 5.5, there are 92.14% of errors among the 140 that falls within the range of $\mu \pm \sigma$, while 7.86% falls outside the range of $\mu \pm \sigma$. The errors within the range of $\mu \pm \sigma$ are greater than the minimum threshold of 0%, and the errors beyond the range of $\mu \pm \sigma$ are smaller than the maximum threshold of 100%. For every rule of Chebyshev's inequality obeyed, a symbol of "✔" is marked under the column "verdict" to indicate that the errors distribution is accepted, indicating the results are conforming to probability theory and they can be accepted as a reliable piece of information.

Table 5.5: Chebyshev's inequality check for reliability and outliers (Source: Author).

k	% within k standard deviations of mean			% beyond k standard deviations from mean		
	This research	Minimum threshold	Verdict (> min)	This research	Maximum threshold	Verdict (< max)
1	92.14%	0%	✔	7.86%	100%	✔
√2	95.71%	50%	✔	4.29%	50%	✔
1.5	95.71%	55.56%	✔	4.29%	44.44%	✔
2	95.71%	75%	✔	4.29%	25%	✔
2√2	97.86%	87.5%	✔	2.14%	12.5%	✔
3	98.57%	88.8889%	✔	1.43%	11.1111%	✔
4	98.57%	93.75%	✔	1.43%	6.25%	✔
5	98.57%	96%	✔	1.43%	4%	✔
6	99.29%	97.2222%	✔	0.71%	2.7778%	✔
7	99.29%	97.9592%	✔	0.71%	2.0408%	✔
8	100.00%	98.4375%	✔	0.00%	1.5625%	✔
9	100.00%	98.7654%	✔	0.00%	1.2346%	✔
10	100.00%	99%	✔	0.00%	1%	✔

Overall, the errors distribution is in accordance with the rules of Chebyshev's inequality. It is also noted that 92.14% of errors falls within the $\mu \pm \sigma$ range, indicating that 92.14% of the responses is very close to the final aggregated result, which signifies the responses are highly convergence.

There are some errors lie between the $\mu \pm 2\sigma$ and $\mu \pm 3\sigma$ range, which are originated from academics and managers' responses associated with C_1-monetary dimension. Overall, the academics think that dimension C_1 is less importance thus have given it a relative importance slightly lower than the mean, contributing to a negative error between the $\pm 2\sigma$ and $\mu \pm 3\sigma$ range. Conversely, the practitioners think that dimension C_1 is slightly more important, thus contributing to a positive error in the range.

This finding supports that practitioners particularly highlighted monetary dimension compared to other dimensions for assessment of circularity (Potting et al., 2017). Both academics and practitioners have a slight disagreement, particularly on the importance of monetary dimension, producing an error between the $\mu \pm 2\sigma$ and $\mu \pm 3\sigma$ range. This can be explained by the different focuses among the academics and practitioners in arriving at this result. Practitioners are much more economic oriented and motivated by the performance associated with monetary. Any decision made in the industry must be associated with the possibility to sustain the business or generate greater income for the company, so as to ensure the business can make profits and continue to operate (Murray et al., 2015; Kirchherr, 2017; Potting et al., 2017).

Another error that lies between the $\mu \pm 2\sigma$ and $\mu \pm 3\sigma$ range is item C_{1f}-profit or saving per recyclable input consumed. This item is deemed to be very important by the professors, who are more knowledgeable among the academics. The professors think that the other items within dimension C_1 such as C_{1a}, C_{1b}, C_{1c}, C_{1d} and C_{1e} are not as important as C_{1f}. This is because C_{1f} can easily be measured and can most directly reflect the level of monetary performance. This is true because profit is the item that can be most easily understood in a performance report compared to cost, as profit is the clear result of subtracting all associated costs from the revenue, giving an indication of monetary performance of a business. This makes C_{1f} highly easy to use, thus is given a slightly higher weight by the professors.

Notably, there is one error lies outside the $\mu \pm 6\sigma$ and $\mu \pm 7\sigma$ range, both originated from assistant professors' responses, associated with dimension C_1-monetary and C_2-environment and energy respectively. This can be explained by the fact that assistant professors are over-emphasizing on the C_2-energy and environment dimension compared to C_1-monetary dimension, thus producing highly positive error in C_2 and consequently highly negative error in C_1. The reason for assistant professors to over-emphasize certain dimension is because of over reliance on theory while answering the questionnaire (e.g., over relying on some literature that are highly pro-environment, such as Boyce (2002)). This also contributes to an error situated between the $\mu \pm 2\sigma$ and $\mu \pm 3\sigma$ range associated with C_3-material dimension, which is a weakly negative error due to over-emphasizing on the C_2 that causes the reduction of importance in both dimensions C_2 and C_3.

5.1.2.2 Reliability of Responses Depending on Seniority and Profession of Respondents in Sustainability

Same as previous section, this section presents the mean, median, SD and Chebyshev's inequality analysis for the errors obtained within sustainability criteria, as shown in Table 5.6. The errors for each profession and seniority (i.e., professor, associate professor, assistant professor, academic and practitioner or manager), are obtained by comparing individual results to the final aggregate result.

Table 5.6: Analysis of errors in sustainability according to profession and seniority (Source: Author).

	Academic				Practitioner
	Professor	Associate professor	Assistant professor	Total	Managers
Mean	0.0013%	0.0007%	0.0000%	-0.0007%	-0.0013%
median	-0.41%	-0.66%	-0.63%	-0.31%	-0.41%
SD	5.08%	4.80%	8.47%	2.80%	3.20%

From the table, within the academics, the mean (μ) for assistant professors is the lowest, which is 0.0000%, compared to academic with higher seniority, i.e., 0.0007% for associate professors and 0.0013% for professors. This indicates that responses for assistant professors are slightly closer to final aggregate as compared to associate professors or professors. This implies that accuracy is independent of seniority and a good mix of seniority within academic is necessary. By aggregating the academics' responses, the mean of error is -0.0007%, which is slightly smaller than the practitioners' mean of -0.0013%. This is likely due to the deeper understanding of sustainability within academics compared to practitioners, resulting in a slightly smaller error of mean.

In terms of median, professors have a smaller median of -0.41% as compared to median of lower seniority, which is -0.66% and -0.63% respectively for associate professors and assistant professors. This indicates that professors have higher precision than academics of lower seniority in sustainability criteria, thus most of the results are closer to each other. By aggregating the academics' responses, the median of error is -0.31%, which is slightly smaller than practitioners' median of -0.41%. This suggests that the practitioners are slightly more conservative than the academics, since most of the responses are lower than the final aggregate result.

As for standard deviation (σ), assistant professors have a bigger standard deviation of

8.47% as compared to professors and associate professors, which has 5.08% and 4.80% respectively. This shows that the responses for assistant professors are slightly more widespread, probably due to less of state-of-the-art knowledge and experience in the field. Nevertheless, it is also discovered that professors which are more knowledgeable and experience have higher standard deviation than associate professors. Having said that, this result coincides with the previous analysis in the circularity criteria, showing that professors which are more knowledgeable and experience in the field do not necessarily have a smaller spread of errors, suggesting a good mix of academics of seniority is necessary in the study. By aggregating the academics' responses, the standard deviation of error is 2.80%, which is slightly smaller than practitioners' standard deviation of 3.20%. This indicates that practitioners' opinions are slightly more widespread as compared to academics, probably due to the different exposure to sustainability in their respective company. Furthermore, it implies that the relative importance of dimensions and items within sustainability is relatively more difficult to estimate or measure, resulting in more widespread of errors. This research supports the finding of Mayer et al. (2004) and Harmancioglu and Barbaros (2013) who assert that sustainability is a philosophical concept that is often poorly defined and is difficult to be measured.

Same as circularity, the errors for all professions and seniority are analysed using Chebyshev's inequality to check whether the data are acceptable and reliable, and no outlier greater than maximum allowance is present and distorts the overall results in the data. Overall, there are 75 errors for sustainability (15 for each profession and seniority). The mean, μ of the 75 errors is 0.0000% and the standard deviation, σ is 5.2675%. The range of errors falls within $\mu \pm k^*\sigma$ are shown in Table 5.7. The ranges within and outside the $\mu \pm k^*\sigma$ are checked against the minimum and maximum thresholds to ensure the data are reliable and no outlier is present.

From Table 5.7, there are 78.67% errors of the 75 errors that falls within the range of $\mu \pm \sigma$, while 21.33% falls outside the range of $\mu \pm \sigma$. The errors within the range of $\mu \pm \sigma$ are greater than the minimum threshold of 0%, and errors beyond the range of $\mu \pm \sigma$ are smaller than the maximum threshold of 100%. Same as circularity, a symbol of "✔" is marked under the column "verdict" for every rule of Chebyshev's inequality complied with, indicating that the errors distribution is conforming to probability theory, which can be accepted as a reliable result.

Table 5.7: Chebyshev's inequality check for reliability and outliers (Source: Author).

k	% within k standard deviations of mean			% beyond k standard deviations from mean		
	This research	Minimum threshold	Verdict (> min)	This research	Maximum threshold	Verdict (< max)
1	78.67%	0%	✔	21.33%	100%	✔
√2	89.33%	50%	✔	10.67%	50%	✔

1.5	89.33%	55.56%	✔	10.67%	44.44%	✔
2	96.00%	75%	✔	4.00%	25%	✔
$2\sqrt{2}$	97.33%	87.5%	✔	2.67%	12.5%	✔
3	97.33%	88.8889%	✔	2.67%	11.1111%	✔
4	98.67%	93.75%	✔	1.33%	6.25%	✔
5	100.00%	96%	✔	0%	4%	✔
6	100.00%	97.2222%	✔	0%	2.7778%	✔
7	100.00%	97.9592%	✔	0%	2.0408%	✔
8	100.00%	98.4375%	✔	0%	1.5625%	✔
9	100.00%	98.7654%	✔	0%	1.2346%	✔
10	100.00%	99%	✔	0%	1%	✔

Overall, the errors distribution is compliance to the rules of Chebyshev's inequality. There are some errors lie between the $\mu\pm 2\sigma$ and $\mu\pm 3\sigma$ range, which are originated from associate professors' responses regarding S_3. It is a highly negative error because associate professors think that social sustainability is not as important compared to other dimensions, while other academics think that social sustainability is very important, which contributed to positive errors. Once again, it is shown that the view regarding relative importance of dimension within sustainability is slightly more diverged, and it is independent of seniority of academics, and that sustainability is a philosophical concept and is still difficult to be measured.

Notably, there is one error outside the $\mu \pm 3\sigma$ range and $\mu \pm 4\sigma$ range, which are both from assistant professors' responses associated with S_1 and S_3, respectively. The phenomenon of assistant professors over-emphasizing on the dimension other than C_1-monetary dimension in circularity, can also be observed here in sustainability, where assistant professors are over-emphasizing on the dimension other than S_1-economic dimension. This generates a highly negative error on dimension S_1 in favour of S_3, resulting in a highly positive error in S_3. This is because of exaggeration of responses due to over relying on theory when answering the questionnaire, driven by the literature that favours social sustainability and condemns sole focus on economic (e.g. Boyce, 2002).

5.1.2.3 Comparing the Reliability of Responses Depending on Seniority and Profession of Respondents in Circularity and Sustainability

Overall, this section shows that by comparing the final aggregated response of all 18 respondents to the responses of different professions and seniority, a highly cohesive responses can be observed. The mean, median and SD for the errors for both circularity and sustainability criteria are ranged from -0.0013% to +0.0014%, -0.73% to -0.09% and 1.81% to 8.47% respectively. The mean and median for the errors are very close to 0 and the SD is relatively very small, proving that differences in profession or seniority do not affect the accuracy, reliability and cohesiveness of the results.

Generally, by comparing the errors obtained for all professions and seniority for the two criteria circularity and sustainability, it is discovered that the 75 errors pertaining to sustainability criteria are slightly more dispersed than the 140 errors related to circularity, with ($\mu \pm \sigma$) of (0.0000% + 5.2675%) and (-0.0001% + 3.9596%) for sustainability and circularity respectively. The central tendency for both errors is very close to 0, indicating the accuracy of responses.

Sustainability is having a standard deviation, σ slightly higher than circularity, proving that even though the sustainability has been a well-established concept, it is still a philosophical concept that is difficult to be quantified and measured. This can also be visualized when comparing the errors that fall within the range of $\mu \pm \sigma$ in Tables 5.5 and 5.7. It can be seen that only 78.67% of the errors pertaining to sustainability criteria falls within the range of $\mu \pm \sigma$, but as much as 92.14% of the errors pertaining to circularity criteria falls within the range of $\mu \pm \sigma$, supporting the claims of sustainability philosophical concept that is difficult to be quantified and measured due to bigger errors made among the respondents.

5.1.3 Analysis of the Relative Importance of Dimensions and Items Within the Circularity and Sustainability Criteria

This section shows the analysis of the data using FAHP. The responses collected from the respondents are transferred into a comparison matrix following a set of rules, as shown in the example in Table 5.8. Firstly, the responses are recorded in the upper triangular matrix following the first rule. If dimension A is "m" times more important than dimension B, then "m" is recorded in row A under column B. Similarly, if dimension B is "r" times more important than dimension D, then "r" is recorded under row B and column D. The second rule dictates that the diagonal is always 1, because the diagonal is comparing the same item which has equal importance. The third rule is related to the method of filling the lower triangular matrix, which is filled using formula $a_{ij} = \frac{1}{a_{ji}}$ (Saaty, 1990).

Table 5.8: Relative importance, an example (Source: Author).

	A	B	C	D	E
A	**1**	m	n	o	p
B	1/m	**1**	1/q	r	s
C	1/n	q	**1**	t	1/u
D	1/o	1/r	1/t	**1**	v
E	1/p	1/s	u	1/v	**1**

Next, the elements in each comparison matrix are converted into a fuzzy triangular scale (i.e., fuzzification) according to Table 4.5 as shown in Section 4.3.2. The comparison matrix of 18 respondents is aggregated into one aggregated decision matrix, using geometric mean method as shown in Equations (2), (3) and (4). The results obtained for circularity and sustainability are discussed in the next sub-section.

5.1.3.1 Analysis of the Relative Importance of Dimensions and Items Within the Circularity Criteria

5.1.3.1.1 Analysis of the Relative Importance of Dimensions Within the Circularity Criteria

The aggregated decision matrix for the dimensions within circularity is obtained by aggregating the 18 responses (see Tables F1-F18) as tabulated in Table 5.9. The CR for this matrix is calculated using Equation (8). From the calculation, the CR is 0.0119, by taking the ratio of CI to RI for a 5 x 5 matrix, which is 0.0131 and 1.11 respectively. Since the CR is less than 0.1, it implies that no mistakes or conflicting ratings are made by the DMs, and the judgments are acceptable for the weight calculation (Saaty, 1990).

Table 5.9: The aggregated decision matrix of dimensions (level 2) under circularity (aggregation of F1-F18) (Source: Author).

	C_1	C_2	C_3	C_4	C_5
C_1	(1,1,1)	(1,7/6,7/5)	(12/7,2,22/9)	(2,7/3,14/5)	(4/3,11/7,11/6)
C_2	(5/7,6/7,1)	(1,1,1)	(1,5/4,3/2)	(9/4,8/3,28/9)	(4/3,3/2,5/3)
C_3	(2/5,1/2,4/7)	(2/3,1/2,1)	(1,1,1)	(5/3,2,19/8)	(3/4,1,9/8)
C_4	(1/3,3/7,1/2)	(1/3,3/8,4/9)	(3/7,1/2,3/5)	(1,1,1)	(1/3,2/5,1/2)
C_5	(1/2,5/8,3/4)	(3/5,2/3,3/4)	(8/9,1,4/3)	(13/6,13/5,3/1)	(1,1,1)

Using the aggregated decision matrix in Table 5.9, the fuzzy geometric mean value ($\widetilde{r_i}$), fuzzy weight ($\widetilde{w_i}$), and de-fuzzified weight (M_i) is calculated using Equations (5), (6) and (7) and tabulated in Table 5.10. The normalised weight (N) is obtained by taking the ratio of M_i to the sum of all M_i. The resulting normalised weight (N) represents the relative weight of importance for each dimension within circularity.

Table 5.10: Fuzzy geometric mean, fuzzy weight, de-fuzzified weight and normalised weight for dimensions (level 2) under circularity (Source: Author).

	$\widetilde{r_i}$	$\widetilde{w_i}$	M_i	N
C_1	(1.3460,1.5530,1.7707)	(0.2199,0.2949,0.3786)	0.2978	**29.07%**
C_2	(1.1764,1.3346,1.5083)	(0.1922,0.2534,0.3225)	0.256	**25.00%**
C_3	(0.8086,0.8434,1.0794)	(0.1321,0.1601,0.2308)	0.1744	17.02%
C_4	(0.4368,0.4984,0.5742)	(0.0714,0.0946,0.1228)	0.0963	9.40%
C_5	(0.9088,1.0370,1.1886)	(0.1485,0.1969,0.2542)	0.1998	**19.51%**
Sum	(4.6767,5.2665,6.1212)	-	1.0243	100.0%

According to normalised weight in Table 5.10, monetary dimension (C_1) is the most important dimension with a relative importance of 29.07% and is the most influential dimension on circularity of a recycling alternative compared to other dimensions in the eye of decision makers, as highlighted. It is followed by energy and environment dimension (C_2), efficiency (C_5), material (C_3) and temporal (C_4) with a relative importance of 25%, 19.51%, 17.02% and 9.40% respectively.

This result implies that the monetary dimension (C_1) is the most influential dimension that affects circularity. This dimension is deemed to have the strongest influence on circularity because they are most closely related to hasten the attainment of the circularity goals (i.e., to lower or eliminate waste output, resources input and pollution, and to increase resources utility, resources value and economic prosperity). For example, the low cost required to purchase recyclable raw materials or CE technology as well as low cost to repair a product will encourage uptake of CE related practice, which contributes towards achieving the goal of circularity aimed at lowering or eliminating waste output, resources input and to increase resources utility. The ability to generate high profit per every unit of recyclable material consumed, greatly contributes towards achieving the goal to increase resources value and economic prosperity, which ultimately contributes to economic prosperity as envisioned in the CE goal (Stahel, 2013; Murray et al., 2015; Kirchherr, 2017). Evidently, monetary also represents the most commonly employed dimension in constructing a CE indicator among academics (Murray et al., 2017; Sassanelli et al., 2019; Kristensen and Mosgaard, 2020) as well as practitioners (Potting et al., 2017). For many businesses, the revenue-generating activities are prioritised along with the actions to reduce non-essential costs, while other measures to protect environments or benefit stakeholders and employees are viewed as costly and unnecessary (Placet et al., 2005). This also supports that monetary dimension is strongly influencing circularity since they are highly prioritised. Ultimately, this result shows that monetary is the most influential dimension on circularity, which is also verifying the studies of Stahel (2013), Murray et al. (2015), Geissdoerfer et al. (2017) and Kirchherr (2017) who argued that circularity focuses particularly on the economy as a direct consequence of monetary being the most influential dimension affecting the circularity.

Energy and environment dimension (C_2) is the next most influential dimension on circularity, with a relative weight of 25%. The reason this dimension is deemed influential is not only its ability to catalyse attainment of circularity goals (i.e., in lowering or eliminating resources input and pollution). It is also because currently, around three-quarter of energy generated in the world are originated from fossil fuel, which emits surplus of greenhouse gasses that could not be sequestered by the nature, subsequently contributing greatly to the environmental issue (Korhonen et al., 2018). The high usage of fossil fuels will not only pollute our environment, but also deplete our non-renewable sources because the source of the energy, fossil fuel is non-renewable, resembling a typical linear economy system of “taking” the fuels, “making” energy and “dispose” of the fuels which pollute our environments. By learning the catastrophic effects that the said energy sources can bring to our environment, the decision makers agree that this dimension is crucial in influencing circularity, as there is a need to shift away from using fossil fuels as the source of energy into using only renewable energy sources, such that our consumption pattern is circular at both tangible level (i.e., material consumption) and intangible level (i.e., energy consumption). Besides this dimension being strongly related to the goal of circularity, it is also very closely aligned to many definitions of Circular Economy and Circular Supply Chain (CSC) (e.g., *the production systems that generate no solid, liquid, and gaseous wastes, as well as run only on renewable energy* (Ehrenfeld and Gertler, 1997; McDonough and Braungart, 2010), *the circular economy refers to an industrial economy that is restorative by intention; aims to reply on renewable energy* (Webster, 2015)*;The core of CE is expected to achieve an efficient economy while discharging fewer pollutants* (Yuan et al., 2006)). Consequently, the decision makers will be intuitively agreed that this dimension is one of the most important dimensions that influences the circularity of a recycling alternative.

Efficiency (C_5) is the succeeding dimension with high influence on circularity, with a relative weight of 19.51%. This dimension has high influence on circularity because it can reduce the level of waste output significantly by increasing the efficiency of CE processes, hence achieving CE goal in lowering waste output. These efficient processes will recover high amount of resources from the EOL products, substituting the virgin raw materials and negating the needs to harvest them, whereby will contribute to another CE goal aiming to lower the raw virgin material input. Efficiency of resources usage, as captured by this dimension, will also affect resources utility, contributing to another CE goal. Nevertheless, this dimension has lower influences on circularity in comparison to monetary dimension or energy and environment dimension. This is because it does not address the goal of CE to increase economy prosperity and reduce environmental pollution as effectively as monetary (C_1) or energy and environment (C_2). Often, the attempts to increase efficiency indefinitely to achieve efficiency close to 100% would require extra cost and energy which might not be able to be compensated from the benefits it can provide (Reddy, 1991; Maheswaran et al., 2012). Even when the cost could be offset, the extra energy required in improving the efficiency would also produce more GHG, contributing to more environmental problems (Maheswaran et al., 2012). Because of the potential trade-off between efficiency dimension and monetary or energy and environment dimension, the decision makers rated this dimension with smaller relative importance for influencing the circularity of recycling alternative.

Material dimension (C_3) has slightly lower influence on circularity compared to other dimensions, with a relative weight of 17.02%. This dimension influences circularity by arriving at two CE goals – lowering waste output and resources input, by inspecting the source of material input into the supply chain and handling method of waste produced in the supply chain. This dimension also can attain another CE goal of increasing value of the materials, by scrutinising the flow of recovered material, either recycling internally or selling to CLSC or OLSC depending on which can generate more value. Nevertheless, this dimension is deemed slightly less influential on circularity as it does not address a very important goal, which is lowering pollution. One can utilise 100% recycled materials in their supply chain, recycle all the intermediate waste internally as well as recover materials from EOL product via CLSC, but still relying on fossil fuel energy to maintain their business and operation. One can argue that there is an indirect contribution to lower the energy consumption such as using 100% recycled materials in their supply chain, nevertheless, this effect is insignificant as compared to the disfavoured energy consumption pattern in the supply chain. Furthermore, the materials input (whether it is recycled or virgin) into the supply chain and the materials leaving the supply chain (whether it is recycled internally, landfilled, or entering CLSC/OLSC) do not indicate economic prosperity. Sometimes, it could, in fact, lead to economic hardship. For example, material entering CLSC is aimed to preserve its quality which does not necessarily maximise the overall economic performance for either party in the supply network (Kalverkamp and Young, 2019). Even though it has been shown that this dimension is being used abundantly to measure circularity of SC (e.g., Jain et al., 2018), this research discovers that this dimension is less influential on circularity, compared to other dimensions, such as monetary, energy and environment or efficiency.

Among the 5 dimensions, temporal dimension (C_4) is the least influential dimension on circularity for decision makers. Temporal is the least influential dimension on circularity for two reasons. Firstly, this dimension does not effectively address the CE goal related to lowering pollution and increasing economic prosperity. Like material dimension, a supply chain can produce a product with a long lifetime but it still uses fossil fuel energy which pollutes our environment. Secondly, temporal dimension is relatively new in the literature (Ellen MacArthur Foundation, 2013; Bakker et al., 2014; Franklin-Johnson et al., 2016), resulting in many DMs not knowing how it can be used for circularity measurement, adversely affecting the weight given to this dimension.

Drawing from this result, this research can infer that the two CE goals in increasing economic prosperity and lowering pollution are slightly more important than other goals that aiming at lowering waste or resources input and increasing value or utility of materials. This is because the dimensions that target these goals are deemed to be more influential on circularity and were given more weight by the Delphi panels. On the contrary, dimensions that do not lead to these goals are considered to be relatively less influential on circularity.

As a summary, monetary, energy and environment as well as efficiency dimensions represent the most influential dimensions on circularity. A recycling alternative that is circularity-focused can emphasis on monitoring and improving these dimensions in order to achieve high circularity arriving at the aforementioned CE goals.

5.1.3.1.2 Analysis of the Relative Importance of Items Within the Circularity Criteria

Next, the responses pertaining to the relative importance of the 23 items within circularity (see Tables G1-G18), are fuzzified and aggregated into one aggregated decision matrix, tabulated in Table 5.11. The CR for this aggregated decision matrix is calculated using Equation (8). From the calculation, the CR is 0.00288 by taking the ratio of CI to RI for a 23 x 23 matrix, which is 0.0429 and 1.49 respectively. Since the CR is less than 0.1, it implies that no mistakes or conflicting ratings are made by the DMs, and the judgments are acceptable for the weights' calculation (Saaty, 1990).

In FAHP, the common method used to evaluate the weight for the items at level 3 of the hierarchy (i.e., global priority weights) is by multiplying the local weight of the item with the weight of its parent dimension that is situated above the items on level 2 of the hierarchy (i.e., dimensions' weight), assuming that the sub-levels are dependent on those at higher level in the hierarchy (Saaty, 1990). Nevertheless, there is an innate methodological flaw to this method. Errors will be generated when this method is applied on the hierarchy structure that does not satisfy this assumption (i.e., sub-levels are dependent on those at higher level) (Epstein and King, 1982). The incorrectly clustered items and the mistakenly calculated importance value for the higher-level elements could also further complicate the problem, resulting in more errors in the results (Song and Kang, 2016).

As a conclusion, this research calculates the global priority weights of the items at level 3 of the hierarchy by using pairwise comparison among all the items at that level, without taking into account of the weights of parent dimension at level 2 of the hierarchy, which by doing so could mitigate the errors such as incorrect clustering or possibility of miscalculation of upper level dimensions, in turn affecting the accuracy of lower level items. Ultimately, the accuracy and reliability of the results can be greatly improved.

Table 5.11: The aggregated decision matrix of items (level 3) under circularity (aggregation of G1-G18) *(Source: Author).*

	C_{1a}	C_{1b}	C_{1c}	C_{1d}
C_{1a}	(1,1,1)	(3/2,16/9,2/1)	(3/2,5/3,2/1)	(11/6,2/1,13/6)
C_{1b}	(1/2,5/9,2/3)	(1,1,1)	(1/1,10/9,9/7)	(1/1,5/4,3/2)
C_{1c}	(1/2,3/5,2/3)	(7/9,1/1,1/1)	(1,1,1)	(1/1,6/5,10/7)
C_{1d}	(1/2,1/2,1/2)	(2/3,4/5,1/1)	(2/3,5/6,1/1)	(1,1,1)
C_{1e}	(2/3,3/4,5/6)	(2/1,5/2,3/1)	(5/3,2/1,12/5)	(2/1,12/5,17/6)
C_{1f}	(1/4,2/7,1/3)	(1/2,3/5,2/3)	(1/2,3/5,5/7)	(2/3,4/5,1/1)
C_{2a}	(4/5,1/1,6/5)	(2/3,5/6,1/1)	(9/7,11/7,2/1)	(13/7,16/7,8/3)
C_{2b}	(6/5,7/5,5/3)	(4/5,1/1,4/3)	(4/3,5/3,2/1)	(3/2,9/5,2/1)
C_{2c}	(4/7,5/7,7/8)	(5/6,1/1,4/3)	(7/5,5/3,2/1)	(11/9,3/2,9/5)
C_{2d}	(3/7,1/2,3/5)	(2/7,1/3,3/8)	(1/2,4/7,2/3)	(1/2,3/5,5/7)
C_{2e}	(4/7,2/3,5/6)	(2/5,1/2,4/7)	(2/3,4/5,1/1)	(5/6,1/1,6/5)
C_{2f}	(2/3,7/9,1/1)	(5/7,4/5,1/1)	(6/5,10/7,5/3)	(1/1,4/3,11/7)
C_{3a}	(5/7,8/9,8/7)	(3/7,4/7,7/9)	(2/3,5/6,1/1)	(7/8,1/1,9/7)
C_{3b}	(4/9,1/2,2/3)	(2/5,1/2,3/5)	(5/8,4/5,1/1)	(1/1,7/6,11/8)
C_{3c}	(5/9,2/3,4/5)	(5/7,8/9,9/8)	(3/5,3/4,1/1)	(3/2,16/9,2/1)
C_{3d}	(3/4,1/1,6/5)	(5/9,5/7,1/1)	(1/1,5/4,3/2)	(1/1,9/7,3/2)
C_{4a}	(5/8,3/4,1/1)	(2/3,4/5,1/1)	(5/6,1/1,1/1)	(3/4,6/7,1/1)
C_{4b}	(1/1,4/3,14/9)	(3/2,7/4,2/1)	(13/8,17/9,11/5)	(2/1,19/8,14/5)
C_{5a}	(4/5,1/1,5/4)	(3/4,8/9,10/9)	(3/5,3/4,1/1)	(1/1,5/4,3/2)
C_{5b}	(3/5,3/4,1/1)	(5/6,1/1,11/8)	(1/1,9/7,14/9)	(1/1,11/9,3/2)
C_{5c}	(1/2,2/3,5/6)	(3/7,1/2,2/3)	(1/2,5/8,4/5)	(7/9,1/1,7/6)
C_{5d}	(1/2,3/5,5/7)	(1/2,4/7,3/4)	(1/1,7/6,10/7)	(5/7,7/8,10/9)
C_{5e}	(1/1,11/9,3/2)	(11/9,3/2,9/5)	(1/1,11/9,10/7)	(3/2,11/6,11/5)

C_{2b}	C_{2a}	C_{1f}	C_{1e}
(3/5,5/7,5/6)	(5/6,1/1,11/9)	(3/1,7/2,19/5)	(6/5,4/3,3/2)
(3/4,1/1,5/4)	(1/1,6/5,13/9)	(10/7,5/3,2/1)	(1/3,2/5,1/2)
(1/2,3/5,3/4)	(1/2,5/8,7/9)	(7/5,5/3,2/1)	(3/7,1/2,3/5)
(1/2,5/9,2/3)	(3/8,4/9,1/2)	(1/1,5/4,3/2)	(1/3,3/7,1/2)
(1/1,6/5,10/7)	(1/1,6/5,3/2)	(7/3,14/5,13/4)	(1,1,1)
(2/5,1/2,4/7)	(5/8,5/7,6/7)	(1,1,1)	(1/3,1/3,3/7)
(3/5,3/4,8/9)	(1,1,1)	(7/6,11/8,8/5)	(2/3,5/6,1/1)
(1,1,1)	(10/9,4/3,13/8)	(7/4,2/1,12/5)	(2/3,5/6,1/1)
(1/2,5/9,2/3)	(4/5,1/1,6/5)	(3/2,17/9,19/8)	(4/7,2/3,6/7)
(2/9,1/4,1/3)	(1/2,3/5,2/3)	(6/7,1/1,6/5)	(1/2,3/5,2/3)
(1/5,1/4,1/3)	(1/2,5/9,2/3)	(4/3,11/7,11/6)	(3/5,2/3,4/5)
(1/3,2/5,1/2)	(3/8,3/7,1/2)	(4/3,13/8,2/1)	(4/5,1/1,10/9)
(1/3,2/5,1/2)	(6/7,1/1,9/7)	(11/8,5/3,2/1)	(5/8,3/4,1/1)
(1/4,1/3,2/5)	(1/2,3/5,5/7)	(1/1,7/6,7/5)	(5/8,5/7,6/7)
(3/8,4/9,1/2)	(1/2,5/8,5/6)	(2/1,16/7,19/7)	(3/4,7/8,1/1)
(1/3,1/3,2/5)	(5/7,8/9,10/9)	(3/2,9/5,11/5)	(3/4,8/9,1/1)
(2/7,1/3,3/7)	(1/2,4/7,2/3)	(9/8,4/3,3/2)	(5/7,4/5,1/1)
(2/3,5/6,1/1)	(11/8,12/7,2/1)	(7/3,11/4,22/7)	(1/1,9/8,4/3)
(3/7,1/2,4/7)	(2/3,4/5,1/1)	(3/2,5/3,13/7)	(1/1,1/1,4/3)
(2/5,1/2,1/2)	(5/9,2/3,7/9)	(11/5,8/3,19/6)	(5/6,1/1,6/5)
(1/3,2/5,4/9)	(2/5,4/9,1/2)	(1/1,1/1,9/7)	(5/9,2/3,6/7)
(3/7,1/2,3/5)	(4/9,1/2,3/5)	(3/2,9/5,13/6)	(5/6,1/1,9/7)
(3/5,5/7,6/7)	(5/7,7/8,1/1)	(7/5,7/4,17/8)	(11/9,3/2,7/4)

C_{2f}	C_{2e}	C_{2d}	C_{2c}
(1/1,9/7,3/2)	(6/5,13/9,7/4)	(5/3,2/1,19/8)	(8/7,7/5,12/7)
(1/1,5/4,10/7)	(7/4,2/1,17/7)	(8/3,3/1,7/2)	(3/4,1/1,6/5)
(3/5,5/7,5/6)	(1/1,5/4,3/2)	(3/2,7/4,2/1)	(1/2,3/5,5/7)
(5/8,3/4,1/1)	(5/6,1/1,6/5)	(7/5,13/8,2/1)	(5/9,2/3,5/6)
(1/1,1/1,5/4)	(5/4,13/9,5/3)	(3/2,5/3,17/9)	(7/6,10/7,12/7)
(1/2,3/5,3/4)	(1/2,2/3,3/4)	(5/6,1/1,7/6)	(3/7,1/2,2/3)
(2/1,7/3,11/4)	(3/2,16/9,2/1)	(10/7,5/3,2/1)	(5/6,1/1,5/4)
(2/1,18/7,3/1)	(29/9,4/1,29/6)	(16/5,4/1,41/9)	(14/9,11/6,2/1)
(1/1,9/8,11/8)	(19/8,20/7,17/5)	(2/1,7/3,11/4)	(1,1,1)
(2/5,1/2,4/7)	(1/2,4/7,2/3)	(1,1,1)	(3/8,3/7,1/2)
(2/5,4/9,1/2)	(1,1,1)	(13/9,7/4,2/1)	(2/7,1/3,3/7)
(1,1,1)	(2/1,9/4,5/2)	(16/9,2/1,5/2)	(5/7,8/9,1/1)
(3/2,12/7,2/1)	(6/5,13/9,7/4)	(5/3,17/9,13/6)	(1/2,4/7,5/7)
(7/8,1/1,6/5)	(2/3,7/9,1/1)	(13/9,12/7,2/1)	(1/2,5/8,3/4)
(1/1,10/9,4/3)	(1/1,5/4,3/2)	(13/9,12/7,2/1)	(2/3,4/5,1/1)
(8/7,7/5,12/7)	(6/5,13/9,7/4)	(16/9,2/1,19/8)	(3/5,3/4,7/8)
(2/5,1/2,3/5)	(8/9,1/1,4/3)	(1/1,5/4,7/5)	(5/8,3/4,7/8)
(1/1,6/5,13/9)	(5/3,2/1,11/5)	(2/1,20/9,5/2)	(3/2,7/4,2/1)
(1/2,5/9,2/3)	(1/1,10/9,4/3)	(1/1,6/5,10/7)	(4/5,1/1,6/5)
(1/2,3/5,3/4)	(7/6,7/5,5/3)	(1/1,11/9,13/9)	(3/5,5/7,6/7)
(1/3,3/8,1/2)	(1/2,3/5,5/7)	(3/4,6/7,1/1)	(1/3,2/5,1/2)
(1/3,3/8,4/9)	(3/4,1/1,1/1)	(3/4,1/1,9/8)	(4/9,1/2,5/8)
(3/4,8/9,1/1)	(4/3,14/9,9/5)	(7/4,2/1,7/3)	(3/4,7/8,1/1)

C_{3d}	C_{3c}	C_{3b}	C_{3a}
(5/6,1/1,4/3)	(5/4,3/2,16/9)	(3/2,11/6,20/9)	(7/8,9/8,10/7)
(1/1,7/5,16/9)	(8/9,9/8,7/5)	(5/3,19/9,18/7)	(9/7,7/4,16/7)
(2/3,4/5,1/1)	(1/1,4/3,5/3)	(1/1,5/4,11/7)	(1/1,6/5,13/9)
(2/3,7/9,1/1)	(1/2,4/7,2/3)	(5/7,6/7,1/1)	(7/9,1/1,8/7)
(1/1,9/8,4/3)	(1/1,8/7,4/3)	(7/6,11/8,13/8)	(1/1,4/3,11/7)
(1/2,5/9,2/3)	(3/8,3/7,1/2)	(5/7,6/7,1/1)	(1/2,3/5,3/4)
(1/1,9/8,7/5)	(11/9,11/7,2/1)	(7/5,5/3,2/1)	(7/9,1/1,7/6)
(17/7,17/6,13/4)	(13/7,11/5,13/5)	(5/2,22/7,34/9)	(2/1,5/2,3/1)
(8/7,11/8,5/3)	(1/1,5/4,3/2)	(4/3,8/5,2/1)	(7/5,7/4,11/5)
(3/7,1/2,4/7)	(1/2,3/5,2/3)	(1/2,3/5,2/3)	(1/2,1/2,3/5)
(4/7,2/3,5/6)	(2/3,4/5,1/1)	(1/1,9/7,3/2)	(4/7,2/3,5/6)
(3/5,5/7,7/8)	(3/4,1/1,1/1)	(5/6,1/1,8/7)	(1/2,4/7,2/3)
(3/4,6/7,1/1)	(1/1,5/4,3/2)	(12/7,2/1,7/3)	(1,1,1)
(1/2,5/9,2/3)	(1/2,1/2,5/8)	(1,1,1)	(3/7,1/2,3/5)
(7/9,1/1,10/9)	(1,1,1)	(8/5,11/6,15/7)	(2/3,4/5,1/1)
(1,1,1)	(1/1,1/1,9/7)	(14/9,9/5,2/1)	(1/1,7/6,4/3)
(5/8,3/4,5/6)	(1/2,3/5,2/3)	(5/6,1/1,9/8)	(2/5,1/2,4/7)
(14/9,2/1,7/3)	(1/1,6/5,7/5)	(13/7,11/5,13/5)	(3/2,17/9,9/4)
(2/3,4/5,1/1)	(7/9,1/1,1/1)	(4/3,11/7,13/7)	(3/4,1/1,7/6)
(2/3,4/5,1/1)	(1/2,5/8,3/4)	(1/1,7/6,10/7)	(5/7,5/6,1/1)
(3/8,3/7,1/2)	(1/2,5/8,3/4)	(2/3,4/5,1/1)	(1/3,2/5,1/2)
(1/2,4/7,2/3)	(2/5,1/2,5/9)	(7/5,13/8,13/7)	(1/2,3/5,2/3)
(1/1,10/9,5/4)	(8/9,10/9,4/3)	(4/3,11/7,9/5)	(1/1,10/9,4/3)

C_{5b}	C_{5a}	C_{4b}	C_{4a}
(10/9,11/8,5/3)	(4/5,1/1,5/4)	(2/3,3/4,1/1)	(10/9,4/3,8/5)
(3/4,1/1,6/5)	(1/1,10/9,11/8)	(1/2,4/7,2/3)	(1/1,11/9,13/9)
(2/3,7/9,1/1)	(1/1,4/3,5/3)	(1/2,1/2,5/8)	(1/1,1/1,6/5)
(2/3,4/5,1/1)	(2/3,4/5,1/1)	(1/3,3/7,1/2)	(1/1,7/6,4/3)
(5/6,1/1,6/5)	(3/4,1/1,10/9)	(3/4,8/9,1/1)	(1/1,5/4,11/8)
(1/3,3/8,4/9)	(1/2,3/5,2/3)	(1/3,3/8,3/7)	(2/3,3/4,8/9)
(9/7,3/2,9/5)	(1/1,11/9,13/9)	(1/2,4/7,3/4)	(13/9,7/4,13/6)
(11/6,13/6,5/2)	(12/7,2/1,7/3)	(1/1,11/9,3/2)	(19/8,20/7,24/7)
(7/6,11/8,5/3)	(5/6,1/1,5/4)	(1/2,4/7,2/3)	(8/7,4/3,11/7)
(2/3,4/5,1/1)	(2/3,5/6,1/1)	(2/5,4/9,1/2)	(5/7,4/5,1/1)
(3/5,5/7,6/7)	(3/4,1/1,1/1)	(4/9,1/2,3/5)	(3/4,1/1,9/8)
(11/8,5/3,2/1)	(3/2,16/9,15/7)	(2/3,5/6,1/1)	(5/3,2/1,17/7)
(1/1,6/5,11/8)	(6/7,1/1,4/3)	(4/9,1/2,2/3)	(7/4,2/1,17/7)
(5/7,6/7,1/1)	(1/2,5/8,3/4)	(3/8,4/9,1/2)	(8/9,1/1,6/5)
(4/3,13/8,2/1)	(1/1,1/1,9/7)	(5/7,5/6,1/1)	(10/7,13/8,13/7)
(1/1,5/4,3/2)	(1/1,5/4,3/2)	(3/7,1/2,2/3)	(6/5,11/8,8/5)
(1/2,3/5,5/7)	(4/9,1/2,2/3)	(2/7,1/3,3/8)	(1,1,1)
(11/7,15/8,15/7)	(7/6,10/7,5/3)	(1,1,1)	(21/8,3/1,7/2)
(6/5,10/7,5/3)	(1,1,1)	(3/5,5/7,6/7)	(3/2,11/6,20/9)
(1,1,1)	(3/5,2/3,5/6)	(1/2,1/2,5/8)	(11/8,12/7,2/1)
(1/3,3/8,4/9)	(2/5,3/7,1/2)	(1/3,3/8,1/2)	(5/6,1/1,6/5)
(5/8,5/7,4/5)	(4/7,2/3,5/6)	(1/3,3/8,1/2)	(5/4,3/2,9/5)
(11/9,3/2,7/4)	(5/7,5/6,1/1)	(8/9,1/1,6/5)	(12/5,23/8,10/3)

C_{5e}	C_{5d}	C_{5c}
(2/3,4/5,1/1)	(11/8,5/3,2/1)	(6/5,3/2,11/6)
(5/9,2/3,5/6)	(11/8,7/4,15/7)	(3/2,2/1,19/8)
(5/7,4/5,1/1)	(2/3,6/7,1/1)	(5/4,11/7,2/1)
(4/9,1/2,2/3)	(1/1,8/7,10/7)	(6/7,1/1,9/7)
(4/7,2/3,4/5)	(7/9,1/1,6/5)	(7/6,3/2,9/5)
(1/2,4/7,5/7)	(1/2,5/9,2/3)	(7/9,1/1,1/1)
(1/1,8/7,7/5)	(5/3,2/1,16/7)	(2/1,11/5,18/7)
(7/6,7/5,13/8)	(5/3,2/1,16/7)	(9/4,23/9,20/7)
(1/1,8/7,4/3)	(11/7,15/8,20/9)	(2/1,17/7,17/6)
(3/7,1/2,4/7)	(8/9,10/9,4/3)	(1/1,7/6,11/8)
(5/9,2/3,3/4)	(1/1,10/9,4/3)	(7/5,5/3,2/1)
(1/1,9/8,4/3)	(11/5,8/3,16/5)	(13/6,21/8,19/6)
(3/4,1/1,1/1)	(10/7,5/3,2/1)	(2/1,5/2,3/1)
(5/9,5/8,3/4)	(1/2,5/8,5/7)	(1/1,5/4,3/2)
(3/4,8/9,10/9)	(9/5,13/6,23/9)	(4/3,8/5,2/1)
(4/5,1/1,1/1)	(10/7,7/4,2/1)	(2/1,7/3,19/7)
(2/7,1/3,2/5)	(5/9,2/3,4/5)	(5/6,1/1,6/5)
(5/6,1/1,9/8)	(19/9,21/8,22/7)	(15/7,21/8,3/1)
(1/1,11/9,7/5)	(6/5,10/7,12/7)	(2/1,7/3,18/7)
(4/7,2/3,5/6)	(11/9,10/7,13/8)	(9/4,11/4,13/4)
(3/8,4/9,1/2)	(2/7,1/3,4/9)	(1,1,1)
(5/9,2/3,4/5)	(1,1,1)	(11/5,11/4,10/3)
(1,1,1)	(11/9,3/2,11/6)	(2/1,9/4,13/5)

Using the aggregated decision matrix in Table 5.11, the fuzzy geometric mean value ($\widetilde{r_i}$), fuzzy weight ($\widetilde{w_i}$) and de-fuzzified weight (M_i) are calculated using Equations (5), (6) and (7), tabulated under Table 5.12. The normalised weight (N) is obtained by taking the ratio of M_i to the sum of all M_i. The resulting normalised weight (N) represents the relative weight of importance for each item within circularity.

Table 5.12: Fuzzy geometric mean, fuzzy weight, de-fuzzified weight and normalised weight for items (level 3) under circularity (Source: Author).

		$\widetilde{r_i}$	$\widetilde{w_i}$	M_i	N
C_1	C_{1a}	(0.6303,0.7416,0.8805)	(0.0220,0.0306,.0430)	0.0318	3.07%
	C_{1b}	(0.7052,0.8487,1.0284)	(0.0246,0.0350,.0502)	0.0366	3.52%
	C_{1c}	(0.9030,1.0729,1.2834)	(0.0315,0.0442,.0627)	0.0461	4.44%
	C_{1d}	(1.0866,1.2958,1.5307)	(0.0379,0.0534,.0747)	0.0553	5.33%
	C_{1e}	(0.6642,0.7780,0.9246)	(0.0232,0.0321,.0451)	0.0335	3.22%
	C_{1f}	(1.4415,1.7064,1.9973)	(0.0503,0.0703,.0975)	0.0727	**7.00%**
C_2	C_{2a}	(0.6384,0.7645,0.9130)	(0.0223,0.0315,.0446)	0.0328	3.16%
	C_{2b}	(0.4406,0.5168,0.6169)	(0.0154,0.0213,.0301)	0.0223	2.14%
	C_{2c}	(0.6548,0.7845,0.9347)	(0.0228,0.0323,.0456)	0.0336	3.24%
	C_{2d}	(1.4280,1.6621,1.9257)	(0.0498,0.0685,.0940)	0.0708	**6.82%**
	C_{2e}	(1.1094,1.3121,1.5463)	(0.0387,0.0541,.0755)	0.0561	5.40%
	C_{2f}	(0.7456,0.8834,1.0465)	(0.0260,0.0364,.0511)	0.0378	3.64%
C_3	C_{3a}	(0.7665,0.9162,1.0929)	(0.0267,0.0378,.0534)	0.0393	3.78%
	C_{3b}	(1.1619,1.3811,1.6196)	(0.0405,0.0569,.0791)	0.0588	**5.67%**
	C_{3c}	(0.7644,0.9113,1.0809)	(0.0266,0.0376,.0528)	0.0390	3.76%
	C_{3d}	(0.7472,0.8881,1.0528)	(0.0260,0.0366,.0514)	0.0380	3.66%
C_4	C_{4a}	(1.2182,1.4296,1.6725)	(0.0425,0.0589,.0817)	0.0610	**5.88%**
	C_{4b}	(0.5029,0.5863,0.6939)	(0.0175,0.0242,.0339)	0.0252	2.43%
C_5	C_{5a}	(0.7972,0.9442,1.1203)	(0.0278,0.0389,.0547)	0.0405	3.90%
	C_{5b}	(0.8604,1.0216,1.2163)	(0.0300,0.0421,.0594)	0.0438	4.22%
	C_{5c}	(1.4928,1.7756,2.0832)	(0.0520,0.0732,.1017)	0.0756	**7.29%**
	C_{5d}	(1.0657,1.2751,1.5147)	(0.0372,0.0525,.0740)	0.0546	5.25%
	C_{5e}	(0.6558,0.7690,0.9111)	(0.0229,0.0317,.0445)	0.0330	3.18%
Sum		20.4806,24.2649,28.6863	-	1.0382	100.0%

Referring to Table 5.12, the five most important items within circularity in the order of importance, are C_{5c} – Recyclability of the product (7.29%), C_{1f} – Profit or saving per kg recyclable input consumed (7.00%), C_{2d} – Total GHG produced per kg product (6.82%), C_{4a} – lifetime of product (5.88%) and C_{3b} – fraction of recycled material used per kg product (5.67%), as highlighted. Each of the five most influential items are originated from different dimensions, namely C_5, C_1, C_2, C_4 and C_3 respectively. Even though C_5 is not as influential as C_1 or C_2 at dimension level, some items in dimension C_5 still outweigh the items of other dimensions at items level due to their extreme importance.

C_{5c} – Recyclability of product is deemed having the highest influence on circularity of a recycling alternative among the 23 items with a relative importance of 7.29%. Recyclability is the ability of material within a product to be recycled into its virgin state, which is its purest form before it is processed or shaped for a specific use, consequently reacquiring the properties that it once had (Villalba et al., 2002). A product that utilises a lot of recycled materials do not necessary indicate that those materials are all recyclable. This is because some ingredients could have been added into the materials during manufacturing, which render the recyclability of the product, for instance, due to toxicity. Some recycled materials used in manufacturing also could have had their properties changed during the process, making it no longer recyclable. Consequently, C_{5c} becomes a measurement item that is separated and dissimilar, but as important as fraction of recycled materials used (C_{3b}) in manufacturing process for circularity measurement.

C_{5c} reveals the level of resources that can be recovered from EOL products, which excelling in it would encourage circulation and retention of resources in the supply chain (i.e., power of circling longer). The recyclability of material thus directly affects the possibility of the materials to be re-introduced into the supply chain, signifying the ability for the supply chain to be closed and circular (Leonas, 2016). Having high recyclability also helps in arriving to the goal of CE in lowering or eliminating waste generated in our society when the materials can be recycled and return to the consumption cycle instead of landfill. Further, it also meets another CE goal to increase the utility of resources, when the materials are retained within the consumption cycle for prolonged usage instead of being sent to landfill.

This item C_{5c} functioned to reflect the recyclability of all the materials within the EOL product of a recycling alternative. A product with high recyclability will ensure sufficient materials are recovered to replace the primary raw materials, negating the harvesting and production of costly and energy intensive raw materials (Broadbent, 2016). This aligns very closely to the goal of CE in eliminating or lowering the harvesting and input of virgin raw materials. Since a lot of raw materials are no longer required to be harvested or processed, this also indirectly contributes to the goal aimed at lowering the pollution in the form of avoided impacts. The materials recycled from the EOL products can also be used or sold to others, creating business opportunities for the supply chain, contributing to economic prosperity. Ultimately, this item is able to achieve many goals of CE directly and indirectly, representing the most influential item on circularity.

The high importance of this item and its high influential on circularity as discovered in this research, also supports the claims of Ellen MacArthur Foundation (2020) who states that a product in a CE needs to be designed for recyclability.

C_{5c} is also the most important item within the dimension C_5, preceding C_{5a} – collection efficiency (3.90%), C_{5b} – modularity of product design (4.22%), C_{5d} – recycling efficiency of recycler (5.25%) and C_{5e} – rental-ability (3.18%). This is because having a high collection efficiency, modularity, recycling efficiency or rental-ability do not necessarily indicate that the materials within the product can be recovered if the recyclability of the product is low. C_{5c} is thus can be viewed as a precursor for other items to be meaningful. Specifically, high recyclability of product directly affects how many materials can return to the consumption cycle. A product needs to be high in recyclability to ensure it can be recycled when it reaches the end of its useful life, so that its value can be maintained, and at the same time, reducing or eliminating waste.

Consequently, recyclability is the most fundamental core item that can represent and influence circularity of a recycling alternative, as compared to all other items both inside and outside the dimension C_5 and will aid in the decision-making process.

C_{1f} – Profit or saving per kg recyclable input consumed is the next most important item in representing and influencing circularity of a recycling alternative, with a relative importance of 7.00%. As aforementioned, a business's profit is the total amount of money remaining after the company pays its costs, while saving is the tangible benefit because of action that lowers the current spending such as purchasing the less expensive option. This item concerns on the profit and saving acquired because of the use of recyclable input.

Usually, the cost of purchasing recyclable materials is cheaper than virgin raw materials (Bandara et al., 2015), thus using recyclable materials as a substitute for the more expensive virgin materials will provide substantial savings to the business, contributing to profit margin. A recycler in the supply chain processes EOL products to extract and produce recycled materials, which can be sold to customers to generate revenues.

The item C_{1f} thus functioned to reflect the profit or saving for every unit of recyclable input consumed in the supply chain of a recycling alternative, including the profit generated when the collector/recycler sold the recycled materials or when the manufacturer made a saving when virgin raw materials are substituted by recycled materials. Ideally, a higher profit or saving generated for every unit of recyclable input consumed indicates the ability of the businesses to utilise the resources more effectively by maximising the profit of resources. This item is important not only because it can help to arrive at CE goal aiming to increase and maximise the value of resources in monetary term, it also helps to increase economic prosperity by utilising waste streams to make additional profit and saving (Chertow, 2000). Consequently, this item is considered very important and highly influential on circularity.

Furthermore, this particular item has also been used in many research studies as an important measurement item to determine the circularity in different contexts, such as network design (Ene and Öztürk, 2014; Özceylan, 2016; Cin and Kuşakcı, 2017) and supplier selection (Çalık, 2020). Evidently, this item represents one of the most important drivers in order for a recycling alternative to stand out among the competition. This finding also validates the argument made by Stahel (2013) and Murray et al. (2015), who asserted that CE is about economics, particularly the profit maximisation by creative utilisation of waste.

According to Table 5.12, C_{1f} is also discovered to be the most important item within the dimension C_1, preceding C_{1a} – average cost of virgin material per kg virgin material (3.07%), C_{1b} – average repairing price (3.52%), C_{1c} – fraction of cost spent of CE technology to total cost of investments (4.44%), C_{1d} – fraction of cost spent on recyclable material to total cost of materials (5.33%) and C_{1e} – production cost per kg product (3.22%). This is because it is the only item that can indicate and show which recycling alternative is better in utilising the waste and maximising its monetary value. Unlike C_{1f}, other items can show which alternative is using scarce resources (i.e., C_{1a}); which alternative is more likely to retain its material in the consumption cycle (i.e., C_{1b}); which alternative is more dedicated to adopting CE practices (i.e., C_{1c} and C_{1d}); which alternative operates at lower cost of production (i.e., C_{1e}). Nevertheless, none of the item can indicate which alternative is higher in resource productivity as well as better in utilising the waste and maximising its profit like C_{1f} could, eventually leading to higher economic prosperity.

C_{2d} – Total GHG produced per kg product represents the next most significant item that will influence circularity of a recycling alternative, with a relative importance of 6.82%. GHG is the gaseous emission responsible for the global warming leading to climate changes and extinction of animal species. GHG includes gaseous carbon dioxide and methane, which are collected in our atmosphere forming a blanket, creating greenhouse effect that prevents the heat from escaping into the space. The heat trapped in the air will heat up the atmosphere and cause environmental problems including heat waves and droughts. The elevated heat melts the polar ice caps and causes storms and floods that destroy natural habitats. As a result of the heat, the climate is changing and affecting the life on Earth (Ritchie and Roser, 2020).

GHG is mainly emitted when fossil fuels are consumed for energy generation. Activities within the supply chain will also generate a significant amount of GHG, such as logistics. This item concerns particularly on the GHG produced by all the key actors in the supply chain, indicating the most critical impact imparted onto the environment by the processes carried out in businesses. This item thus functioned to reflect all the GHG produced by all the key actors in the supply chain including collectors, recyclers and manufacturers, particularly on the functions such as operations and distribution (Iaquaniello et al., 2018; Liu et al., 2018).

This item C_{2d} is important because lower GHG produced by businesses will reduce the effect of global warming, ensuring the wellbeing of human, living things and our environment. Excelling in this item will help in arriving at the CE goal aiming to lower the pollution by reducing the GHG emission. To effectively reduce GHG production, the consumption of fossil fuels for energy generation will be substituted by using alternative energy sources such as renewable energy, at the same time reducing the resources input (i.e., fossil fuels) to the supply chain, contributing to another CE goal. One of the alternatives for fossil fuel consumption is by utilising the EOL products for energy recovery, such as ELT, plastics, paper, or cardboard as well as biomass such as animal faeces or crops residue, which can simultaneously curb accumulation of waste in the landfill (Stahel, 2016).

This research discovers that GHG produced in the recycling alternative is very important and highly influential on circularity. This can also be evidenced in the literature where many practices are introduced to change the normal ways of making and using a product or food, to reduce GHG production in hoping of improving circularity (Stahel, 2016; Iaquaniello et al., 2018; Liu et al., 2018). For example, Paris Agreement set out a 1.5˚C target to achieve zero emissions of GHG by 2050 via the reduction of reliance on fossil fuels for energy (United Nations, 2020). Practices are introduced to innovate product manufacturing, such as using renewable energy, complemented by energy efficiency which would contribute to as much as 45% GHG emissions reduction (Ellen MacArthur Foundation, 2017).

C_{2d} is also discovered to be the most important item within the dimension C_2 according to Table 5.12, preceding C_{2a} – fraction of energy generated using renewable sources (3.16%), C_{2b} – fraction of energy loss (2.14%), C_{2c} – fraction of energy purchased from renewable sources (3.24%), C_{2e} – total energy consumed per kg product (5.40%) and C_{2f} – total energy generated per kg product (3.64%). It is because this item can more directly reflect the achievement of CE goal aiming at lowering the pollution, while other items could not achieve the same result if they are used individually. For example, C_{2e} is required to be reported with C_{2b} and C_{2c} to reveal the total energy ultimately being consumed that is purchased from non-renewable sources, which is the major culprit responsible for GHG emission. Similarly, C_{2f} is required to be reported along with C_{2a} to reveal the total amount of energy generated using renewable sources, demonstrating the commitment towards combating GHG emission. Consequently, the ease of use of C_{2d} has made this item particularly highlighted by the decision makers. This research extends the literature and supported the claim that this item is indeed one of the most important items in influencing and determining the overall circularity of a recycling alternative, deriving from the standpoint of the decision makers.

C_{4a} – lifetime of product represents the next most significant item in influencing circularity of a recycling alternative, with a relative importance of 5.88%. Lifetime is the duration or period of time during which something exists (Cambridge Dictionary, 2021). This item concerns with the lifetime of product made from different recycling alternatives. C_{4a} functioned to capture the expected lifetime of a product until it reaches its end-of-life, so that it can be used as a basis for comparison to evaluate the product made from different recycling alternatives.

A longer lifetime means that the product will remain in the consumption cycle for a longer period of time, increasing its intensity of usage and contributing to CE goal that aims to increase resources utility. Retaining the product for a longer period within the consumption cycle reduces the demand for new resources required to manufacture a new product to replace it, thus contributing to the CE goal of reducing raw material input. Concurrently, waste is also lowered because fewer products are being disposed to landfill as they have a long lifetime, contributing to another CE goal that aims to lower or eliminate waste output.

This research discovers that C_{4a} is one of the most important and influential items on circularity. It is also evidenced in the CE literature, where this item is started to gain popularity in measuring circularity (Tecchio et al., 2017; Selvefors et al., 2019).

C_{4a} is also discovered to be the most important item within the dimension C_4 according to Table 5.12, preceding C_{4b} – time to reach CE goal (2.43%). This is because this item is highly responsible for the rate of accumulation of waste in landfill. Even if a business has taken a short time to reach CE goals and subsequently achieving a near ideal CE capabilities and efficiency, a product with a fleeting lifetime will render all the aforementioned efforts useless. This is because material cannot be recycled indefinitely within a consumption cycle, as it will eventually exit the consumption loop after several lifetimes, e.g., via EOL strategies such as energy recovery due to deterioration in its quality. Subsequently, a product with a long lifetime is a necessity to ensure material can be retained in the consumption cycle as long as possible, and together with business with high commitment towards CE and near ideal CE capabilities and efficiency, then the CE goals can be attained.

C_{3b} – fraction of recycled material used per kg product represents the next most significant item in influencing circularity of a recycling alternative, with a relative importance of 5.67%. The recycled materials are the materials obtained from collecting and processing an EOL product that would otherwise be disposed as waste in landfill.

This item functioned to reflect the materials input used to produce a product, particularly on the fraction of inputs comprised of recycled material. A business that sourced its materials input from the recycled streams rather than virgin materials sources contributes directly to two goals of CE, which are the ability to reduce harvesting raw virgin materials as well as minimising waste in our society, since the EOL products are recycled instead of being landfilled.

C_{3b} is also discovered to be the most important item within the dimension C_3 according to Table 5.12, preceding C_{3a} – fraction of recycler output to original supply chain (3.78%), C_{3c} – fraction of waste recycled internally (3.76%) and C_{3d} – total weight of unrecoverable waste per kg product (3.66%). It is discovered that all the items in C3 have highly similar relative weight and C_{3b} is given about 1.5 times higher weight than others. This is because the approach towards arriving at CE goals is slightly different. C_{3c} and C_{3d} arrive at the CE goal (i.e., reducing waste) in a proactive manner by reducing the waste before it is created, via increasing waste recycling internally and reducing total weight of unrecoverable waste. However, C_{3b} attains the same CE goal in a reactive manner, by retrieving more waste from the landfill, via the use of more recycled materials from the EOL products that are otherwise being landfilled (Chen et al., 2012).

The latter is discovered to be more important by this research, since our current waste accumulation is too high (McKie, 2016), which would surpass the Earth's waste assimilation capacity (Boumans et al., 2002; Hoekstra and Wiedmann, 2014). This situation requires a reactive mechanism to consume the already accumulated waste in landfills by recovering the materials within it. Even though proactive mechanism can slow down the waste accumulation rate in the landfill, it could not help in reducing the already saturated landfills.

Consequently, C_{3b} is deemed to be more important than C_{3c} and C_{3d} as it is a reactive mechanism while the latter are proactive. Furthermore, C_{3a} is not more important than C_{3b} as it does not concern with reducing waste in landfill but merely improving the quality and value of the waste by encouraging the waste to be returned to the original supply chain. The reason being that it believes the quality of waste can be best preserved when it is returned to the original supply chain. Nevertheless, C_{3a} is slightly more important than C_{3c} and C_{3d} as it can better help to achieve one of the CE goals aiming at increasing the monetary value of waste.

In summary, the five items discussed above represent the most important items for a recycling alternative to excel in circularity. A recycling alternative that is circularity-focused can emphasis on monitoring and improving the recyclability of the product, profit OR saving per kg recyclable input consumed and total GHG produced per kg product, product lifetime and fraction of recycled material used per kg product, as a mean to improve the circularity of the recycling alternative.

5.1.3.2 The Relative Importance of Dimensions and Items Within the Sustainability Criteria

5.1.3.2.1 The Relative Importance of Dimensions Within the Sustainability Criteria

The same process is repeated for sustainability criteria. The responses pertaining to the relative importance of the dimension within sustainability (see Table H1-H18) are fuzzified and aggregated into one aggregated decision matrix and shown in Table 5.13. The CR for this matrix is calculated using Equation (8). From the calculation, the CR is 0.0144 by taking the ratio of CI to RI for a 3 x 3 matrix, which is 0.0084 and 0.58 respectively. Since the CR is less than 0.1, it implies that no mistakes or conflicting ratings are made by the DMs, and the judgments are acceptable for the weight calculation (Saaty, 1990).

Table 5.13: The aggregated decision matrix of dimensions (level 2) under sustainability (aggregation of H1-H18) (Source: Author).

	S_1	S_2	S_3
S_1	(1,1,1)	(1/2,4/7,2/3)	(4/5,1,1)
S_2	(3/2,12/7,2/1)	(1,1,1)	(4/3,13/8,17/9)
S_3	(1,1,5/4)	(1/2,5/8,3/4)	(1,1,1)

Using the aggregated decision matrix in Table 5.13, the fuzzy geometric mean value ($\widetilde{r_i}$), fuzzy weight ($\widetilde{w_i}$), and de-fuzzified weight (M_i) is calculated using Equations (5), (6) and (7), and tabulated under Table 5.14. The normalised weight (N) is obtained by taking the ratio of M_i to the sum of all M_i. The resulting normalised weight (N) represents the relative weight of importance for each dimension within sustainability.

Table 5.14: Fuzzy geometric mean, fuzzy weight, de-fuzzified weight and normalised weight for dimensions (level 2) under sustainability (Source: Author).

	$\widetilde{r_i}$	$\widetilde{w_i}$	M_i	N
S_1	(0.7354,0.8175,0.9031)	(0.2141,0.2642,0.3244)	0.2676	26.37%
S_2	(1.2642,1.4069,1.5558)	(0.3681,0.4547,0.5588)	0.4605	**45.38%**
S_3	(0.7845,0.8695,0.9758)	(0.2284,0.2810,0.3505)	0.2866	28.25%
Sum	(2.7841,3.0938,3.4347)	-	1.0148	100%

Table 5.14 reveals that Environmental sustainability (S_2) is the most important dimension among the three dimensions in measuring the sustainability of a recycling alternative, with a relative importance of 45.38%, as highlighted, followed by social sustainability (S_3) and economy sustainability (S_1) receiving less weight with a relative importance of 28.25% and 26.37% respectively.

Based on Table 5.14, environmental sustainability (S_2) is the most important dimension in the eye of decision makers, which is as much as 1.5 times higher than other dimensions of sustainability. As described in Section 2.6.1, environmental sustainability is the dimension associated with conservation of resources and ecosystems as well as preservation of pollution-free land, atmosphere and water (Schwarz et al., 2002). This dimension reflects the resources consumption of key resources such as energy, water and materials, as well as the negative impact on our environment including atmosphere, fresh water and ocean and land.

Environmental sustainability dimension is given higher weight because it has received substantial attention in both academics and practitioners lately. The current state of Earth that we live in, as described in Section 2.1.1, has put the issue of environmental sustainability in the limelight, reducing the attention towards other sustainability dimensions, such as economic sustainability which was used to be the primary focus in the past (Caniato et al., 2012). This research also confirms that today, environmental sustainability is more important than other sustainability dimensions, particularly from the context of ELT recycling industry.

Besides, environmental sustainability dimension is also given higher weight because it has created the largest impact as well as most visible and observable changes in our life, affecting how we live. For example, businesses are regulated and are being monitored periodically to prevent pollution and to curb carbon emissions. Furthermore, consumers are also being educated and are reminded frequently through various medias to protect our environments. Both these changes in daily lives had shaped the people' mind to equate sustainability with environmental issues, intuitively giving higher weight to environmental sustainability which is a phenomenon being observed and shown in the literature (Dresner, 2008; Thiele, 2016). Further, environmental sustainability dimension is being heavily involved in the 17 sustainable development goals set by UNDP (United Nation Development Programme, 2020), including good health and wellbeing, clean water and sanitation, climate action, life below water and life on land. This also influences the decision-makers in agreeing environmental sustainability is more important.

Environmental sustainability influences the consumption habits towards key resources such as energy, water and materials, driving productivity (i.e., more efficient use of resources) (Bleischwitz, 2010; Thiele, 2016) and intensive (i.e., use less resources) (Dresner, 2008; Thiele, 2016). This dimension reflects and minimises the effect of resources consumption on environment, safeguarding the atmosphere, fresh water and ocean and land, so as to ensure it will not collapse and the new generations can enjoy the environment like the current generation. Ultimately, a company with a proven record of environmental compliance may also improve the brand and increase the opportunity to expand its revenue-generating operations such as siting a new plant in a developing country, indirectly contributing and benefiting the economical sustainability.

Social sustainability (S_3) is the next most influential dimension on sustainability for decision makers with a weight of 28.25%. As described in Section 2.6.1, societal sustainability is the dimension associated with the ability to create wellbeing of society at all levels, from individual to organisation, community and country (Dresner, 2008; Portney, 2015; Thiele, 2016).

This dimension is functioned to reflect the wellbeing of the relevant stakeholders both internal and external to the business, also ensuring no unethical practices are performed that violate equity and justice of the stakeholder. The wellbeing of internal stakeholders within the business, such as the employees, can be monitored using employees' wages and their health and safety. On the contrary, the wellbeing of external stakeholders can be examined using job opportunity created. Unethical practices such as employing child labour are also being monitored to ensure it is not being exploited.

Societal sustainability dimension is given high weight because without a sound social system, a community cannot continue to exist peacefully even with a superior economic system. A collective society with low social wellbeing and equity will result in high unemployment rate and poverty, in turn leading to several social problems such as homelessness, hunger, robbery, violence, drug abuse, prostitution, corruption, high crime rate as well as uptaking unethical practices such as child labour (Thiele, 2016). Like environmental sustainability, social sustainability has also received a lot of attention in both academics and practitioners in recent years, especially towards supply chain decisions after the discovery of child labours exploitation to cut cost (Edmonds and Pavcnik, 2005; Hutchins and Sutherland, 2008).

Also, societal sustainability dimension is given high weight because there are currently various programmes and rigorous checks of legislation are placed to ensure that people's health and wellbeing are strongly protected. Health and safety officers are also being appointed in many businesses to oversee and ensure superior employees' wellbeing (Latif et al., 2017). These programmes or checks ensure people's quality of life is not compromised while maintaining the access towards basic resources. These provide a deep impression to people, subconsciously agreeing that social sustainability is very important and highly influencing sustainability (United Nations Human Rights, 2011; Magee et al., 2012).

Social sustainability dimension is also a prerequisite in several important goals among the 17 sustainable development goals set by UNDP (United Nation Development Programme, 2020). Particularly, the goal to achieve no poverty, zero hunger, good health and wellbeing, quality education, gender equality, reduced inequality, sustainable cities and communities, peace, justice and strong institution, as well as partnership for the goals. Nevertheless, social sustainability dimension can also reflect the wellbeing of relevant stakeholders internally and externally to the business, leading to improvement in wellbeing and equity and contribution to the achievement of sustainable development goals.

Economic sustainability (S_1) is the least important dimension for decision makers, only given a weight of 26.37%, a tad less than social sustainability. As described in Section 2.6.1, economic sustainability is the dimension associated with the elements that reflect the ability of an institution to produce operational profit to continue its operation. It is a prerequisite for an institution, business or practice to have the capability to create an impact to societies at large, utilising its extra profit to create an infrastructure and more opportunities for the society, helping them to meet their own needs, as well as addressing the environment and social issues (Dresner, 2008; Portney, 2015; Thiele, 2016). Economic sustainability is functioned to reflect the cost and profit related to the business, ensuring profit is generated to continue its operation.

Economic sustainability contributes to the achievement of several goals among the 17 sustainable development goals set by UNDP (United Nation Development Programme, 2020). Specifically, it is required to achieve no poverty, zero hunger, quality education, affordable and clean energy, industry, innovation and infrastructure as well as responsible consumption and production.

Nevertheless, economic sustainability is deemed the least influential on sustainability because as described in previous section, the current state of our living spaces has required extra effort to be put into improving environmental and societal sustainability. As a result, the importance of economic sustainability is lowered, compared to environmental or social sustainability. Excelling in economic sustainability will also trade-off environmental sustainability (Diamond, 2013; Špička et al., 2020) since thriving in economic sustainability are at the expense of consuming more resources, consuming he Earth's ecosystem services which are its life support system, causing our environmental system to collapse (Diamond, 1997; Abbey, 2016). Further, it is impossible to achieve a high economic growth and economical sustainability without consuming more resources, as postulated in Jevons Paradox (Cleveland and Ruth, 1998) and the thermodynamic law (i.e., second law of thermodynamics) (Huesemann and Huesemann, 2011). Evidently, chasing for extreme economical sustainability will inevitably result in a net increase in resources consumed and pollution elevated (See Cleveland and Ruth, 1998 and Huesemann and Huesemann, 2011). As a result, economic sustainability is perceived to be the least important in the context of sustainability, because stressing it too much would trade off environmental and societal sustainability, according to Jevons Paradox and thermodynamic law. Consequently, in this research, it is shown that merely achieving the bottom line in economic sustainability is sufficient.

5.1.3.2.2 Analysis of The Relative Importance of Items Within the Sustainability Criteria

Next, the responses pertaining to the relative importance of the items within sustainability (see Table I1-I18) are fuzzified and aggregated into one aggregated decision matrix as shown in Table 5.15. As aforementioned in Section 5.1.3.1.2, this research calculates the global priority weight of the items at level 3 of the hierarchy, by using pairwise comparison among all the items at that level. This process does not take into account of the weights of parent dimension at level 2 of the hierarchy. It is argued that this can mitigate the errors such as incorrect clustering or possibility of miscalculation of upper-level dimensions affecting the lower level items. Consequently, the overall accuracy and reliability of the results can be improved. Similarly, the CR for this matrix is also calculated using Equation (8). From the calculation, the CR is 0.0077, by taking the ratio of CI to RI for a 12 x 12 matrix, which is 0.0468 and 1.54 respectively. Since the CR is less than 0.1, it implies that no mistakes or conflicting ratings are made by the DMs, and the judgments are acceptable for the weight calculation (Saaty, 1990).

Table 5.15: The aggregated decision matrix of items (level 3) under sustainability (aggregation of I1-I18) *(Source: Author).*

	S_{1a}	S_{1b}	S_{1c}	S_{2a}	S_{2b}	S_{2c}
S_{1a}	(1,1,1)	(1/4,1/3,3/8)	(7/3,8/3,3/1)	(1/1,8/7,11/8)	(5/3,2/1,12/5)	(1/1,7/6,11/8)
S_{1b}	(11/4,29/9,26/7)	(1,1,1)	(7/3,8/3,3/1)	(3/2,11/6,9/4)	(5/2,3/1,18/5)	(7/5,5/3,2/1)
S_{1c}	(1/3,3/8,3/7)	(1/3,3/8,3/7)	(1,1,1)	(8/9,1/1,9/7)	(1/1,8/7,11/8)	(3/5,5/7,5/6)
S_{2a}	(3/4,7/8,1/1)	(4/9,5/9,2/3)	(7/9,1/1,9/8)	(1,1,1)	(3/2,7/4,2/1)	(2/3,3/4,6/7)
S_{2b}	(3/7,1/2,3/5)	(2/7,1/3,2/5)	(5/7,7/8,1/1)	(1/2,4/7,2/3)	(1,1,1)	(3/5,2/3,3/4)
S_{2c}	(5/7,6/7,1/1)	(1/2,3/5,5/7)	(6/5,7/5,5/3)	(7/6,4/3,3/2)	(4/3,3/2,5/3)	(1,1,1)
S_{2d}	(6/7,1/1,11/9)	(2/5,4/9,1/2)	(3/4,7/8,1/1)	(4/3,3/2,9/5)	(12/7,2/1,16/7)	(4/7,2/3,5/6)
S_{3a}	(1/1,4/3,8/5)	(5/7,8/9,10/9)	(9/8,9/7,3/2)	(9/7,11/7,2/1)	(9/4,21/8,3/1)	(1/1,1/1,5/4)
S_{3b}	(9/8,11/8,5/3)	(2/3,4/5,1/1)	(1/1,8/7,9/7)	(11/9,3/2,13/7)	(2/1,9/4,5/2)	(2/3,4/5,1/1)
S_{3c}	(2/3,3/4,8/9)	(2/3,7/9,1/1)	(1/1,1/1,7/6)	(2/5,1/2,4/7)	(2/1,15/7,7/3)	(6/7,1/1,1/1)
S_{3d}	(3/4,6/7,1/1)	(7/9,1/1,1/1)	(9/8,5/4,4/3)	(5/7,5/6,1/1)	(3/2,7/4,2/1)	(5/6,1/1,1/1)
S_{3e}	(7/5,5/3,2/1)	(3/2,12/7,2/1)	(12/7,2/1,16/7)	(13/6,13/5,3/1)	(17/5,4/1,40/9)	(2/1,15/7,7/3)

S_{3e}	S_{3d}	S_{3c}	S_{3b}	S_{3a}	S_{2d}
(1/2,3/5,5/7)	(1/1,7/6,4/3)	(9/8,4/3,3/2)	(3/5,5/7,8/9)	(5/8,3/4,1/1)	(5/6,1/1,7/6)
(1/2,4/7,2/3)	(1/1,1/1,9/7)	(1/1,9/7,3/2)	(1/1,11/9,3/2)	(1/1,9/8,11/8)	(17/9,20/9,23/9)
(4/9,1/2,3/5)	(3/4,4/5,8/9)	(6/7,1/1,1/1)	(7/9,7/8,1/1)	(2/3,7/9,8/9)	(1/1,8/7,11/8)
(1/3,3/8,1/2)	(1/1,11/9,7/5)	(12/7,17/8,13/5)	(1/2,2/3,4/5)	(1/2,2/3,7/9)	(5/9,2/3,3/4)
(2/9,1/4,2/7)	(1/2,4/7,2/3)	(3/7,1/2,1/2)	(2/5,4/9,1/2)	(1/3,3/8,4/9)	(3/7,1/2,4/7)
(3/7,1/2,1/2)	(1/1,1/1,6/5)	(1/1,1/1,7/6)	(1/1,5/4,3/2)	(4/5,1/1,1/1)	(6/5,13/9,12/7)
(1/3,1/3,3/8)	(2/3,3/4,6/7)	(3/5,2/3,4/5)	(1/2,5/9,2/3)	(5/8,3/4,5/6)	(1,1,1)
(6/7,1/1,10/9)	(20/9,5/2,20/7)	(5/2,3/1,18/5)	(2/1,7/3,21/8)	(1,1,1)	(6/5,4/3,11/7)
(2/5,4/9,5/9)	(5/6,1/1,1/1)	(2/1,15/7,7/3)	(1,1,1)	(3/8,3/7,1/2)	(3/2,9/5,15/7)
(2/7,1/3,3/8)	(2/3,3/4,7/8)	(1,1,1)	(3/7,1/2,1/2)	(2/7,1/3,2/5)	(5/4,10/7,5/3)
(2/5,4/9,1/2)	(1,1,1)	(8/7,4/3,3/2)	(1/1,1/1,6/5)	(1/3,2/5,4/9)	(7/6,4/3,3/2)
(1,1,1)	(2/1,9/4,5/2)	(13/5,25/8,29/8)	(11/6,11/5,23/9)	(1/1,1/1,7/6)	(19/7,3/1,10/3)

Using the aggregated decision matrix in Table 5.15, the fuzzy geometric mean value ($\widetilde{r_i}$), fuzzy weight ($\widetilde{w_i}$), and de-fuzzified weight (M_i) are also calculated using Equations (5), (6) and (7), and tabulated in Table 5.16. The normalised weight (N) is obtained by taking the ratio of M_i to the sum of all M_i. The resulting normalised weight (N) represents the relative weight of importance for each dimension within sustainability.

Table 5.16: Fuzzy geometric mean, fuzzy weight, de-fuzzified weight and normalised weight for items (level 3) under sustainability (Source: Author).

		$\widetilde{r_i}$	$\widetilde{w_i}$	M_i	N
S_1	S_{1a}	(0.8545,0.9951,1.1515)	(0.0584,0.0778,0.1033)	0.0798	7.79%
	S_{1b}	(0.5540,0.6447,0.7557)	(0.0378,0.0504,0.0678)	0.0520	5.07%
	S_{1c}	(1.1521,1.3159,1.4950)	(0.0787,0.1029,0.1341)	0.1052	**10.27%**
S_2	S_{2a}	(0.9929,1.1614,1.3633)	(0.0678,0.0908,0.1223)	0.0936	9.13%
	S_{2b}	(1.7008,1.9621,2.2183)	(0.1162,0.1534,0.1990)	0.1562	**15.24%**
	S_{2c}	(0.8657,0.9827,1.1150)	(0.0591,0.0768,0.1000)	0.0786	7.67%
	S_{2d}	(1.0985,1.2618,1.4500)	(0.0750,0.0986,0.1300)	0.1012	9.88%
S_3	S_{3a}	(0.5679,0.6542,0.7599)	(0.0388,0.0511,0.0682)	0.0527	5.14%
	S_{3b}	(0.8095,0.9308,1.0700)	(0.0553,0.0728,0.0960)	0.0747	7.29%
	S_{3c}	(1.1648,1.3334,1.5135)	(0.0796,0.1042,0.1357)	0.1065	**10.39%**
	S_{3d}	(0.9599,1.0670,1.1979)	(0.0656,0.0834,0.1074)	0.0855	8.34%
	S_{3e}	(0.4294,0.4838,0.5518)	(0.0293,0.0378,0.0495)	0.0389	3.79%
Sum		(11.1498,12.7931,14.6419)	-	1.0249	100.0%

From Table 5.16, the three most important items within sustainability are S_{2b} – Resources consumption (15.24%), S_{3c} – Workers health and safety (10.39%), and S_{1c} – Net profit (10.27%), as highlighted. These three most influential items are originated from the different dimensions, namely S_2, S_3 and S_1 respectively. This order of importance of the items coincides with the order of importance at dimension level, emphasising the high degree of importance of dimension S_2 and S_3 compared to S_1.

S_{2b} – Resources consumption represents the most influential item on sustainability of a recycling alternative, with a relative weight of 15.24%. Resources consumed within the recycling alternative includes key resources such as energy, water and materials. This item concerns with the total consumption of the key resources of all the supply chain actors like collectors, recycler and manufacturer in producing a unit weight of product.

This item is deemed most influential on sustainability as it is the root of most of the environmental problems. As shown in Section 2.6.1, over-consumption of resources such as energy will require burning of more fossil fuels, which releases various toxic chemicals that pollute the atmosphere, fresh water and ocean and the land. Over-consumption of water will require extraction of water from already diminishing aquifers and major rivers, changing the water system connecting to the ocean leading to changing ocean current and resulting in climate change and food supply disruption. Over-consumption of materials such as woods, mineral, ores, foods and chemicals, are accompanied by production of pollutants that cannot be assimilated by the natural system, polluting the world. Over-consuming materials also require extensive deforestation and mining, resulting in habitat loss and extinction of flora and fauna.

S_{2b} is very important as it concerns with resources consumption and prevents environmental problem that would arise due to over-consumption. As aforementioned in the previous section, it is believed that there is no economic or social system without a healthy environment. Only with a clean environment, life can continue to exist. This is made possible by carefully monitoring consumption of resources in our planet. This item is therefore the most important item in influencing sustainability.

This item can also be seen to have important uses in sustainability accounting in many contexts, such as optimising process industry supply chain operations (Zhou et al., 2000), optimising crop farming (Fasakhodi et al., 2010), or indicators to investigate mobile phone uses (Paiano et al., 2013) and national sustainability performance (Ercin et al., 2013; Joshua and Bekun, 2020).

S_{2b} is also the most influential item among all the items in environmental sustainability dimension, as compared to S_{2a} – gas emission (9.13%), S_{2c} – acidification and eutrophication potential (7.67%) and S_{2d} – renewable energy generation (9.88%). This is because it represents the root of all causes, indirectly affecting all the items in the dimension. For example, higher resources consumption releases more gas emission inflicting higher acidification and eutrophication. A recycling alternative that has high resources consumption will also be likely to be recommended in using more renewable energy to substitute the energy generated via burning of fossil fuels. As a result, resources consumption is the most influential item that can indirectly affect other items in environmental sustainability dimension, subsequently altering the overall sustainability. From the results, it is also noticed that renewable energy generation and gas emission have given a weight higher than acidification and eutrophication potential, symbolising that the decision makers concern more about the air pollution in the atmosphere, comparing to the water pollution affecting the freshwater and oceans.

S_{3c} – Workers health and safety represents the next most influential item on sustainability of a recycling alternative, with a relative importance of 10.39%, which is almost 1.5 times less than S_{2b}, the most important item. This item concerns with the health and safety of the employees within an institution, organisation or practice. S_{3c} is functioned to reflect the health and safety of all employees within the key actors of the supply chain by monitoring frequency of sick leave and injury.

This item is very important within the social dimension of sustainability as it perceives every human being as a unique and non-replenishable resource that should receive little to no negative impact while being utilised in a workplace (Latif et al., 2017). A safe working environment can maintain the workers' health and foster a good quality of life for all workers at the individual level, which will subsequently aggregate to result in good quality of life in the group and community level. Only by then, the current generation can create a healthy and liveable community, which in turn supports the capacity of future generations to meet their own healthy and liveable communities (Hicks, 1997; United Nations Human Rights, 2011; Magee et al., 2012). At such, this item is the most influential item on social sustainability of a recycling alternative.

S_{3c} is also being used abundantly in the literature as the most important item in the social sustainability accounting, such as manufacturing industry (Lozano and Huisingh, 2011; Latif et al., 2017; Guimarães et al., 2018) or companies in general (White, 2005; Weiss, 2013; Evangelinos, et al., 2018), suggesting and verifying a high significance of this item in the social sustainability.

This item is also discovered to be the most influential item among all the items within the societal sustainability dimension comparing to S_{3a} – job creation (5.14%), S_{3b} – working hours and wages (7.29%), S_{3d} – child labour (8.34%) and S_{3e} – local citizen participation (3.79%). This is because workers' health and safety is one of the most recognisable key performance indicators that must be reported under the regulations of Occupational Safety and Health Administration (OSHA) (Reese and Eidson, 2006). Indeed, the health and safety of workers is viewed as the most fundamental item in ensuring the wellbeing of an individual, subsequently affecting the community and the society. All the equity and social justice as aforementioned are built upon a safe and healthy society. As long as the living spaces are safe and the health of people is maintained or improving, the society will continue to exist. This item represents a fundamental enabler for a society to exist and persist, playing a significant role in influencing a social wellbeing and social sustainability.

S_{1c} – Net profit is the next most influential item on the sustainability of a recycling alternative, with a relative importance of 10.27%, only slightly less than its preceding item S_{3c}, signifying its high importance. This item concerns with the net profit of the business after considering all the costs or subsidies. Unlike C_{1f} in circularity that concerns only with the profit or saving generated particularly on recyclable materials consumed (which is functioned to compare the ability of alternatives to maximise monetary value of waste), S_{1c} is concerns with the profit of the overall business to understand feasibility of business in continuing its operation. This item is functioned to reflect the net profit of the key actors within the circular supply chain.

It is imperative that a business must be making enough profit to sustain the business, besides maintaining environmental and social sustainability. Businesses that trade-off economic viability to improve environmental and social sustainability contravenes the initial motive of sustainability (Wu and Pagell, 2011; James and Magee, 2016; Zhang et al, 2019). As aforementioned, profit is utmost required if a business intends to create an impact to the societiy at large or even address the environment and social issues (Dresner, 2008; Portney, 2015; Thiele, 2016). As a result, this item is crucial to the decision makers.

Evidently, S_{1c} is also used abundantly in different research contexts as a key indicator or measurement item of sustainability, for example sustainable supply network (Zore et al., 2017; Hendiani et al., 2020), sustainable recycling network (Harijani et al., 2017) and industrial system (Piluso et al., 2008).

This item is discovered to be the most influential item within the economic sustainability dimension, preceding S_{1a} – operational cost (7.79%) and S_{1b} –capital cost (5.07%). This is because having an operational or capital cost that is low does not necessarily indicate that a business is making profit. Low cost is just a contributing factor for a business to make profit, but not represents a direct causal relationship for a business to generate profit. Consequently, profit is deemed more important in this regard, demonstrating the capability of a business to continue its operation.

These three items represent the most important items for a recycling alternative to excel in sustainability. A recycling alternative that is sustainability focused should pay attention to check and refine the dimension pertaining to environmental and societal sustainability. At the item level, resources consumption, workers health and safety and net profit should be highlighted to enhance sustainability of the recycling alternative.

5.1.3.3 Comparing the Relative Importance of Dimensions and Items Within the Circularity and Sustainability Criteria

The highest relative weight given to each dimension and item under each criterion are extracted from Tables 5.10, 5.12, 5.14 and 5.16. The results are tabulated in Table 5.17.

Table 5.17: The relative importance of dimension or items for both sustainability and circularity (Source: Author).

Criteria	Dimension		Item	
Sustainability	S_1 (Economic)	26.37%	S_{1c}	10.24%
	S_2 (Environmental)	**45.38%**	$\underline{S_{2b}}$	**15.4%**
	S_3 (Social)	**28.25%**	$\underline{S_{3c}}$	**10.39%**

Circularity	C_1 (Monetary)	**29.07%**	C_{1f}	**7.00%**
	C_2 (Environmental and energy)	**25.00%**	C_{2d}	6.82%
	C_3 (Material)	17.02%	C_{3b}	5.67%
	C_4 (Temporal)	9.40%	C_{4a}	5.87%
	C_5 (Efficiency)	19.51%	C_{5c}	**7.29%**

It is discovered that both the circularity and sustainability have distinctive different focuses, as highlighted. At the dimension level, it is observed that circularity prioritises monetary dimension above others such as energy and environment, efficiency, material or temporal; while sustainability highlights environmental sustainability and social sustainability over economic sustainability.

At the item level, the most influential items within circularity are related to recyclability of products and profit or savings. Nevertheless, the crucial items within sustainability are on resources consumption and workers health and safety. These findings strengthen the claims that circularity and sustainability have different emphases (Stahel, 2013; Murray et al., 2015; Geissdoerfer et al., 2017).

It is worth noting that this finding disagreed with some research studies which assert that circularity would completely encompass all sustainability elements, recommending the mere use of circularity to measure the performance of recycling alternatives. The distinctive differences between circularity and sustainability as discovered in this research dissuaded the use of either of them as a standalone method to measure the performance of recycling alternatives, which is inappropriate and could result in partiality in decision-making.

5.2 The Results and Analysis for Phase 2: Rankings of The ELT Recycling Alternatives

An ELT collector company based in France was invited to take part in this research and provided data for phase 2 of the study. As explained in Section 3.1, an ELT collector that supplies their ELT to the four largest ELT market namely the artificial turf, sports surface, moulded objects and cement as well as foundries are selected to provide data for this study. This is because the four recycling alternatives covered the majority (i.e., 92%) of the ELT market. Additionally, foundries is selected as a confirmative analysis to compare performance of mechanical recycling and chemical recycling.

The five recycling alternatives are named as 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 details of each alternative can be examined in Section 3.1. The performance of each recycling alternative is evaluated against circularity and sustainability using the 7-point Likert Scale ratings, as tabulated in Tables J1 to J6 in Appendix J. Using the responses provided by the managers, the five outlets are ranked by FTOPSIS procedures as shown in Section 4.4. Firstly, the lingustic responses from the three managers (see Tables J1-J6) are fuzzified according to Table 5.18 and are aggregated into an aggregated decision matrix using Equation (9). The aggregated decision matrix will then be normalised using Equations (10) and (11) and multiplied with the weight obtained from phase 1 of the research following Equation (12), producing a weighted normalised aggregated decision matrix. It will then be used to calculate the Fuzzy positive ideal solution (FPIS or A^*) and Fuzzy negative ideal solution (FNIS or A^-) using Equations (13) and (14) respectively. Subsequently, the distance of each alternative from FPIS and FNIS is obtained using Equations (15), (16) and (17). The sum of FPIS and FNIS for different alternatives (i.e., D_i*, D_i^-) are determined and are used to calculate the closeness coefficient using Equation (18), which lead to ranking determination.

Table 5.18: Linguistic variable for rating of the alternatives (Source: Kannan et al., 2013).

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5.2.1 Ranking of The ELT Recycling Alternatives Based on Circularity

The aggregated decision matrix of circularity criteria for the three managers (see Tables J1-J3) are obtained and shown in Table 5.19. The weight obtained from phase 1 of the research (see Section 5.1.3) is shown under the column $\widetilde{w_i}$ of the same table. The weighted normalised decision matrix, FPIS and FNIS, as well as the distance of each alternative from FPIS, FNIS for each item for circularity, are shown in Appendix J (see Tables J7 and J8). The rating of alternatives is inspected and analysed using the mean value b_{ij} within the triangular fuzzy numbers $\widetilde{x}_{ij} = (a_{ij} , b_{ij} , c_{ij})$ to represent an alternative.

To facilitate the analysis and discussion, the items are divided into benefit criteria and cost criteria. In benefit criteria, an alternative that is rated “7” is better. In contrast, in cost criteria, an alternative that is rated “1” is better. Among the 23 circularity items, 8 of them are cost criteria (i.e., C_{1a}, C_{1b}, C_{1e}, C_{2b}, C_{2d}, C_{2e}, C_{3d} and C_{4b}) while the rest of the 15 items are benefit criteria.

Table 5.19: The aggregated decision matrix and fuzzy weights under circularity (for all DMs)

		A1	A2	A3	A4	A5	$\widetilde{w_i}$
C_1	C_{1a}	(1,5,9)	(1,5,9)	(0,3,7)	(0,1/3,3)	(0,4/3,5)	(0.0220,0.0306,.0430)
	C_{1b}	(0,3,7)	(0,3,7)	(0,3,7)	(1,5,9)	(1,5,9)	(0.0246,0.0350,.0502)
	C_{1c}	(3,7,10)	(3,7,10)	(3,7,10)	(0,4/3,5)	(1,11/3,7)	(0.0315,0.0442,.0627)
	C_{1d}	(1,5,9)	(1,5,9)	(0,3,7)	(0,4/3,5)	(0,3,7)	(0.0379,0.0534,.0747)
	C_{1e}	(1,5,9)	(1,5,9)	(3,7,10)	(0,4/3,5)	(3,7,10)	(0.0232,0.0321,.0451)
	C_{1f}	(0,3,7)	(0,3,7)	(1,5,9)	(0,1/3,3)	(0,4/3,5)	(0.0503,0.0703,.0975)
C_2	C_{2a}	(0,4/3,5)	(0,4/3,5)	(0,4/3,5)	(7,29/3,10)	(5,26/3,10)	(0.0223,0.0315,.0446)
	C_{2b}	(0,3,7)	(0,3,7)	(0,3,7)	(0,4/3,5)	(0,4/3,5)	(0.0154,0.0213,.0301)
	C_{2c}	(0,1/3,3)	(0,1/3,3)	(0,1/3,3)	(0,1/3,3)	(0,1/3,3)	(0.0228,0.0323,.0456)
	C_{2d}	(0,3,7)	(0,3,7)	(0,3,7)	(0,3,7)	(0,3,7)	(0.0498,0.0685,.0940)
	C_{2e}	(0,3,7)	(0,3,7)	(1,5,9)	(0,1/3,3)	(0,1/3,3)	(0.0387,0.0541,.0755)
	C_{2f}	(0,1/3,3)	(0,1/3,3)	(0,1/3,3)	(0,1/3,3)	(0,1/3,3)	(0.0260,0.0364,.0511)
C_3	C_{3a}	(0,1/3,3)	(0,1/3,3)	(0,1/3,3)	(0,1/3,3)	(0,1/3,3)	(0.0267,0.0378,.0534)
	C_{3b}	(7,29/3,10)	(3,7,10)	(3,7,10)	(7,29/3,10)	(7,29/3,10)	(0.0405,0.0569,.0791)
	C_{3c}	(3,7,10)	(3,7,10)	(1,5,9)	(5,26/3,10)	(3,7,10)	(0.0266,0.0376,.0528)
	C_{3d}	(0,4/3,5)	(0,4/3,5)	(0,4/3,5)	(0,1/3,3)	(0,1/3,3)	(0.0260,0.0366,.0514)
C_4	C_{4a}	(5,26/3,10)	(5,26/3,10)	(3,7,10)	(0,1/3,3)	(0,1/3,3)	(0.0425,0.0589,.0817)
	C_{4b}	(1,5,9)	(1,5,9)	(1,5,9)	(1,5,9)	(1,5,9)	(0.0175,0.0242,.0339)
C_5	C_{5a}	(1,5,9)	(3,7,10)	(3,7,10)	(3,7,10)	(5,26/3,10)	(0.0278,0.0389,.0547)
	C_{5b}	(1,5,9)	(0,3,7)	(0,4/3,5)	(1,5,9)	(1,5,9)	(0.0300,0.0421,.0594)
	C_{5c}	(5,26/3,10)	(3,7,10)	(1,5,9)	(1,5,9)	(1,5,9)	(0.0520,0.0732,.1017)
	C_{5d}	(3,7,10)	(3,7,10)	(3,7,10)	(1,5,9)	(1,5,9)	(0.0372,0.0525,.0740)
	C_{5e}	(0,20/3,10)	(0,20/3,10)	(0,20/3,10)	(0,10/3,10)	(0,10/3,10)	(0.0229,0.0317,.0445)

5.2.1.1 Ranking of the ELT Recycling Alternatives Based on Dimension C_1.

According to Table 5.19, the best alternative under item C_{1a} - average cost of virgin material per kg virgin material, arranged in the descending order of rating is A4> A5> A3> A1= A2, with a rating of 1/3, 4/3, 3, 5 and 5 respectively. The average cost of virgin materials for cement is the cheapest because it involves only limestone and clay (US Environment Protection Agency, 2010; Scrivener, 2014). Foundries, on the other hand, involve coke and coal in the production process, which have a higher virgin materials price compared to cement (Arasu, 2010). Nevertheless, the cost of virgin materials for moulded objects is slightly higher as it involves chemical binders (known as polyurethane), which would slightly elevate the overall cost of virgin materials as it is more expensive (US Environment Protection Agency, 2010). The chemical binders are very important in making moulded objects to yield a stronger product with a smoother surface that is comparable to produce virgin materials (Morton-Jones and Ellis, 1986). Sports surface, besides using polyurethane resin binders in creating sports surface, also involves the use of coloured acrylic resin above the rubber layer to increase grip, thus further increases the cost of virgin materials (Ecopneus, 2020). Finally, the production of artificial turf involves the highest amount of virgin materials, which significantly increases the cost of virgin materials. The production of artificial turf requires the making of numerous grass-like fibres using synthetic fibres (e.g., polyethylene) and a backing layer, made of two layers of nonwoven polypropylene textiles and latex to hold the grass-like fibres (Morehouse, 1992; Sassi et al., 2011). This causes the cost of virgin material for artificial turf to be highest compared to other alternatives.

The best alternative under item C_{1b} – average repairing price, arranged in the descending order of rating is A1 = A2 = A3 > A4= A5, with a rating of 3, 3, 3, 5 and 5 respectively. Artificial turf is very easily repaired, provided there is a large number of infill losses due to extreme mismanagement or natural disaster. Only grounded ELT of the size of ±2 mm are required for the repair, by refilling the infill and compressing it to an original depth of 2.5 to 4 cm (Morehouse, 1992; Sassi et al., 2011). Sports surface can also be easily repaired, which required only coloured acrylic resin to be reapplied over the sports surface to increase grip (US Environment Protection Agency, 2010; Ecopneus, 2020). A moulded object requires only adhesive resin or filler to repair the faulty surface (Gachaco et al., 2013). Overall, the repairing price for the product of these 3 alternatives are lower, increasing the tendency for the products to be repaired rather than being disposed. The repairing price for cement and foundries is slightly higher because cement and the iron produced in foundries are usually integrated in large buildings or machinery structure, where it is slightly expensive for repair to be carried out (Czarnecki et al, 1999; US Environment Protection Agency, 2010).

The best alternative under item C_{1c} – fraction of cost spent on CE technology to total cost of investment, arranged in the descending order of rating is A1 = A2 = A3 > A5> A4, with a rating of 7, 7, 7, 11/3 and 4/3 respectively. The artificial turf, sports surface and moulded products require the ELT to be grounded to finer particles (i.e., 2mm-5mm) and all the reinforcing wire in the ELT to be separated and removed to avoid puncture wounds or injury during use. Therefore, more sophisticated disassembly machines in the supply chain, such as advanced recycling machines, grinders, magnets, or disassembly robots, are required which increase the cost spent on technology associated to CE (Shuman, 2004; US Environment Protection Agency, 2010). Foundries involve less CE technology because larger pieces of shredded tyre are used instead of fine grounded ELT, hence sophisticated grinders used in other alternatives are not required (US Environment Protection Agency, 2010). The reinforcing wire in the ELT are also not required to be removed as it can be used as feedstock along with the ELT in producing cast metals, which further reduces the cost to purchase a disassembly robot. Cement involves the least CE technology as the manufacturing of cement uses ELT directly as a whole, negating the needs for most of the aforementioned CE technology (Fattuhi and Clark, 1996).

The best alternative under item C_{1d} – fraction of cost spent on recyclable material to total cost of material, arranged in the descending order of rating is A1 = A2 > A3 = A5> A4, with a rating of 5, 5, 3, 3 and 4/3 respectively. Most of the raw materials used for the production of all recycling alternatives are recyclable, for example rubber and polyethylene fibres in artificial turf, polyurethane binders in sports surface and moulded objects, as well as limestone in foundries and cement production (US Environment Protection Agency, 2010). Instead, the materials used for operations or packaging are the major source of non-recyclable materials consumption, for example, Styrofoam and plastic film or wrap used for packaging and adhesive chemicals used in operations or packaging (Cathie, 1994; Hawkins, 2018). Both artificial turf and sports surface do not require additional packaging, reducing the need for non-recyclable materials and allowing them to spend more money on the recyclable raw materials for product manufacturing. However, moulded objects, foundries and cement require more non-recyclable materials in operations or packaging (with cement requiring the highest amount), which lower the cost spent on recyclable raw materials for product manufacturing (Colares-Moreira and Mainier, 2019; Ma et al., 2019).

The best alternative under item C_{1e} – production cost per kg product, arranged in the descending order of rating is A4 > A1 = A2 > A3= A5, with a rating of 4/3, 5, 5, 7 and 7 respectively. Cement has the lowest cost of production because the combustion of ELT could generate enough energy and electricity to sustain the daily energy and electricity required for cement manufacturing (Barlaz et al., 1993). In the process, 75% of the ELT by weight are burnt to produce the energy and electricity required, while 25% of the total weight of the ELT are incorporated into cement. Also, the ELT are not required to be shredded or grounded, further reduces the overall production cost (De Souza and Almeida, 2013). Artificial turf and sports surface require slightly higher production cost because they require more energy and electricity to dissemble the ELT, separate the components, and then ground the ELT into fine particles (US Environment Protection Agency, 2010). The manufacturing process for artificial turf is also demanding high energy and electricity for cutting the grass-like plastic filament, tucking them into the backing and compressing the grounded ELT between the filaments (Jastifer et al., 2019). Moulded object and foundries incurred the highest production cost among the alternatives. Moulded object requires high energy to heat the mixture of grounded ELT, binder and additives to create semi-viscous homogeneous material, which allows them easily flow into a mould (Marco et al., 2006). Unlike cement, the energy required in making of moulded object is not generated by burning the ELT. In the moulding process, high pressure is needed to be applied to the mixture before the product is released from the mould becoming a solid object that meets the defined design, shape and specification. The entire moulding process is also very labour intensive, hence incurring a high production cost (US Environment Protection Agency, 2010). Foundries also requires high temperature in the manufacturing and a great amount of electricity and energy are required to carry the materials to the inlet at the top of the blast furnace which is usually 20m to 35m high. Hence, these foundries processes would incur high production cost (Pehlken, 2006; Sahajwalla et al., 2011).

The best alternative under item C_{1f} – profit or saving per kg recyclable input consumed, arranged in the descending order of rating is A3 > A1 = A2 > A5> A4, with a rating of 5, 3, 3, 4/3 and 1/3 respectively. Generally, the use of ELT to substitute virgin rubber in product manufacturing will generate a saving. Moulded objects would normally generate the highest saving as it requires only ELT with larger particles in the manufacturing (i.e., finer particles are more expensive) (US Environment Protection Agency, 2010). At the same time, moulded objects also have a high profit margin because its complicated manufacturing processes are highly value adding (Crowder, 1989). Overall, it could provide the highest profit or saving in comparison to other recycling alternatives. Since artificial turf and sports surface require ELT grounded to the finest size, the potential of saving made is slightly lower (US Environment Protection Agency, 2010; Jastifer et al., 2019). Since the market is saturated, the profit made from these alternatives are lower too (US Environment Protection Agency, 2010). Even though foundries use larger size grounded ELT, it does not generate high saving as the virgin materials being substituted are coal and coke, which are rather cheap. The saturated market also further compromised its profit margin (Jelinik, 2018). Lastly, cement has the lowest profit and saving potentials. This is because the virgin materials being substituted are cheap and it represents a commodity that has a low profit margin, thus lowering the overall profit or saving for this alternative (Quelch, 2007).

5.2.1.2 Ranking of the ELT Recycling Alternatives Based on Dimension C_2

The best alternative under item C_{2a} – fraction of energy generated using renewable sources, arranged in the descending order of rating is A4 > A5 > A1 = A2 = A3, with a rating of 29/3, 26/3, 4/3, 4/3 and 4/3 respectively. Traditionally, cement and foundries were the major consumer of energy within the industry, and also the major polluter of our environment (Rane, 2009; Amrina and Vilsi, 2015). Consequently, they have been closely being monitored and regulated by the government, bearing more responsible for cutting down the reliance on energy generated using fossil fuels so as to reduce pollution (Mandal, 2010). Today, cement and foundries are generating its own energy, particularly using renewable sources such as biomass, as it will generate less pollution (Ariyaratne et al., 2010; Tsiligiannis and Tsiliyannis, 2019). In the contrary, artificial turf, sports surface and moulded objects have less responsibility on generating energy using renewable sources, because they consume relatively less energy and emitting less pollution.

The best alternative under item C_{2b} – fraction of energy loss, arranged in the descending order of rating is A4= A5> A1 = A2 = A3, with a rating of 4/3, 4/3, 3, 3 and 3 respectively. The manufacturing of cement and foundries requires high temperature in the unit operation up to 1500 ^{0}C (Wojtynek, 2009; Atmaca and Kanoglu, 2012). The high temperature requires investment of thick and advance insulating materials to prevent energy leakage (Hensley and Aguilar, 2012). As a result, cement and foundries have the lowest fraction of energy loss as compared to other alternative. Since the operating temperature for the manufacturing of artificial turf, sports surface and moulded objects are much lower, less insulation materials are invested to contain the energy and prevent leakage, causing the energy loss to be slightly higher (US Environment Protection Agency, 2010).

There is no best alternative under item C_{2c} – fraction of energy purchased from renewable sources as all alternatives have an equal rating of 1/3. This is highly dependent on individual businesses to select the energy provider for the supply chain. It is discovered that the source of energy purchased for all the alternatives are not originated from renewable sources as their rating are very low. This is because the energy generated from renewable sources is much more expensive than energy generated from non-renewable sources such as coal (Heal, 2009; Kaberger, 2018). The desire to purchase energy from renewable sources is low as there is a need to reduce the overall cost for the production in all the recycling alternatives (Timmons et al., 2014).

There is also no best alternative under item C_{2d} – total GHG produced per kg as all alternatives have an equal rating of 3. Generally, higher GHG will be produced when higher temperature is involved in the manufacturing process due to burning of more fuel to sustain the temperature of manufacturing process (Hinrichs and Kelinbach, 2012). Consequently, cement and foundries (which required higher operating temperature) will produce higher GHG than moulded objects, artificial turf or sports surface. Nevertheless, since artificial turf, sports surface and moulded products requires the ELT to be dissembled during collection process and grinded to smaller pieces, the GHG produced during the process, emitted throughout the supply chain, is therefore comparable to cement or foundries (Clauzade et al., 2010; Fiksel et al., 2011; Ortiz-Rodrìguez et al., 2017). As a result of the summation, the total GHG produced per kg is rated as equal for all alternatives at supply chain level.

The best alternative under item C_{2e} – total energy consumed per kg product, arranged in the descending order of rating is A4= A5> A1 = A2 > A3, with a rating of 1/3, 1/3, 3, 3 and 5 respectively. As previously mentioned in C_{1e}, the grounding of ELT into finer particles would require more energy, thus artificial turf and sports surface would generally require more energy for the grounding process, compared to cement or foundries that uses ELT as a whole or shredded to larger pieces (US Environment Protection Agency, 2010; Jastifer et al., 2019). Furthermore, extra energy is also required to dissemble the ELT and remove the wire within the ELT for manufacturing of artificial turf and sports surface. Nevertheless, within the manufacturing process, the total energy required for cement and foundries are compensated by the energy released by the burning of ELT, thus reducing the total energy consumed per kg of product manufactured (Barlaz et al., 1993). The manufacturing process for artificial turf is also demanding high energy in cutting the grass-like plastic filament, tucking them into the backing and compressing the grounded ELT between the filaments (Jastifer et al., 2019). Overall, moulded objects require the highest energy among the alternatives to generate heat and pressurise the mixture, which is not compensated by burning of ELT like in cement or foundries since no burning is involved (Barlaz et al., 1993).

There is no best alternative under item C_{2f} – total energy generated per kg product, as all alternatives have an equal rating of 1/3. This is not a fix phenomenon observable in the industry, but highly dependent on individual businesses to opt in for energy generation on-site (Bot et al., 2019). It is discovered that all the alternatives for this case study company do not produce much energy, signifying that the power plant on-site is very small, just to cover portion of the energy requirement for the business (Ruangpattana et al., 2019). Albeit low, this shows a small step has been taken towards achieving the "nearly zero energy balance in buildings" by 2020, as envisaged by European Union in the new directive 2018/844/EU (Bot et al., 2019).

5.2.1.3 Ranking of the ELT Recycling Alternatives Based on Dimension C_3

There is no best alternative under item C_{3a} – fraction of recycler output to original supply chain, as all alternatives have an equal rating of 1/3. Like C_{2f}, there is no regulation set to regulate against whether an EOL product should be supplied to original supply chain or open loop supply chain (Kalverkamp and Young, 2019). It is discovered that the recyclers for all the alternatives in this case study tend to supply their EOL product to open loop supply chain, since the rating for fraction of recycler output to original supply chain is very low. This is because the quality requirement for the recycled materials to be returned to the original supply chain is very strict, unlike open loop supply chain which has a looser requirement for the recycled material (Kalverkamp and Young, 2019).

The best alternative under item C_{3b} – fraction of recycled material used per kg product, arranged in the descending order of rating is A1= A4= A5> A2 = A3, with a rating of 29/3, 29/3, 29/3, 7 and 7 respectively. Artificial turf, cement and foundries have the highest fraction of recycled material used per kg product, preceding sports surface and moulded objects. Artificial turf can be made using EOL plastics and grounded ELT to produce grass-like filaments, backing and infills (Jastifer et al., 2019). Cement can use EOL bricks, EOL concretes, EOL glass and ELT as substitutes for virgin limestone, clay and coal fuel (Pavlu, 2018). Foundries can use EOL metal and shredded tyre to substitute iron ore and coke (Echterhof, 2021). On the contrary, the chemical binders used to produce sports surface and moulded objects are produced using virgin materials and not recycled materials, thus reducing the overall fraction of recycled material used per kg product (Chen et al., 2018).

The best alternative under item C_{3c} – fraction of waste recycled internally, arranged in the descending order of rating is A4> A1= A2= A5 > A3, with a rating of 26/3, 7, 7, 7 and 5 respectively. Cement alternative has the highest fraction of waste recycled internally because the manufacturing waste can be reused as feedstock without affecting the overall composition of the final product. The water used for cooling off the cement are also recycled extensively (De Souza and Almeida, 2013). Artificial turf, sports surface and foundries on the other hand will produce more waste that cannot be recycled internally, such as over-cut filament and over-cut backing thread in artificial turf (Jastifer et al., 2019), trimming of over-size sports surface (Chen et al., 2018) as well as slag produced in foundries furnace (Wojtynek, 2009; Atmaca and Kanoglu, 2012). These wastes could not be recycled internally as they can no longer be used for product making and must be recycled externally. Moulded objects have the lowest fraction of waste recycled internally, as the majority of the product that do not meet specification could not be recycled internally because many chemicals are involved in the process of manufacturing of moulded object (US Environment Protection Agency, 2010; Chen et al., 2018).

The best alternative under item C_{3d} – total weight of unrecoverable waste, arranged in the descending order of rating is A4= A5> A1 = A2 = A3, with a rating of 1/3, 1/3, 4/3, 4/3 and 4/3 respectively. Cement has the least total weight of unrecoverable waste because the majority of the waste or products that do not meet specification can be recycled internally without affecting the overall composition of the final product, as the ratio of the feedstock mixture can be easily changed (Schneider, 2015). The waste that could not be recycled internally in foundries such as slag could be reused as feedstock in agriculture to treat acid soils (Wojtynek, 2009; Atmaca and Kanoglu, 2012). Artificial turf, sports surface and sports surface would produce more unrecoverable waste because chemical is involved in the manufacturing process, rendering the usefulness of the waste (US Environment Protection Agency, 2010; Chen et al., 2018).

5.2.1.4 Ranking of the ELT Recycling Alternatives Based on Dimension C_4

The best alternative under item C_{4a} – lifetime of product, arranged in the descending order of rating is A1= A2> A3> A4 = A5, with a rating of 26/3, 26/3, 7, 1/3 and 1/3 respectively. Artificial turf and sports surface has the longest lifespan, which is estimated to be a minimum of 10 years with minimal need to add more ground rubber to replace material lost (US Environment Protection Agency, 2010; Ecopneus, 2020). Moulded objects have a slightly shorter lifetime due to disintegration of chemicals while exposed to UV rays of sunlight (Goodwin Jr et al., 2020). The ELT used in cement and foundries are immediately disintegrated during the manufacturing process, losing its original properties. The resulting cement has a lifespan of 6 months if it is correctly stored (Schmidtmeier et al., 2010). The resulting iron from foundries would last for a few years before it becomes rusty (Whitney, 1903).

There is no best alternative under item C_{4b} – time to reach CE goal, as all alternatives have an equal rating of 5. This result shows that all the alternatives have a good planning on time to reach a pre-set CE goal, such as time planned to reach designated amount of recycling rate of waste internally. Therefore, they have an equal commitment and similar mindset towards integrating CE principle in the daily operation.

5.2.1.5 Ranking of the ELT Recycling Alternatives Based on Dimension C_5

The best alternative under item C_{5a} – collection efficiency, arranged in the descending order of rating is A5> A2= A3= A4 > A1, with a rating of 26/3, 7, 7, 7 and 5 respectively. The iron produced in foundries has the highest collection efficiency as it can be easily separated and collected from other materials using magnets, in comparison to products in other alternatives (Li et al., 2010). Sports surface, moulded objects and cement have lower collection efficiency because the materials within the product are slightly more difficult to be separated as they are strongly bonded by chemicals (US Environment Protection Agency, 2010). Solvent will be required to remove the chemicals, resulting in more waste after the collection process (Zhao et al., 2018). Artificial turf has the lowest collection efficiency as it has too many materials connected to each other. The separation process for plastic filaments and backing from grounded ELT infills is difficult and collection of useful material is difficult as they have quite similar physical and chemical properties (US Environment Protection Agency, 2010; Jastifer et al., 2019). The disassembly and collection process will also result in severe damages on the materials, eventually generating more waste in the process.

The best alternative under item C_{5b} – modularity of product design, arranged in the descending order of rating is A1= A4= A5> A2 > A3, with a rating of 5, 5, 5, 3 and 4/3 respectively. Modular design is an approach in product design that consists of distinct detachable modules for efficienct upgrading, replacement and disassembly (Gu et al., 1997). Generally, all products in the 5 alternatives have low modularity as the materials within the products cannot be easily dissembled and replaced by new or upgraded materials. Nevertheless, artificial turf, cement and foundries irons have higher modularity as compared to sports surface and moulded objects. Artificial turf has more components and can be dissembled and replaced easily if one component fails (Jastifer et al., 2019). Sports surface and moulded objects, however, involve fewer and are usually one complete piece of component, thus making the dissembling process and replacing more difficult (US Environment Protection Agency, 2010).

The best alternative under item C_{5c} – recyclability of product, arranged in the descending order of rating is A1> A2> A3= A4 = A5, with a rating of 26/3, 7, 5, 5 and 5 respectively. Artificial turf has higher recyclability as plastic filaments, backing and grounded ELT infills are all recyclable (Jastifer et al., 2019). Sports surface and moulded objects have lower recyclability as chemical binders used to produce sports surface and moulded objects are not recyclable (Chen et al., 2018). Like moulded surface, both cement and iron from foundries also have slightly lower recyclability, depending on the additives during manufacturing process or physical coating applied over the resulting cement and iron (US Environment Protection Agency, 2010).

The best alternative under item C_{5d} – recycling efficiency of recycler, arranged in the descending order of rating is A1= A2= A3> A4 = A5, with a rating of 7, 7, 7, 5 and 5 respectively. Artificial turf, sports surface and moulded objects have higher recycling efficiency because these alternatives require the ELT grounded to finer particle size, and thus more sophisticated recycling machines are used, which not only able to grind ETL to finer particle size but also more efficient in nature (US Environment Protection Agency, 2010). Cement and foundries have lower recycling efficiency since the alternative do not require the use of finely grounded ELT, thus less sophisticated recycling machines are used, which is also less efficient in nature (De et al., 2005).

The best alternative under item C_{5e} – rental-ability, arranged in the descending order of rating is A1= A2= A3> A4 = A5, with a rating of 20/3, 20/3, 20/3, 10/3 and 10/3 respectively. Artificial turf, sports surface and moulded objects have higher rental-ability as they can be rented out to other users for additional revenue (Durgee et al., 1995). On the contrary, cement and foundries iron are used to build buildings or machine which is usually proprietary and less rental-able (Huseynova, 2014).

5.2.1.6 Summary of Ranking of the ELT Recycling Alternatives Under Circularity

Overall, the best alternative under circularity can be determined by applying the above ratings into the equations as described in Section 4.4. The circularity of the alternatives arranged in the descending order of rating is A1> A2> A3> A5 > A4, with a rating of 0.2966, 0.2614, 0.1977, 0.1461 and 0.0982 respectively, as shown in Table 5.20. A1-

artificial turf is the best alternative under circularity, because of its excellent performance especially in item C_{1b}, C_{1c}, C_{1d}, C_{3b}, C_{4a}, C_{5b}, C_{5c}, C_{5d} and C_{5e}. Artificial turf is easily repaired, with low C_{1b}-repairing price, thus improving the probability of the product to be repaired and extending its lifespan, instead of being discarded due to unaffordable repairing price. Artificial turf's supply chain is very dedicated to improving its circularity by investing greatly in CE technology and using more recyclable materials as shown by the high C_{1c}-fraction of cost spent on CE technology to total cost of investments, high C_{1d}-fraction of cost spent on recyclable material to total cost of material and high C_{3b}-fraction of recycled material used per kg product. The lifetime of artificial turf is also the highest among the alternatives, as shown in C_{4a}, which is one of the most important elements in CE. The modularity of product design C_{5b} is also the highest, making the components in the product easily dissembled and replaced, thus reducing waste associated to disposal of the whole unit due to components failure. The recyclability of the artificial turf is high, as shown in C_{5c}, because it consists mainly of recyclable plastics and recyclable grounded rubber. Since artificial turf requires fine grounded ELT, the recycling machine used in this alternative is also very advanced and thus having high recycling efficiency as shown in the high C_{5d}.

Table 5.20: Rating of alternatives based on circularity (Source: Author).

Alternative	Circularity		
	Closeness Coefficient	Normalised Closeness Coefficient	Rank
A1	0.7988	0.2966	1
A2	0.7040	0.2614	2
A3	0.5326	0.1977	3
A4	0.2644	0.0982	5
A5	0.3936	0.1461	4

5.2.2 Ranking of the ELT Recycling Alternatives Based on Sustainability

The aggregated decision matrix of sustainability criteria for the three managers (see Tables J4-J6) are obtained and shown in Table 5.21. The weight obtained from phase 1 of the research (see Section 5.1.3.2) is shown under the column $\widetilde{w_i}$ of the same table. The weighted normalised decision matrix, FPIS and FNIS, as well as the distance of each alternative from FPIS, FNIS for each item for sustainability, are shown in Appendix J (see Tables J9 and J10). The rating of alternatives is inspected and analysed. Same as the previous section, the mean value of the triangular fuzzy numbers $\tilde{x}_{ij}$ in Table 5.21, which is b_{ij}, will be used to represent the rating of each alternative. For example, the rating used to represent alternative A1 under item S_{1a} will be 5, which is the middle value in the triangular fuzzy number (1, 5, 9).

Similar to the previous section, the items are divided into benefit criteria and cost criteria to facilitate the analysis and discussion. Among the 12 sustainability items, 7 of them are cost criteria (i.e., S_{1a}, S_{1b}, S_{2a}, S_{2b}, S_{2c}, S_{3c} and S_{3d}) while the rest of the 5 items are benefit criteria.

Table 5.21: The aggregated decision matrix and fuzzy weighs of sustainability (for all DMs) (Source: Author).

		A1	A2	A3	A4	A5	$\widetilde{w_i}$
S_1	S_{1a}	(1,5,9)	(3,7,10)	(5,26/3,10)	(0,1/3,3)	(0,3,7)	(0.0584,0.0778,0.1033)
	S_{1b}	(1,5,9)	(1,5,9)	(3,7,10)	(0,4/3,5)	(0,4/3,5)	(0.0378,0.0504,0.0678)
	S_{1c}	(0,4/3,5)	(0,3,7)	(0,3,7)	(0,4/3,5)	(0,4/3,5)	(0.0787,0.1029,0.1341)
S_2	S_{2a}	(0,4/3,5)	(0,4/3,5)	(0,4/3,5)	(0,1/3,3)	(0,4/3,5)	(0.0678,0.0908,0.1223)
	S_{2b}	(0,3,7)	(0,3,7)	(1,5,9)	(0,1/3,3)	(0,1/3,3)	(0.1162,0.1534,0.1990)
	S_{2c}	(0,4/3,5)	(0,4/3,5)	(0,1/3,3)	(0,3,7)	(1,5,9)	(0.0591,0.0768,0.1000)
	S_{2d}	(3,7,10)	(1,5,9)	(1,5,9)	(7,29/3,10)	(7,29/3,10)	(0.0750,0.0986,0.1300)
S_3	S_{3a}	(0,3,7)	(0,3,7)	(1,5,9)	(0,4/3,5)	(0,4/3,5)	(0.0388,0.0511,0.0682)
	S_{3b}	(1,5,9)	(1,5,9)	(1,5,9)	(0,4/3,5)	(0,4/3,5)	(0.0553,0.0728,0.0960)
	S_{3c}	(0,4/3,5)	(0,4/3,5)	(0,4/3,5)	(1,5,9)	(1,5,9)	(0.0796,0.1042,0.1357)
	S_{3d}	(0,1/3,3)	(0,1/3,3)	(0,1/3,3)	(0,1/3,3)	(0,1/3,3)	(0.0656,0.0834,0.1074)
	S_{3e}	(0,10/3,10)	(0,10/3,10)	(0,10/3,10)	(0,10/3,10)	(0,10/3,10)	(0.0293,0.0378,0.0495)

5.2.2.1 Ranking of the ELT Recycling Alternatives Based on Dimension S_1

According to Table 5.21, the best alternative under item S_{1a} –operational cost, arranged in the descending order of rating is A4> A5> A1> A2> A3, with a rating of 1/3, 3, 5, 7 and 26/3 respectively. Cement has the lowest operational cost because the cost for feedstock and production is low as shown in C_{1a}, C_{1d} and C_{1e}. Additionally, the logistical cost is low because the supply chain members are situated nearer to each other due to the large market for cement, making overall operational cost for cement to be very low (Schmidtmeier et al., 2010). Even though the supply chain members for foundries iron are situated nearer to each other due to the large market, the cost for feedstock and production under C_{1a}, C_{1d} and C_{1e} are slightly higher, thus slightly elevating its operational cost (Wojtynek, 2009). Besides that, the recycling cost and dissembling cost are the lowest for foundries iron and cement, because only the whole or larger pieces of ELT are required in their manufacturing process. On the contrary, the operational cost for artificial turf, sports surface and moulded objects are higher. This is because their production cost is higher, as shown in C_{1e}, because they require fine grounded ELT in their products manufacturing (US Environment Protection Agency, 2010). Particularly, moulded objects will require higher production cost due to high temperature and pressure required in the manufacturing process (Marco et al., 2006). The cost for feedstock for artificial turf, sports surface and moulded objects are also higher as they involved expensive chemicals in the manufacturing (US Environment Protection Agency, 2010). Furthermore, artificial turf, sports surface and moulded objects do not have a market as wide as cement and foundries iron, which are essential commodity in building industry (Schmidtmeier et al., 2010). Consequently, the supply chain members are not as common for artificial turf, sports surface and moulded objects compared to cement and foundries iron supply chain. The logistical cost associated to transferring the materials among supply chain members within the supply chain are thus higher. Since they are not an essential commodity, economic of scale is hard to attain for artificial turf, sports surface and moulded objects supply chain, which will lead to increased operating cost (US Environment Protection Agency, 2010).

The best alternative under item S_{1b} – capital cost, arranged in the descending order of rating is A4= A5> A1= A2> A3, with a rating of 4/3, 4/3, 5, 5 and 7 respectively. All the different alternatives involve different equipment for manufacturing. Cement requires rotating kilns, foundries requires blast furnaces, artificial turf requires advanced cutters, robotic assembly arms and compressors, sports surface requires mixers, trowel machines and compressors, moulded objects needed casting moulds, compressors, heaters, and extruders (US Environment Protection Agency, 2010). The equipment cost for the manufacturing process is comparable, but the equipment cost for recycling and dissembling for artificial turf, sports surface and moulded objects are generally higher, as fine grounded ELT are required in the manufacturing and the foreign materials in the ELT such as wire and textiles are required to be totally removed (De et al., 2005). In this particular case study, the moulded objects recycling alternative also has an exceptionally high capital cost for land and company setup. As a result, the moulded objects are rated with the highest capital cost, followed by artificial turf, sports surface, foundries, and cement.

The best alternative under item S_{1c} – net profit, arranged in the descending order of rating is A2= A3> A1= A4 = A5, with a rating of 3, 3, 4/3, 4/3 and 4/3 respectively. Sports surface and moulded objects have the highest net profit as compared to other products. Although both the alternatives have the highest operational cost and capital cost, they offer made-to-order products that can be customised according to customers' specification, such as colour and printing on the products, thus increasing the overall net profit (Fisher, 1997). On the contrary, even though cement and foundries iron have lower operational cost, the net profit is lower because they represent essential commodities that have lower profit margin (Collin et al., 2009).

5.2.2.2 Ranking of the ELT Recycling Alternatives Based on Dimension S_2

The best alternative under item S_{2a} – gas emission, arranged in the descending order of rating is A4> A1= A2= A3= A5, with a rating of 1/3 for A4 and 4/3 for the rest. As aforementioned, the GHG emission for all alternatives are the same as shown in C_{2d}. The ozone depleting gaseous emission are also low for all alternatives because coolants such as hydrocarbon are not used extensively in the process (US Environment Protection Agency, 2010). Nevertheless, as explained in C_{2a}, since cement industry is traditionally the major polluter of our environment who consumes approximately 15% of the total industry energy and releases 7% of total worldwide CO_2 emission (Ali et al., 2011), they are therefore being closely monitored and regulated by the government to curb their gaseous emission. Consequently, sophisticated scrubber is installed to comply to the regulations, which reduces the overall gaseous emission (Rane, 2009; Amrina and Vilsi, 2015).

The best alternative under item S_{2b} – resources consumption, arranged in the descending order of rating is A4= A5> A1= A2> A3, with a rating of 1/3, 1/3, 3, 3 and 5 respectively. Cement and foundries consumed the least resources as they can produce their own energy to compensate the energy required for the process, thus negating the need for much energy externally. Even though cement and foundries require more water for cooling off the unit operation, it is compensated by the less energy consumption (Wojtynek, 2009; Schmidtmeier et al., 2010; Atmaca and Kanoglu, 2012). Artificial turf, sports surface and moulded objects have bigger energy consumption, especially in the recycling process as they require fine grounded ELT (US Environment Protection Agency, 2010). Moulded objects require extra energy and materials to press the materials into a designated shape and extra water are required to cool down the materials, thus increasing the overall resources consumption (De et al., 2005).

The best alternative under item S_{2c} – acidification and eutrophication potential, arranged in the descending order of rating is A3> A1= A2> A4> A5, with a rating of 1/3, 4/3, 4/3, 3 and 5 respectively. Artificial turf, sports surface and moulded objects have lower acidification and eutrophication potential than cement and foundries, because burning or ELT in cement or foundries release many acidic gases due to high sulphur content in vulcanised rubber of ELT (US Environment Protection Agency, 2010). Cement has slightly lower acidification and eutrophication potential than foundries because some of the sulphurs are integrated in the cement powder while all sulphur within foundries manufacturing are released into the air producing toxic gas (De et al., 2005). Subsequently, the scrubbing process captured and turned acidic gas into acidic water, which is then released into the river, contributing to acidification and eutrophication potential (Srivastava, 2001).

The best alternative under item S_{2d} – renewable energy generation, arranged in the descending order of rating is A4 = A5> A1> A2= A3, with a rating of 29/3, 29/3, 7, 5 and 5 respectively. Cement and foundries are discovered to be generating most of the energy using renewable sources such as biomass. However, other alternatives are generating energy mainly using non-renewable sources such as coal or natural gas, which explains the lower rating. Cement and foundries are more dedicated in generating energy using renewable sources because of the ability of renewable sources to produce less pollution (Wojtynek, 2009; Schmidtmeier et al., 2010; Atmaca and Kanoglu, 2012). This is driven by the fact that cement and foundries are traditionally the major polluter of our environment, thus they are required curb their gaseous emission, as depicted in C_{2a}.

5.2.2.3 Ranking of the ELT Recycling Alternatives Based on Dimension S_3

The best alternative under item S_{3a} – job creation, arranged in the descending order of rating is A3> A1= A2> A4 = A5, with a rating of 5, 3, 3, 4/3 and 4/3 respectively. Moulded objects are the most labour-intensive alternative as high labour forces are required in the production. This is because the process is difficult to be automated due to different composition of input for every subsequent process and the exchange of casting die for each process requires human intervention (US Environment Protection Agency, 2010). Similarly, labours are required to make sports surface, by mixing the grounded ELT with additives and trowel them on the track (Ecopneus, 2020). Labours are also required in making of the artificial turf and installing the turf on playing field (Jastifer et al., 2019). Cement and foundries require the least labour forces as the production is predominately automation (Wojtynek, 2009; Schmidtmeier et al., 2010; Atmaca and Kanoglu, 2012).

The best alternative under item S_{3b} – working hours and wages, arranged in the descending order of rating is A1= A2= A3> A4 = A5, with a rating of 5, 5, 5, 4/3 and 4/3 respectively. Since artificial turf, sports surface and moulded objects are not a basic and essential commodity like cement and foundries iron, thus they can make a higher net profit as shown in C_{1c}, and also able to pay higher wages per hour (Fisher, 1997).

The best alternative under item S_{3c} – workers' health and safety, arranged in the descending order of rating is A1= A2= A3> A4= A5, with a rating of 4/3, 4/3, 4/3, 5 and 5 respectively. Artificial turf, sports surface and moulded objects have less health and safety issue as compared to cement and foundries. This is due to the high temperature working environment in cement and foundries disrupted the workers' concentration, resulting in more health and safety issues (Wojtynek, 2009; Schmidtmeier et al., 2010; Atmaca and Kanoglu, 2012). Cement also produces a lot of fine particulate matters that suspended in the air, making the atmosphere not as safe in the workplace (Schmidtmeier et al., 2010; US Environment Protection Agency, 2010).

In rare circumstances, toxic fumes could also escape during production and jeopardise the workers' health and safety (US Environment Protection Agency, 2010).

There is no best alternative under the item S_{3d} – child labour as all alternatives have an equal rating of 1/3 respectively. All the alternatives have low rating, indicating that no child labours are involved. This is safeguarded by the introduction of regulations and laws that forbid employment of child labour in the industry (Warmerdam and Katteler, 2007; Selby, 2008).

Lastly, there is no best alternative under the item S_{3e} – local citizen participation as all alternatives have an equal rating of 10/3 respectively. All the alternatives have moderate low rating of local citizen participation, indicating that they have limited involvement and support of local citizen in the business' projects, such as involving in community-led projects.

5.2.2.4 Summary of the Ranking of the ELT Recycling Alternatives Under Sustainability

Overall, the best alternative under sustainability, arranged in the descending order of rating is A3> A2> A1> A4 = A5, with a rating of 0.2816, 0.2413, 0.2026, 0.1372 and 0.1372 respectively, as shown in Table 5.22. Alternative A3 is the best alternative under sustainability, because of the excellent performance in S_{1c}, S_{2c}, S_{3a}, S_{3b} and S_{3c}. Moulded objects has the highest net profit because of the higher profit margin for offering made-to-order products, which is enough to compensate the effect of high operating and capital cost. Because of that it can give the highest wages per hour to their employees as shown in high S_{3b}. This process is also very labour intensive, thus generating the highest job opportunities as shown in S_{3a}. Moulded objects also have the least workers' health and safety issues, making this alternative a good working environment. Moulded objects also produce the least gas emission as well as acidification and eutrophication potential as shown in low S_{2a} and S_{3c}, which implies that it generates the least environmental impact to the surrounding.

Table 5.22: Rating of alternatives based on sustainability (Source: Author).

Alternative	Sustainability		
	Closeness Coefficient	Normalised Closeness Coefficient	Rank
A1	0.4836	0.2026	3
A2	0.5761	0.2413	2
A3	0.6724	0.2816	1
A4	0.3276	0.1372	5
A5	0.3276	0.1372	4

5.2.3 Ranking of the ELT Recycling Alternatives Based on Circularity and Sustainability

Using the results from Table 5.20 and Table 5.22, the five alternatives can be placed in a four-quadrant matrix as shown in Figure 5.5. The x-axis of the figure represents Circularity and y-axis represents Sustainability. For each alternative A_i, the x-coordiante is obtained from Table 5.20 and the y-coordinate is obtained from Table 5.22.

The "Most favourable" quadrant, in the upper right corner, represents the alternative that is high in both the circularity and sustainability. The "Less favourable" quadrants, in the lower right and upper left corners, show that excels in either the circularity or sustainability would trade-off another. The "Least favourable" quadrant in lower left corner, embodies that the alternative is low in both the circularity and sustainability.

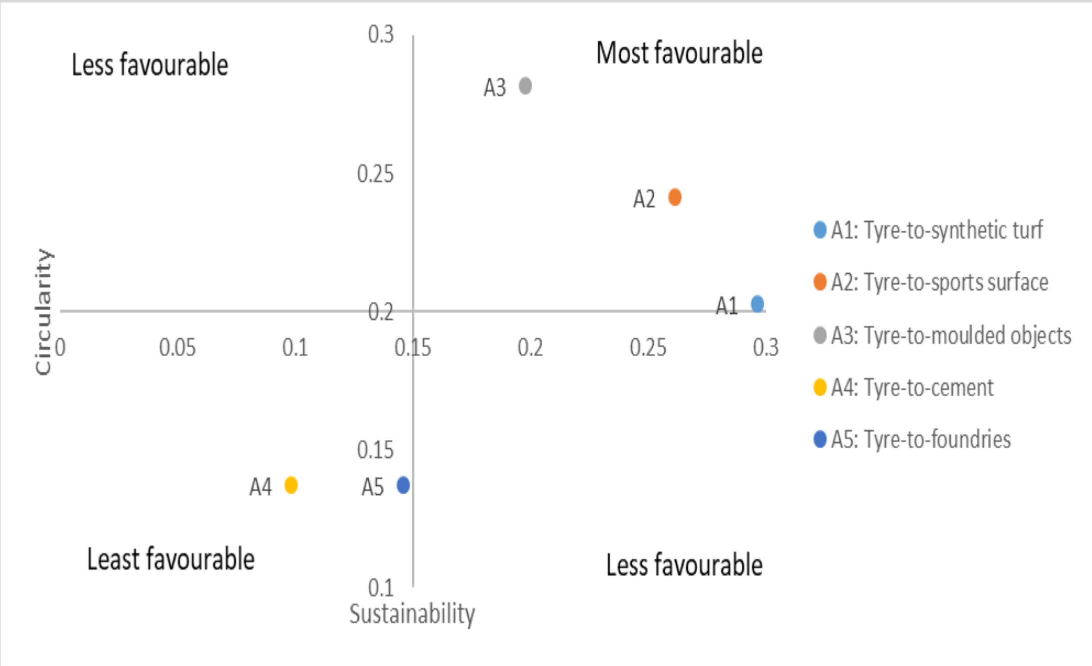

Figure 5.5: The circularity and sustainability of recycling alternatives (Source: Author).

Alternatives 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 lies close to the end of horizontal axis and situated away from vertical axis, with a higher circularity but lower sustainability, compared to A2 and A3 from the same quadrant. This suggests that A1 is favourable when the circularity is much preferred compared to sustainability in selecting a recycling alternative.

On the contrary, A3 lies closer to the end of vertical axis and away from horizontal axis, with a lower circularity but higher sustainability, compared to A1 and A2 from the same quadrant. This suggests that A3 would be favourable when the sustainability is much desired. A2 has moderate circularity and sustainability, which makes A2 favourable when both circularity and sustainability are equally important in selecting a recycling alternative.

Alternatives A4 and A5 that fall into the "Least favourable" quadrant have low circularity and sustainability, which make them a unfavourable choice among the alternatives. It is also noticed that the alternatives are either falling into "Most favourable" or the "Least favourable" quadrant and no alternative is falling into "less favourable" quadrant. This is because an alternative that invests in either one of circularity or sustainability would also invest in its counterpart, putting them in the "Most favourable". Similarly, an alternative that is not eager in investing in either one of circularity or sustainability would also not be investing in its counterpart, putting them in the "Least favourable" quadrant. This research also shows that no alternative would either invest in circularity or sustainability alone without investing in its counterpart, which would put them into "less favourable" quadrant. They would either invest in both, but with slightly more emphasis on circulairty or sustainability like A1 or A3, or paying attention to both circulairty or sustainability without either of them outperform each other like A2, or they will not invest in either of circulairty or sustainability. This is because there is an overlap between circularity and sustainability (i.e., in terms of dimension and items), thus investing in one criterion will resulting in investing in another, but not in proportion.

5.3 The Results and Analysis for Phase 3: Optimising Product Allocation to Alternative(S)

Figure 5.5 reveals the alternative selection strategy depending on the preference of circularity or sustainability. Nevertheless, this selection strategy does not take into account of the resources limitation, capacity and demand which always exist in reality (Emrouznejad and Marra, 2017). One should not solely select an alternative and allocate all resources into that particular alternative without considering its demand for resources. When aforementioned real-life constraints are introduced to the problem, it becomes very complicated to allocated resources among the recycling alternatives, with the goal to maximise both the circularity and sustainability.

To remedy the problem, a MOLP is formulated to obtain a resources allocation strategy with the goal to maximise both the circularity and sustainability, considering capacity, demand and resources limitation. Table 5.23 lists the business data collected from the French ELT collection company. The survey reveals that the annum ELT production capacity of that company is 369,603 tonnes, representing the maximum amount of resources that could be produced and allocated to the alternatives. The company sales to each recycling alternative in the previous years are also been sought and tabulated under the column "Company sales" in Table 5.23. It is discovered that the ELT allocated to A1, A2, A3, A4 and A5 are 40,000 tonnes, 40,000 tonnes, 20,000 tonnes, 170,000 tonnes and 8,000 tonnes respectively, with a total of 278,000 tonnes ELT allocated to the alternatives in the previous years.

It is intended to investigate how the ELT (i.e., 278,000 tonnes) should be allocated differently such that the circularity and sustainability of the entire supply network can be increased. The ELT is freely reallocated to the 5 alternatives, under the constraint that the allocation does not exceed the regional demand of each alternative. The demand of each alternative is obtained from Pourriahi (2016) and Bermejo (2019), shown under the column "EU27 demands" in Table 5.23. These figures are used as constraints to effectively optimise the proposed MOLP model.

Table 5.23: Sales and demands of each alternative (Source: Author).

Alternative	ELT amount (percentage)	Company sales		EU27 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%)

By introducing the figures in Table 5.20 and 5.22 (i.e., Normalised Closeness Coefficient) into Equations (19) and (20), the objective functions are obtained as shown below:

$$Max\ (Circularity) = 0.2966\, X_1 + 0.2614\, X_2 + 0.1977\, X_3 + 0.0982\, X_4 + 0.1461\, X_5$$

$$Max\ (Sustainability) = 0.2026\, X_1 + 0.2413\, X_2 + 0.2816\, X_3 + 0.1372 X_4 + 0.1372\, X_5$$

The sales and demand value from Table 5.23, as well as the annum capacity are substituted into Equations (21) and (22), forming the constraints as listed below. Since the demand for alternatives A1, A2 and A3 have exceeded the ELT production capacity, the maximum allocation to the alternative is thus limited to the ELT production capacity at 369603 tonnes. The maximum allocation to alternatives A4 and A5, however, are limited to individual regional demand because the demand value is lower than the ELT production capacity.

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

The MOLP is solved using NSGA-II coded in MATLAB, following the procedure as shown in Section 4.5. An initial population of 100 is used to generate parents with higher gene variation. The MOLP yields 573 Pareto solutions. There is no one single universal solution among the 573 solutions that can allocate the ELT such that the circularity and sustainability can be simultaneously maximised. It is discovered that maximising one objective would trade off another objective, producing a set of equally efficient solutions, with a different objective is being emphasised in a different solution.

The objective value of circularity and sustainability for each solution is mapped into the satisfaction level ranged from 0% to 100% using Equations (26) and (27). The maximum and minimum value for circularity objective function in the 573 solutions, are identifies as $Z_{max,\ circ}$ and $Z_{min,\ circ}$ respectively and substituted into Equation (26). Similarly, the maximum and minimum value for sustainability objective function in the 573 solutions, are identified as $Z_{max,}$

sust and $Z_{min,\ sust}$ respectively and substituted into Equation (27).

$$\mu_{z,circ} = \frac{Z(x) - Z_{\min,circ}}{Z_{\max,circ} - Z_{\min,circ}} \times 100\%, \ Z_{min,circ} \leq Z(x) \leq Z_{max,circ} \text{------------------------- (26)}$$

$$\mu_{z,sust} = \frac{Z(x) - Z_{\min,sust}}{Z_{\max,sust} - Z_{\min,sust}} \times 100\%, \ Z_{min,sust} \leq Z(x) \leq Z_{max,sust} \text{---------------------- (27)}$$

The ELT allocation profile for 5 different scenarios is extracted for discussion. The 1st set solution are pertaining to the circularity and sustainability satisfaction levels of ratio 0:100, indicating the ELT allocation that would yields 0% circularity (i.e., minimum circularity) and 100% sustainability (i.e., maximum sustainability). The 2nd, 3rd, 4th and 5th sets are the ELT allocation solution that would produce 25:75, 50:50, 75:25 and 100:0 of circularity and sustainability satisfaction levels respectively, as shown in Table 5.24.

Table 5.24: The ELT allocation among recycling alternatives (Source: Author).

		Base Case	The ELT allocation				
			Set 1	Set 2	Set 3	Set 4	Set 5
			Circ: Sust = 0: 100	Circ: Sust = 25: 75	Circ: Sust = 50: 50	Circ: Sust = 75: 25	Circ: Sust = 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
Circularity		44137	55425	61244	67393	73467	79396
Increment		(+ 0%)	(+ 26%)	(+ 39%)	(+ 53%)	(+ 66%)	(+ 80%)
Sustainability		47810	76463	73142	69696	65903	58934
Increment		(+ 0%)	(+ 60%)	(+ 53%)	(+ 46%)	(+ 38%)	(+ 23%)

According to Table 5.24, the ELT allocation in Set 1 provides the lowest circularity and the highest sustainability; Set 2 provides low circularity but high sustainability; Set 3 provides moderate circularity and sustainability; Set 4 provides high circularity and low sustainability; while Set 5 provides the highest circularity and the lowest sustainability.

The ELT allocation by the French company, shown under base case, is substituted into Equations (19) and (20) to obtain the base circularity and sustainability of the current condition in the company. From the calculation, the base circularity and sustainability are 44137 and 47810 respectively. This value will be used as basis to compare the effectiveness of the ELT allocation suggested by the model in increasing circularity and sustainability.

In Set 1, the ELT is suggested to be allocated mainly to A3, with a value of 255163 tonnes, preceding A2, A5, A1 and A4 with an allocation of 14129, 8599, 97 and 5 tonnes respectively. This is the solution that would yield 0% circularity (i.e., minimum circularity) and 100% sustainability (i.e., maximum sustainability). The majority of resources should be allocated to A3 because it has the highest sustainability, followed by alternatives A2 and A1 as shown in Section 5.2.2. Consequently, most of the ELT are suggested to be allocated to A3, while some portions are allocated to A2 and A1. This allocation strategy increases the circularity of the supply network by 26% and sustainability by 60% compared to base case.

The solution of Set 2 is highly similar to Set 1, where the ELT is suggested to be allocated mainly to A3, with a value of 213124 tonnes, followed by A1, A2, A5 and A4 with an allocation of 63434, 758, 657 and 11 tonnes respectively. This is the solution that yields 25% circularity (i.e., circularity that is 25% higher than the minimum circularity) and 75% sustainability (i.e., sustainability that is 75% of the maximum sustainability). Since circularity in Set 2 is slightly higher than Set 1, some resources are diverted from A3 into A1 because A1 has the highest circularity among the alternatives. Nevertheless, A3 still retains the highest amount of ELT allocated because it has the highest sustainability, and sustainability is the main objective in this particular set. Consequently, most of the ELT are suggested to be allocated to A3, while some portions are allocated to A1 and A2, with the portion allocated to A1 slightly bigger than A2. This allocation strategy increases the circularity of the supply network by 39% and sustainability by 53% compared to the base case.

In Set 3, most of the ELT are suggested to be allocated to A2, with a value of 180103 tonnes, followed by A3, A1, A5 and A4 with an allocation of 83567, 11304, 3006 and 13 tonnes respectively. This is the solution that yields 50% circularity (i.e., circularity that is 50% higher than the minimum circularity) and 50% sustainability (i.e., sustainability that is 50% of the maximum sustainability). Majority of resources should be allocated to A2 because it does not incline towards either circularity or sustainability like A1 or A3, but instead score moderately under both criteria, with almost the same normalised closeness coefficient (i.e., 0.2614 and 0.2413). This makes A2 highly suitable for the situation when both the circularity and sustainability carry an equal level of importance. This allocation strategy increases the circularity of the supply network by 53% and sustainability by 46% compared to the base case.

In Set 4, most of the ELT are suggested to be allocated to A2, with a value of 241980 tonnes, followed by A1, A3, A5 and A4 with an allocation of 31752, 3442, 753 and 55 tonnes respectively. This is the solution that yields 75% circularity (i.e., circularity that is 75% higher than the minimum circularity) and 25% sustainability (i.e., sustainability that is 25% of the maximum sustainability). Set 4 is highly similar to Set 3, with the majority of ELT being allocated to A2. Nevertheless, A2 and A1 are receiving more resources which are being diverted from A3, to reduce the overall sustainability in the favour of circularity. Since A3 is highest in sustainability, resources are required to be moved to other alternatives that have higher circularity such as A1 and A3, to improve the overall circularity of the network while sacrificing some sustainability. This allocation strategy increases the circularity of the supply network by 66% and sustainability by 38% compared to the base case.

In Set 5, most of the ELT are suggested to be allocated to A1, with a value of 201927 tonnes, followed by A2, A5, A3 and A1 with an allocation of 72723, 3229, 114 and 1 tonnes respectively. This is the solution that yield 100% circularity (i.e., maximum circularity) and 0% sustainability (i.e., minimum sustainability). Most of the ELT are suggested to be allocated to A1 because of its high circularity. Due to the need to concurrently increase the overall sustainability while maximising the circularity, portion of resources are allocated to A2 because of its substantial performance in circularity and sustainability. This allocation strategy increases the circularity of the supply network by 80% and sustainability by 23% compared to the base case.

The results are transformed into a chart as shown in Figure 5.6. In general, moving from Set 1 to Set 5, the majority of the ELT are diverted from A3 to A2 and finally to A1. This trend of the ELT allocation enables the circularity to increase from 55,425 to 61,244, 73,467 and 79,396, which is 26%, 39%, 53%, 66% and 80% increment respectively, as compared to the base case. Nevertheless, this allocation trades off sustainability, causing it to decrease from 76,463 to 73,142, 69696, 65,903 and 58,934, still it represents an increment of 60%, 53%, 46%, 38% and 23% respectively, compared to the base case. It can be seen that all allocation strategies could improve both the circularity and sustainability greatly as compared to the base case. Among them, the highest attainable increment of the circularity is 80% and the highest attainable increment of the sustainability is 60%.

This finding of Set 5 aligns with the current situation that can be observed in the industry, where approximately 565 thousand tonnes of ELTs in Europe has been processed as infill annually, correspond to 80% of the total infill placed on the market. It is estimated that the market has yet to reach the maximum demand and has further potential for growth. Currently, no other alternatives can absorb this volume of ELT rubber like synthetic turf infill does. The use of ELT rubber as infill for artificial turf is so effective and it is estimated that every Euro invested in artificial turf, a return as high as 10-fold is obtained, contributing to the society in the form of economic (US Environment Protection Agency, 2010; European Tyre and Rubber Manufacturers Association, 2020).

Generally, the least amount of the ELT should be allocated to A4 and A5 in all 5 sets of solution due to their low circularity and sustainability. Nevertheless, a discrepancy between the ELT allocation suggested by the model and the actual situation can be observed. It is observed that the company allocated most of its ELT to alternative A4 as shown under the "Base case", while the model suggests that the ELT should be allocated to other alternatives instead to increase the circularity or sustainability of the overall supply network. The reason for this discrepancy is because of the foreseeable shrinkage of market in alternatives A1, A2 and A3 as shown in next section.

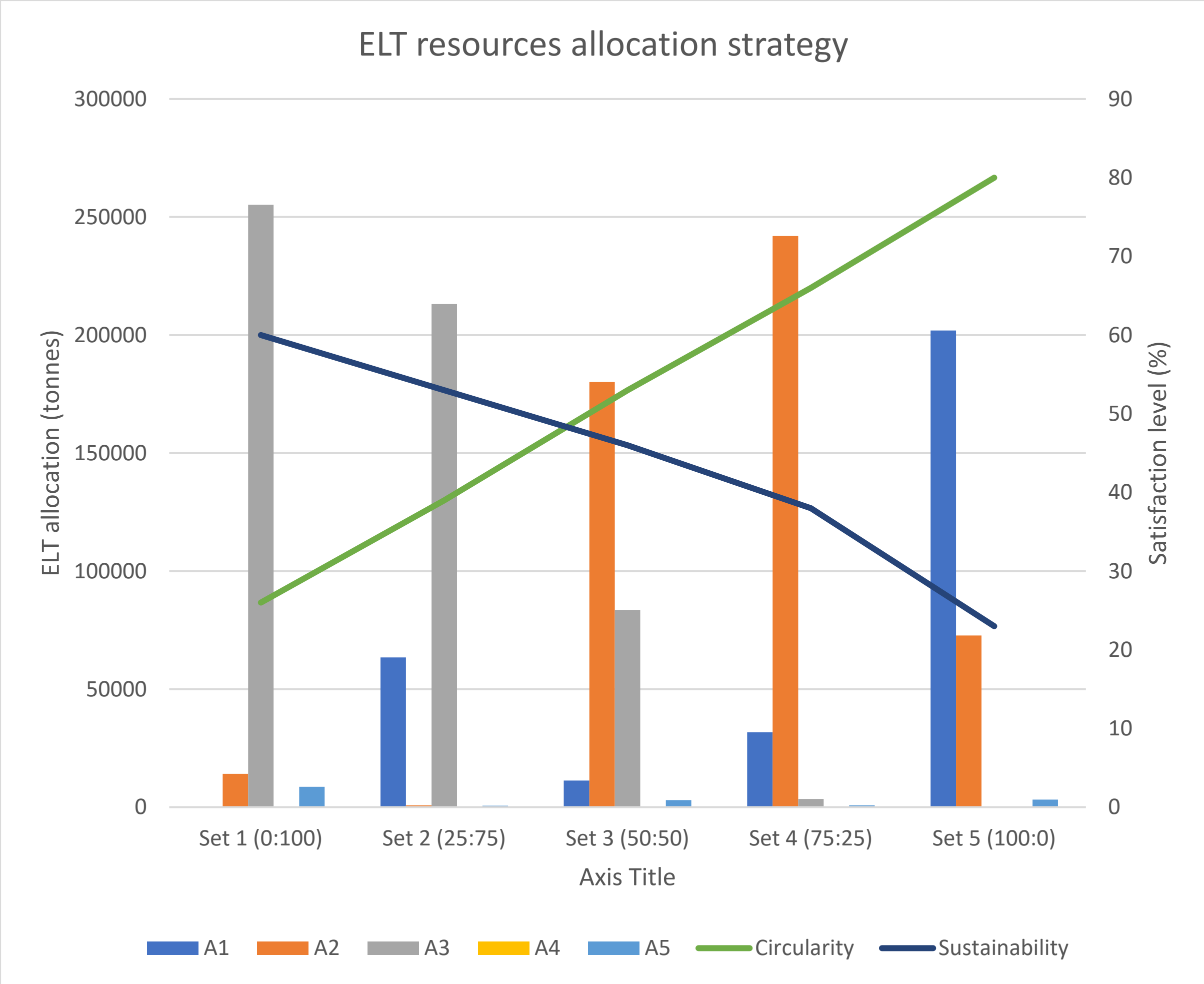

Figure 5.6: ELT resources allocation strategy (Source: Author).

5.4 The Results and Analysis for Phase 4: Explaining Discrepancies Between Modelling Results and Actual Resources Allocation

As listed in Table 5.24, there is a huge discrepancy between the current resources allocation profile and the allocation obtained via computer programming. Currently, among the 278,000 tonnes of ELT produced annually, roughly 62% were sold to A4 (tyre-to-cement), while the remaining were sold to A1 (tyre-to-synthetic turf), A2 (tyre-to-sports surface), A3 (tyre-to-moulded objects) and A5 (tyre-to-foundries) at 14%, 14%, 7% and 3% respectively. This study discovers that there is a big room for improvement for both circularity and sustainability when the resources are redirected from A4 to other alternatives such as A1 or A3, because A4 has a very low circularity and sustainability among them. When resources are allocated to A1 or A3, the circularity and sustainability can be tremendously improved up to 80% from the current value, greatly enhancing the overall the circularity and sustainability of the supply chain.

This discrepancy between the current resources allocation profile and the allocation obtained via computer programming leads to several questions, particularly on why A4 is selected over the more circular and sustainable alternatives such as A1 or A3. The answer for these questions were sought using a semi-structured interview with the managers as described in Section 4.6.

The interview reveals that the current allocation of ELT are driven primarily by cost and profit. Although they recognise the increasing importance of environmental and societal impacts, cost and profit would remain the key indicators for the decision-making. Various barriers that obstruct the uptake of more circular or sustainable allocation of resources are also being uncovered in this interview. The company is willing to follow the guidance provided by this study provided the barriers are sufficiently removed.

The first barrier towards uptake of more circular or sustainable allocation of resources, is the constant worry about the viability of the business especially under the competitive business setting, as manager A explained:

> "*… Ideally, it will be legislation that is advising and guiding the outlet selection. But now, it is driven mainly by profit and cost. We are worried about the viability and growth of the company. We can go out of business if we do not make sure that our company continue to make enough profit. Even today, we are considered lucky if we can cover the cost of collecting and processing the ELT. That's the reason for what we are doing right now, as long as they can give us high profit with the lowest cost required…*"

It is being evidenced that a business would not be able to remain profitable and will still fail even after many years of operation (Knaup, 2005; Thiele, 2016). For example, the life-expectancy for Fortune-500 companies is merely around 50 years before they are superseded by competitors (De Geus, 2002; Sharma and Dixit, 2017). The constant worrying about the viability of the business as well as the pressure to maintain its operations thus causes the business to always try their best effort to make a profit in order to maintain its operations. Ultimately, this makes cost and profit the most important criteria in decision-making for a business, causing them to be less concern in catering for another dimensions or items within circularity and sustainability. This phenomenon is frequently being observed in many businesses, even when it has been existed for a long time (Knaup, 2005; Sharma and Dixit, 2017).

This situation is further exacerbated by the existence of high competition in the industry. It is particularly difficult for the company to differentiate from its competitors in terms of quality or branding in the ELT collection industry since ELT is not a type of innovative product (Fisher, 1997), making price the only reasonable differentiator to stand-out among the competition (Villalobos et al., 2010). Thus, to vie with the competitors, the business has been lowering the profit margin just to gain more sales (Karmakar and Pitbladdo, 1997; Geradin and O'Donoghue, 2005), which ultimately exhausts the capability of the company to make more profit and to cater for more dimensions and items within circularity and sustainability, as managers B and C explained:

> *"…The market is very competitive. We are considered lucky if we get $50/ tonne max by selling the ELT just to cover the cost. Our profit margin is very low currently and we don't have the luxury to pay extra attention on other dimension or items within circularity or sustainability…"*

> *"…We can't really compete by offering a luxurious product with superior brand, since the ELT are going to be grinded to pieces or powder anyway. So we can only compete by offering a product with low price, which makes our profit margin very low and makes us focus primarily on the profit ..."*

Besides the above-mentioned barriers, the interview further reveals that negative consumers' perception towards recycled products as another crucial barrier towards uptake of more circular or sustainable allocation of resources. It also highlights the role of media and press in shaping the mind set of consumers towards the acceptance of the use of recycled materials in product manufacturing, as managers A and B explained:

> *"…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…"*

> *"…Exactly, 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…"*

This phenomenon can also be observed in the literature, where the demand for products made from recycled products are dwindling (Govindan et al., 2014) because the quality of the products made from recycled materials are perceived to be lower than that of products made from virgin raw materials (Essoussi and Linton, 2010). This occurrence is more prominent on the products made from materials derived from recycled ELT (Sheppard, 2019), especially in artificial turf. Even when it is proven that the infill behaves like a sediment and only relatively small amounts of infill would leave the pitch due to body movement, wind or rain, the losses of infills into the aquatic environment is practically negligible (Regnell, 2019; Mechanical Tyre Recycling Branch, 2020). The metals or organic compounds within the rubber infills also proved not representing an acute or chronic health or environmental hazard to users. Nevertheless, these is not enough to combat the stigma and prejudice over recycled materials (Govindan et al., 2014).

Furthermore, this situation is also worsened when the media and press fail to instil correct information in relation to the use of recycled materials in many of the consumer products, causing consumers to be influenced by the media and press in perceiving products made from recycled materials are less superior or even dangerous. This scenario has been frequently exhibited in the literature (Hirschman and Thompson, 1997; Campbell and Kirmani, 2000; Duffett, 2017), highlighting the media and press as one of the mediating factors that affects the consumers' perception towards recycled products, and thus causing the demands for A1, A2 or A3 to decrease and resulting in current resources allocation that favours A4, which is low in circularity and sustainability.

Besides that, the difficulty of processing the ELT as supply chain performance also directly influences the selection of recycling outlets, resulting in current resources allocation, as manager C explained:

> "…*the shredded tyre can the 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…*"

The difficulty of processing the ELT prior to manufacturing also represents a setback for the collectors to allocate their resources to alternatives other than A4 (tyre-to-cement). Since A4 does not require extra processing, this will lower the cost required to process the ELT collected, such as removing the tyre from the wheel rim, which will lead to tremendous cost saving in operational and labour cost. This is because the thought of "A penny saved is much better than a penny earned" is very strongly carved in the mind set of practitioners (Javed and Arshad, 2009; Bowersox et al., 2010; Kohli et al, 2014). Ultimately, cost is used predominantly in decision-making such as this company, contributing to the current resources allocation model that favours A4 (WBCSD, 2018). It is proven that the use of scrap tyres in cement kilns is one of the best technologies for a complete and safe utilisation of ELT, which also has proven to be energy and economic justifiable while being environmentally friendly (Khatib and Bayomy, 1999; US Environment Protection Agency, 2010).

In addition, it is also discovered that although cement manufacturing is not as profitable or as circular as other alternatives, it remains a popular alternative if other market could not absorb the excess supply of ELT, especially when the supply is more than demand (Rodrigues and Joekes, 2011; Nakomcic-Smaragdakis et al., 2016).

This study also shows that the managers are unaware of the magnitude of improvements that can be achived in circularity and sustainability when the resources are reallocated, and they can be enticed by the improvement of circularity and sustainability, hence more willing to address the whole dimensions and items of circularity and sustainability for decision-making. Nevertheless, this will be subjected to the financial burden lifted by either making more profit in the business by looking for new market or receiving financial support from the governments in the form of subsidies, as explained by managers A and B respectively. Essentially, these represent the strategies to overcome the barriers and promote the uptake of more circular or sustainable allocation of resources.

"…Currently, we are aiming to gain more profit by selling the ELT to the new emerging market, such as high-value technical product manufacturer who is willing to pay more, like tyre manufacturer. When their technology is mature, they will purchase many ELTs available in the market with higher price, since their product has bigger profit margin. By making more profits, we can then focus less on profit and shift to focus more on circularity or sustainability…"

Particularly, the strategy to uplift financial burden by looking for new markets that is willing to pay more, as mentioned by the managers, is highly possible especially in the ELT recycling industry (Kim and Mauborgne, 1999; US Environment Protection Agency, 2010). This is because many open loop supply chains are now started to be aware of the potential of utilising the materials in recycled ELT in making their products, substituting the use of virgin materials. This will increase the opportunities for the ELT to be used in a more diverse market (US Environment Protection Agency, 2010). Besides, the possibility of emergent of a new customer that is willing to pay more will also increase. It is also expected that the demand for ELT will greatly increase when more manufacturers started to use recycled materials from ELT to manufacture their products, ultimately increasing the profit that can be made when the demand is greater than supply.

"…Some companies in the industry which have financial supports from the government can select the outlet with the best-known technology to recycle the ELT and sell the products. The financial supports can lessen their worries on cost or profit, allowing them to look for outlet that is more circular or sustainable…"

Financial support from the government, as explained by the managers in the interview, also represents a very important enabler to promote an innovative practice in the business by lifting the company from financial difficulties and allowing it to embrace a more circular and sustainable alternative. This is being substantially evidenced in the literature (Tsai and Liao, 2017; Chen et al., 2019), for example, UK government has introduced feed-in tariffs to promote uptake of new renewable technologies (Wells et al., 2013). Similarly, Brazil and Indonesia government presented fuel subsidies to encourage uptake of clean fuel such as LPG (Lucon et al., 2004; Puzzolo et al., 2016). It has been proven that government subsidies are a highly effective intervention in solving financial difficulties issue and promoting uptake of an innovation (Huang and Li, 2019; Li et al., 2019).

Furthermore, increasing exposure of the safety for using recycled ELT in making products that have close contact with body via media and press is another important strategy, to educate and guide consumers towards a better understanding of the use of recycled materials, thus effectively rekindle the demand for the ELT usage in the alternatives, ultimately boosting the circularity and sustainability of supply chain via a better reallocation of resources, as manager B mentioned:

"…Media and press ought to educate and guide the customers to understand the safety of using recycled materials, instead of tarnishing the image of products made by

recycled tyre. Some consumers do not really check the credibility of sources and will be easily influenced and sway by the media and press. Only when customers are accepting the products made using recycled ELT, the market can be restored…"

Furthermore, increasing capability of processing ELT via extensive R&D represents another strategy that could impact the resources allocation strategy to cater for more circular and sustainable alternatives, as manager C explained:

"…*If other alternative can use the ELT without complicated processing like cement, I think they can definitely be our primary customers, since we do not have to spend extra cost to process the ELT, which hurting our net profit. But this will depend on the advancement of the technology, which I think a lot of R&D effort is required to be put in it…"*

Table 5.25 summarises the barriers that would obstruct the uptake of more circular or sustainable allocation of resources, as well as the strategies or enablers that can elevate the situation.

Table 5.25: Drivers and barriers in the ELT recycling industry (Source: Author).

Barriers	Enablers
1) Worry of the viability of business	1) Government support (subsidies)
2) Competition in the industry	2) Looking for a new market
3) Consumers' perception of recycled products	2) Increasing exposure of safety via media and press
4) The technical difficulty of processing the ELT	3) R&D

This interview concludes that both circularity and sustainability will be a very important aspect that will influence the practices in the supply chain in the near future, including allocation of resources, as pointed out by the managers A and B that:

"… *There are some partners in the supply chain that are aiming to be more sustainable and circular, such as 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,

circularity and sustainability have become more and more important nowadays and will be prominent aspects in the near future…"

5.5 The Results and Analysis for Phase 5: Relationship Between the Circularity and Sustainability

This section investigates the relationship between the circularity and sustainability by using the results of the Pareto solutions in phase 3. For every solution in the 573 Pareto solutions, the function value of sustainability and the circularity is obtained using Equations (19) and (20). This produces 573 function value pairs, which can be plotted against each other using a scatter plot to reveal the relationship between them. Figure 5.7 shows the scatter plot of sustainability against circularity of the 573 Pareto solutions. The scatter plot demonstrated that the sustainability decreased almost linearly as the circularity increases. Moreover, achieving any amount of the circularity will trade off the sustainability in an almost equal magnitude.

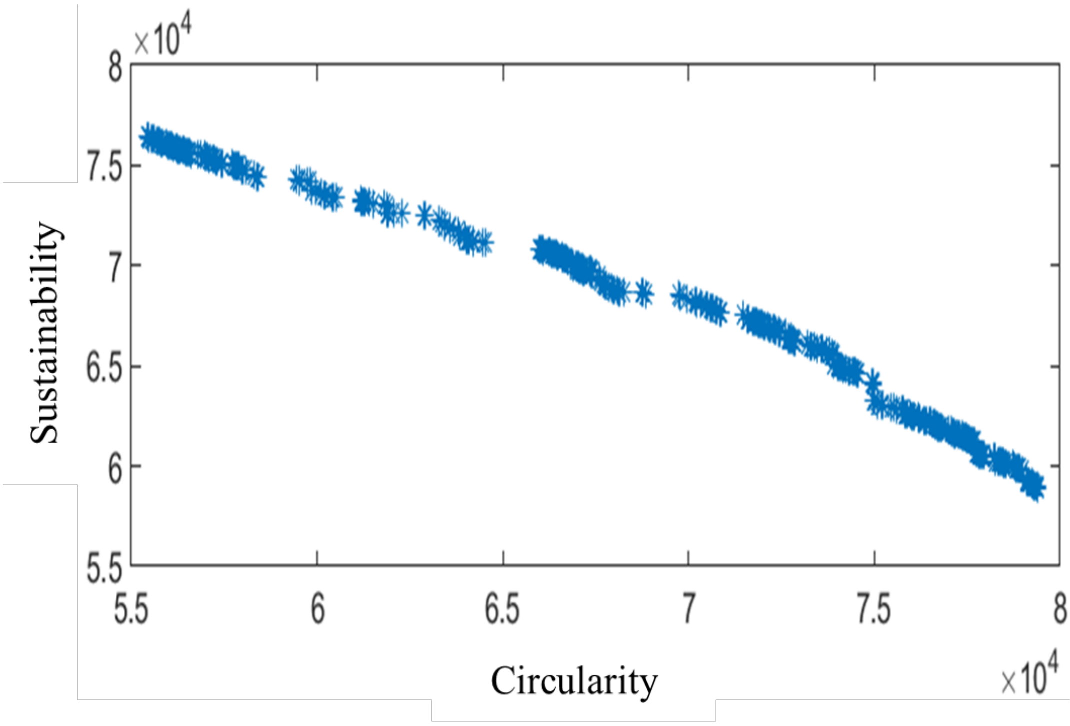

Figure 5.7: The relationship between the circularity and sustainability (Source: Author).

To be circular implies that most of the resources should be allocated to A1, according to Figure 5.6. This is because alternative A1, when compared to other alternatives, excels highly on certain items such as C_{1b}-average repairing price, C_{1c}-fraction of cost spent on CE technology to total cost of investments, C_{1d}-fraction of cost spent on recyclable material to total cost of material, C_{2c}-fraction of energy purchased from renewable sources, C_{3b}-fraction of recycled material used per kg product, C_{4a}-lifetime of product, C_{5b}-modularity of product design, C_{5c}-recyclability of product, C_{5d}-recycling efficiency of recycler and C_{5e}-rental-ability, as shown in Table 5.19 in Section 5.2.1. Particularly, some of the items such as C_{5c}, C_{4a}, C_{3b}, C_{1d} and C_{5d}, also represent the most important and influential items on circularity, with a relative importance of 7.29%, 5.88%, 5.67%, 5.33% and 5.25% respectively, as shown in Table 5.12 in Section 5.1.3.1.2. These characteristics cause alternative A1 to outshine other alternatives in becoming the most circular alternative.

Therefore, alternative A1 can be described as a highly circular alternative that produces products, which have the highest recyclability and highest lifetime in comparison to other alternatives, by using the highest fraction of recycled materials and packed by using highly recyclable packaging material. The recycler in A1 is also the most efficient by means of producing the least waste and recovering the highest number of materials back into the supply chain.

Nevertheless, even though allocating resources to alternative A1 can increase circularity substantially, alternative A1 performs poorly especially on items such as S_{1a}–operational cost, S_{1b}–capital cost, S_{1c}–net profit, S_{2a}–gas emission, S_{2b}–resources consumption, S_{2d}–renewable energy generation and S_{3a}-job creation as shown in Table 5.21 in Section 5.2.2. Particularly, some items such as S_{2b}, S_{1c}, S_{2d}, S_{1a} and S_{3a} also represent the most important items on sustainability, with a relative importance of 15.24%, 10.27%, 9.88%, 7.79% and 5.14% respectively as shown in Table 5.16 in Section 5.1.3.2.2, thus causing sustainability to drop significantly when circularity is being emphasised as shown in Figure 5.7.

This phenomenon to disregard some important sustainability items such as cost and profit in pursuit for circularity like alternative A1, is also being evidenced in the literature. For example, a more circular alternative or solution can sacrifice cost and reduce overall profit just to be more circular. This is shown in Andersen (2007), Genovese et al. (2017) and Duin and Best (2018), where the cost to procure certain recycled materials is relatively higher than virgin materials, since the suppliers for recycled materials are limited and could be located very far away, unlike virgin materials that have higher availability locally, implying that being circular could be more costly, ultimately reducing profit generated. Further, Andersen (2007) demonstrated that the circular business that involves in collection and retrieval of materials from EOL products are facing reduced profit when they are forced to supply their recycled materials at lowered prices to nearby plants that are willing to accept them, as prospect customers are limited and could be located some distance away, implying circular business is not really profitable. The cost to recycle certain EOL products such as PET bottles is also higher than the profit that could be generated by selling the recycled materials, making the business not feasible and relying greatly on government subsidy to be viable (Genovese et al., 2017; Haupt et al., 2018). Galvão et al., (2020) also suggested that circular business will take very long to achieve the same level of financial performance accomplished through linear business model.

Furthermore, this research discovers that a more circular alternative like A1 will emit more gaseous emission. This finding supports the literature which stated that circular economy strategy that aims at using recycled materials instead of virgin materials in product manufacturing, such as recycled paper, will result in higher CO_2 emission because recycling the materials from the used papers will emit more CO_2 compared to producing papers using virgin woods (Allwood, 2014). Other circular strategy that aims at improving circularity by recycling the materials in the original supply chain can result in higher CO_2 emission, when compared to a less circular alternative that recycles the materials in OLSC. For example, collecting and turning glass bottles back into bottles will result in higher CO_2 emission, compared to turning the glass containers into the making of insulation materials. Similarly, turning papers and cardboards back into linerboards or newsprints emit more CO_2 than turning them into insulation materials (Haupt et al., 2018). Furthermore, a circular strategy that aims at increasing circularity by recycling EOL products that contain hazardous additives such as polymer is not environmentally desirable, as it may become harmful when the recycled polymer is used for the purpose other than it is designed for (Blum et al., 2020). Some recycling process such as copper recovery from e-waste also requires the use of toxic chemical which produces negative environment impact while trying to reduce waste generated in electronic sector (Hsu et al., 2019).

This research also found that a more circular alternative like A1 will consume more resources, especially energy resources, resonating with the literature which advocated that a more circular strategy will result in higher resources consumption (Allwood, 2014; Cullen, 2017; Smits and Woltjer, 2018). For example, recycling cement from EOL concrete is more energy intensive and will be causing more material losses in the process, far more than the benefits that it can provide in being more circular, in the attempt to reduce concrete waste (Allwood, 2014; Cullen, 2017). Similar finding is discovered in recycling manure waste to produce fertilisers, where the pursuit in being more circular by reducing manure waste, will require more energy, minerals and chemicals at the same time (Smits and Woltjer, 2018). The rebound effect on resources consumption matches the observation of Chen (2021), who stated that some CE activities will result in more resources consumption, even if the initial motive is trying to reduce resources consumption by recovering as many materials from waste as possible.

This research also finds that a more circular alternative like A1 will reduce job opportunities. This finding relates to the literature stating that certain circular business will not create much jobs opportunity as the nature of the circular business usually involves high automation level, as demonstrated in Smits and Woltjer (2018) for the production of fertilisers using manure waste. This is also being shown in Llorente-González and Vence (2020) where job opportunity is only being created in certain CE business related to reuse or repair, but not business related to waste collection and recycling activities. Those jobs created related to CE, such as waste collection and recycling, are also often associated with inequality, with a high rate of informality, hazardous and unhealthy working conditions as well as low wages (Cointreau, 2006; Sassen, 2010; Dauvergne and LeBaron, 2013). The success of CE is highly dependent on the collectors in collecting EOL products, so that the materials within the products can be recycled and returned to the supply chain. Nevertheless, collectors are often exposed to serious psychosocial and mental health hazards as well as safety issue when collecting the EOL products at dumpsite due to unpleasant working environment, which further decrease social sustainability of circular activities (Gutberlet and Baeder, 2008; Chen, 2021).

This research discovers that being circular does not necessarily equate to greater sustainability, supporting various examples shown in the literature. This study also proved that the more circular alternatives can disregard the sustainability in pursuit of a higher circularity, such as elevating recycling efficiency, producing a product that has a longer lifetime and high modularity, but at the price of lowering economic, environmental and social sustainability, by sacrificing cost and profit, jobs creation as well as consuming more resources and emitting more gaseous emission. This finding agrees that the focus on incremental improvements to circularity via CE activities can do more harm than good (Blum et al., 2020).

This research also disagreed with some studies in the literature that insist practicing the CE agenda can help in achieving the sustainability (Rashid et al., 2013; European Environment Agency, 2016; Geissdoerfer et al., 2017). The findings in the literature represent a result of partially segmentation of circularity and sustainability, using niche and incomprehensive measurement of circularity and sustainability in measuring the target (i.e., only some items or some dimensions are used), which causes biasness in the results. Because of that, circularity measurement cannot be used interchangeably with sustainability measurement in measuring either circularity or sustainability of a target, even though they possess some similarity. Evidently, De Oliveira et al. (2021) mapped 58 circularity indicators to 3 pillars of sustainability and discovered that social dimension of sustainability is rarely addressed in the circularity indicator, and asserted that the circularity indicator lacks the robustness to assess the overall sustainability performance of circular systems, thus prohibiting the use of circularity in measuring sustainability.

True relationship between circularity and sustainability can only be attained when comprehensive circularity and sustainability measurements are used for relationship testing. This study discovers that circularity and sustainability have different focuses as shown in Section 5.1.3.3. The circularity prioritises vertically benefiting the economy and environment, while sustainability focuses on a horizontal development of environmental, economic, and social dimensions. Hence, excelling in the circularity agenda does not necessarily promote sustainability. Circularity and CE activities such as service-based systems are a necessary but do not have sufficient condition for a sustainable system (Nakajima, 2000). This finding endorsed the work of Murray et al. (2015) and Geissdoerfer et al. (2017) who argued that the circularity and sustainability have different prioritisations.

Ultimately, a new term known as sustainable circular economy (SCE) has been proposed, which carefully consider economic, environmental, and social aspects in sustainability during the transition towards a CE (Blum et al., 2020). A SCE practice should not only ensure economic value is generated, but also ensuring less harm is done to the environment, such as reducing impact on climate change and protecting natural habitats for animals. Further, better social conditions must be created for all humans, e.g., fewer working poor, better health services or no child labour.

This research expands the literature by introducing the dimensions and items to measure circularity and sustainability. When combined, it can used to measure the performance of sustainable circular economy, thus known as sustain-circularity.

6 Conclusion

This research investigated the most prominently used strategy within Circular Economy (CE), namely the recycling strategy, within the tyre recycling industry as it represents one of the most important raw materials that is facing supply risk (Warren-Thomas et al., 2015; Butler, 2015; The Association of Natural Rubber Producing Countries, 2020) and increasing demands (Wiriyapong, 2016; Research in China, 2017; Wagner, 2019).

Within tyre recycling, there are many new alternatives emerged lately under the influence of circular supply chain, which accept and recycle the End-of-life Tyre (ELT) into making new products such as artificial turf, synthetic sports surface, moulded objects, cement, foundries, civil engineering application, asphalt and pyrolysis. Nevertheless, selecting the best alternative for ELT is a very challenging and complex task. They are plethora of criteria with distinctive indicators that can be used to compare and weight the different alternatives, resulting in different suggestions for the best recycling outlets. Currently, circularity and sustainability criteria are being used predominately in the existing literature in comparing and ranking ELT recycling outlets. Nevertheless, only items that are related to environmental dimension being used extensively for this purpose, while other important dimensions and items within circularity and sustainability criteria are being used sparingly. The use of partial measurement will distort the actual result and cause errors in decision-making, selecting the wrong alternative for a correct purpose.

Consequently, this study evaluated the ELT recycling outlets based on the thoroughly selected circularity and sustainability criteria. The dimensions and items that are suitable to be used for this specific context are obtained via the use of emergent coding or inductive content analysis. In total, five dimensions of circularity encompassing 23 items as well as three dimension of sustainability consist of 12 items are obtained and used for this study. The five circularity dimension are C_1-monetary, C_1-energy and environment, C_3-material, C_4-temporal and C_5-efficiency while the three sustainability dimension are S_1-economy, S_2-enviornment and S_3-social.

The relative importance of the dimensions and items within circularity and sustainability criteria are obtained to better compare the different ELT recycling alternatives. The relative importance is acquired by considering input from 18 Delphi members, which consist of 9 individuals from each academic and practitioner groups.

To test the result, a French ELT collector was invited to provide data for this study. This collector supplies their ELT to five important recycling alternatives, 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 previously defined dimensions and items were used to rate the five recycling alternatives. By analysing the data, this study identified A1 (tyre-to-synthetic turf) as the best alternative measured using circularity and A3 (tyre-to-moulded objects) as the best alternative measured using sustainability.

This study further investigated how the allocation of the ELT among the alternatives will differ under the influence of circularity and sustainability, as compared to the business-as-usual scenario. It is discovered that there is a substantial room for improvement for the actual ELT allocation for the company in terms of circularity and sustainability when compared to the suggested ELT allocation. An interview was conducted to investigate the practicality of using circularity and sustainability to guide the selection and ranking of alternatives, as well as the resources allocation among the alternatives. It is discovered that the future trend is inclined towards the use of circularity and sustainability to guide decision-making in the company, but it is susceptible to several barriers including the issue of the viability of business, high competition in the industry, negative consumers' perception of recycled products as well as the technical difficulty of processing the ELT. Several strategies can be used to eradicate the barriers and thus promote circularity and sustainability within decision-making in the business, including increasing government support (subsidies), looking for new market, increasing exposure of material safety of products made from recycled materials via media and press as well as improve R&D to ease difficulties of processing the ELT.

The key findings of this research are summarised in Table 6.1.

Table 6.1: Key findings of this research (Source: Author).

Research question	Key findings
1) What are the key dimensions and items within circularity and sustainability criteria for the ELT recycling alternatives selection?	• The key dimensions within circularity are monetary (C_1), energy and environment dimension (C_2), material (C_3), temporal (C_4) and efficiency (C_5), with a total of 23 key items within them. • The key dimensions within sustainability are economy sustainability (S_1), environmental sustainability (S_2) and social sustainability (S_3), with a total of 12 key items within them.
2) How important is each dimension and item within circularity and sustainability criteria in decision-making?	• The importance of the dimensions within circularity are 29.08%, 25%, 19.51%, 17.02% and 9.40% respectively for monetary (C_1), energy and environment dimension (C_2), efficiency (C_5), material (C_3) and temporal (C_4) respectively. • The importance of the dimensions within sustainability are 45.38%, 28.25% and 26.37% respectively for environmental sustainability (S_2), social sustainability

	(S_3) and economy sustainability (S_1) respectively. • The five most important items within circularity in the order of importance, which are C_{5c} -Recyclability of the product (7.29%), C_{1f} -Profit or saving per kg recyclable input consumed (7.00%), C_{2d} -Total GHG produced per kg product (6.82%), C_{4a} –Lifetime of product (5.88%) and C_{3b} –Fraction of recycled material used per kg product (5.67%). • The three most important items within sustainability in the order of importance, which are S_{2b} -Resources consumption (15.24%), S_{3c} -Workers health and safety (10.39%), and S_{1c} -Net profit (10.27%).
3) How to allocate the ELT among recycling alternatives in supply networks to maximise the circularity and sustainability?	• Solving the FAHP-FTOPSIS-MOLP model revealed that 0%, 5%, 92%, 0% and 3% of the ELT should be allocated to alternatives A_1, A_2, A_3, A_4 and A_5, such that circularity and sustainability can be improved by 26% and 60% respectively. • Alternatively, 4%, 65%, 30%, 0% and 1% of the ELT should be allocated to alternatives A_1, A_2, A_3, A_4 and A_5, such that circularity and sustainability can be improved by 53% and 46% respectively. • Otherwise, 73%, 26%, 0%, 0% and 1% of the ELT should be allocated to alternatives A_1, A_2, A_3, A_4 and A_5, such that circularity and sustainability can be improved by 80% and 23% respectively.
4) What are the barriers and enablers that influence the uptake of circular and sustainable practices in ELT recycling industry?	• The barriers are worry of the viability of business, tight competition in the industry, negative consumers' perception of recycled products and the technical difficulty of processing the ELT. • The enablers are increasing government support or subsidies, looking for a new

	market, increasing exposure of safety via media and press and increasing technical capabilities via R&D.
5) What is the impact on sustainability while achieving the CE agenda in the ELT recycling industry?	• The pursuit of a higher circularity (increasing the recycling efficiency, producing a product that has a longer lifetime and high modularity) would trade off sustainability by sacrificing jobs creation as well as consuming more resources such as water, land or energy.

6.1 Theoretical Implications

This study sheds light on several theoretical implications. Firstly, the comprehensive list of criteria and items to measure the circularity and sustainability of recycling organisations and their supply chains provided in this research are obtained via a detailed emergent coding (also known as inductive content analysis) of the current circularity and sustainabilty indicators, tailored specifically for this context. This study identified 5 dimension and 23 items in the 50 currently available circularity indicators, representing the first attempt in the research field to uncover the similarity between the circularity indicators and to define them. This study also identified 12 sustainability items within sustainability indicators that are suitable to be used in this research context, guiding the selection and ranking of ELT recycling alternatives. This set of dimensions and items can be used as a theoretical foundation for the construction of a thorough circularity and sustainability formative construct or an evaluation framework. They can be used to evaluate and rank alternatives in another recycling industry such as plastics, papers or metals. This formative construct or evaluation framework can even be expanded to guide circularity and sustainability measurement of other CE strategies (i.e., repurpose, reuse, refurbish etc.) by benchmarking and following the steps involved in obtaining the measurement set in this study.

Secondly, the reason for a dimension or item to be included in circularity criterion, subsequently forming a formative construct for circularity, is being determined. The high degree of importance is related to its capability to achieve six CE goals (i.e., lowering waste output, lowering resources input, lowering pollution, increasing resources utility, increasing resources value, and increasing economic prosperity). For example, the most important item that can promote circularity among the 23 items identified is the “recyclability of the product”. This is because it can demonstrate the level of resources that can be recovered from an EOL product. A product with high recyclability would ensure a high number of materials can be returned to the consumption cycle instead of being disposed as landfill, contributing to circularity by meeting several CE goals such as lowering or eliminating waste generated in our society and increasing utility of the resources, and by keeping the materials within the consumption cycle. Besides, the most important item that can promote sustainability among the 12 sustainability items identified is “resources consumption”. Over-consuming resources such as energy, water, materials, and land will result in various environmental problems like air and water pollution and will jeopardise the future generations in meeting their own needs.

The underlying reasons for why a dimension or item is more important for circularity or sustainability, can thus guide future research to better understand the subject. For example, the identification of the most important items that impact circularity and sustainability can be useful, especially for modelling purposes or framework creation. Some modelling or framework that does not wish to have too many measurement terms involved so that it can function smoothly or retain simplicity, can choose to use only some selected items with the highest level of importance within circularity and sustainability as identified in this study (i.e., items with top five highest importance within circularity and sustainability), so as to reflect the circularity and sustainability as accurately as possible.

Thirdly, by thoroughly incorporating all relevant criteria, this research identifies a trade-off relationship between the circularity and sustainability in the context of the ELT recycling, incorporating the actual data from a case study company. Today, various circularity metrics, activities and strategies are created with the aim to attain sustainability in a business but without using the sustainability metrics. This has been proven incorrect both from this study and from the literature (e.g., see Oliveira et al. 2021).

This study supports the notion that the CE has distinguished focuses in comparison to sustainability, where CE treats economic criteria as top priorities, while environmental and social criteria act as the core of sustainability. This finding is crucial as it provides a proof for the relationship between circularity and sustainability using actual company data. This will influence the future development of circularity and sustainability related research, as many of the research are currently conducted based on assumption that circularity has direct and positive contribution to sustainability. This assumption is causing many researchers to consider that circularity metrics would encompass all sustainability metrics, and even replacing sustainability metrics with circularity metrics (Geissdoerfer et al., 2017), which is found to be inappropriate in this research. Consequently, this study endorsed the development of sustainable circular economy (SCE) and proposed the indicators of sustainable-circularity, which can be used to drive future research direction for the CE related research to better achieve both circularity and sustainability agendas.

Fourthly, the method proposed in this research to rank and allocate resources among the ELT recycling alternatives could also contribute the existing literature by expanding the capacity of the current resources allocation models used in the literature, to incorporate more criteria that span across different dimensions, at the same time include both quantitative and qualitative measurements with different units into the model. This can significantly improve the capability of the model to consider different input with different measurements, thus improving the quality of decision-making. This essentially contributed to the decision theory on strategy to include more heterogeneous measurements while at the same time addressing uncertainty in decision.

This contribution to the theory will impact similar research, including the studies that require experts' opinions and resources allocation, such as supplier selection, resources allocation in project management, warehouse location selection, resources allocation in the supply chain, as well as subproject selection. This method can incorporate the experts' opinions regarding the level of importance of decision criteria and alternative, with the resources allocation modelling which involves various quantitative and qualitative measurements.

Finally, this study also identified barriers and enablers towards the use of circularity and sustainability in recycling alternative selection in ELT recycling industry. This will improve the understanding of potential barriers that hinder the uptake of circularity and sustainability in other recycling industries such as paper and metals, as well as strategies to elevate the circumstances. It may also be applied over other CE strategies and activities with high similarities, serving as groundwork research for the barriers and enablers exploration. Further, it will also contribute to meta-analysis to discover the most frequently cited barriers in a CE, thus significantly extending the existing literature in the fields of the CE and sustainability.

6.2 Practical Implications

This study also elucidated on several practical implications. Firstly, the identification of the most important dimensions and items in the circularity and sustainability in this research offers practitioners a starting point to develop critical circularity and sustainability practices in their organisations, which will ultimately accelerate circular and sustainable development.

An organisation with limited budget can choose to use only some selected items based on the level of importance within circularity and sustainability as identified in this study, to help in monitoring circularity and sustainability as well as to be used in decision-making. Particularly, strategic decision-making that will impart long-term impact may include as many dimensions and items within circularity and sustainability as possible according to the level of importance. Other recycling industry may also follow this guideline with minimal alteration by following the steps in this research to obtain a more scrutinised result.

Secondly, this research also proposed a method which can be utilised by managers to estimate favourability of recycling alternatives, using the circularity and sustainability scores obtained in the phase 2 of the process. The circularity and sustainability score of each alternative can be used as a coordinate (i.e., x-axis: circularity, y-axis: sustainability) and placed in Figure 6.1.

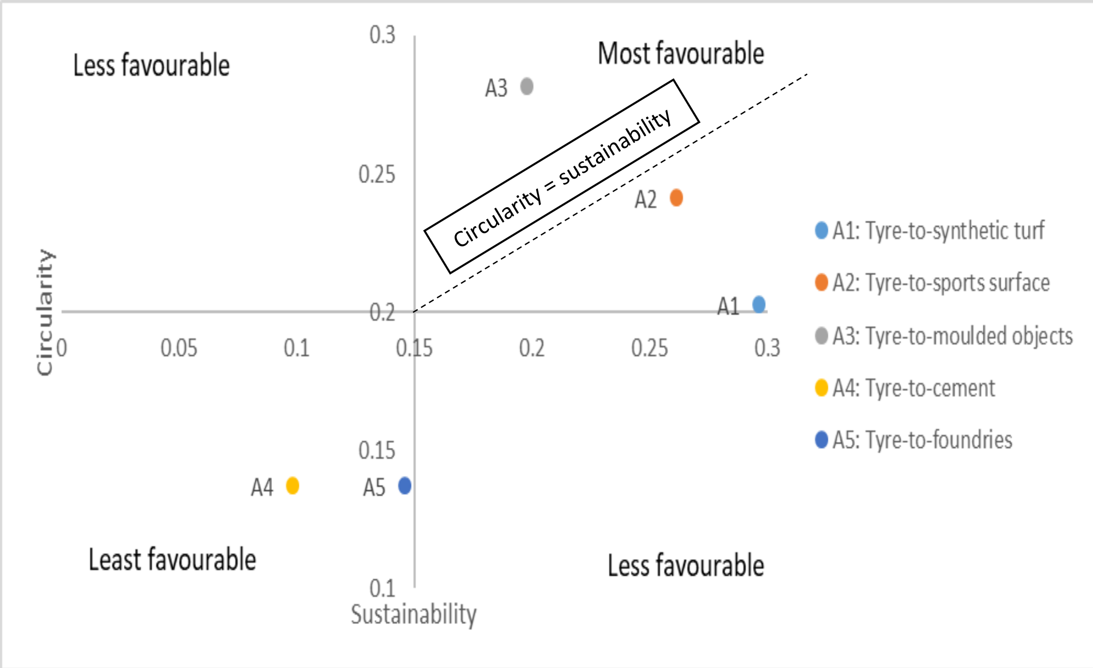

Figure 6.1: The ELT recycling outlets selection matrix (Source: Author).

According to the figure, the recycling alternative that is placed in the lower left quadrant is least favourable, compared to the alternatives that are placed in the upper left or lower right quadrant, which is less favourable. Conversely, the alternative that is placed in the upper right corner is the most favourable. A dotted diagonal line is placed in the most favourable quadrant, which represents the section whereby the circularity of the alternative will be equal to sustainability. This line essentially splits the quadrant into two portions: the lower diagonal represents the area where the circularity of the alternative is greater than sustainability, while the upper diagonal represents the area where the sustainability of the alternative is greater than the circularity.

Depending on the needs of the managers, they can select the alternative which is either placed in the upper diagonal or lower diagonal, if sustainability or circularity has higher priority. Using Figure 6.1, alterantive A1 should be chosen if circularity is much preferred, while A3 should be chosen if sustainability is much desired. Nevertheless, A2 should be chosen when the managers intend to have a balanced focus on the circularity and sustainability. Essentially, the diagram as shown in Figure 6.1 can be used as a general framework for managers to choose an alternative in a quick manner, after calculating the circularity and sustainability scores using the methods as demonstrated in phase 1 and phase 2 of the research.

Thirdly, managers may use the method (i.e., MOLP) outlined in this research to determine the amount of resources that should be allocated to each contending recycling alternative considering all constraints, such that the overall circularity and sustainability of the supply chain and supply network can be maximised. This resources allocation method can effectively utilise various dimensions and items of different nature (i.e., quantitative, qualitative and different units), thus will more accurately reflect the circularity and sustainability of the different options, helping managers to make better decisions.

Finally, managers can also be acquainted with the barriers towards the uptake of more circular or sustainable allocation of resources as identified in this study (i.e, worry of the viability of business, fierce competition in the industry, negative consumers' perception of recycled products and technical difficulty of processing the ELT). Subsequently, managers can increase their efforts in eradicating the obstacles by referring to the enablers discovered in this study, such as applying for government support and subsidies, looking for new market, increasing exposure of safety of materials using recycled ELT via media and press and extensive R&D. These strategies can help managers to increase the probability of successful transition towards more circular or sustainable practice.

6.3 Limitation and Future Direction of Research

There are some limitations in this study. Firstly, the respondents from all phases are originated from developed country, thus the result is mostly applicable to developed country and not necessarily to the developing country. This is because the relative importance of different dimensions and items used for decision-making in developing countries might be different from those in developing countries (Khan, 2019; Rezaei et al., 2020). Future research could focus on replicating the research by inviting respondents and companies from developing countries, subsequently investigate the differences between developed country and developing country as well as the reasons behind it. This will also improve the body of knowledge by understanding how decision-making differs between developed country and developing country.

Secondly, to simplify the problem, the proposed MOLP model in this research assumed that the demand for the ELT is stable, without considering the dynamic nature of demand in real life. Even though this assumption can be sufficiently applied to obtain a reasonable result, it can be relaxed in the future research to investigate how would the resources allocation strategy is affected under dynamic demand (Roul et al., 2015).

Besides the assumption that the demand of ELT is stable, this research also assumed that there is no quantity discount nor there is any competition in the market. Quantity discount may slightly affect the result if this assumption is being relaxed (Li and Liu, 2006). Certain alternative might also become less viable due to the reduced profit margin when competition is introduced to the model in order to win a contract and eliminate competition (Nyström and Mandell, 2019). Future research may introduce more resources constraints such as quantity discount as well as competition using game theory to more accurately model the actual business condition.

Thirdly, instead of using a single echelon supply chain in this research, future research could increase the complexity of the supply chain by using multi-echelon supply chain together with multiple members (nodes or agents) within each tier in the supply chain. This will effectively increase the accuracy of the model but requires highly complex [computational] effort.

Lastly, even though AHP, TOPSIS and NSGA-II are selected to be used as the best tools for analysis purposes among the vast MCDM and optimisation methods. They are newly developed methods that could also be used in conjunction or, to supplement the methods proposed in this research, such as Pythagorean Cubic Fuzzy Methodology (Seker and Kahraman, 2021) and PROBID (preference ranking on the basis of ideal-average distance) method (Wang et al., 2021). Future research may compare the new methods in solving the MCDM or MOLP problems or even propose a new hybrid used for solving the problem in this research, aiming at reducing the computational time as well as more effectively target uncertainty in the decision-making process.

This is because in the future, clients will expect to obtain the result faster, or even on-the-spot, so that decision can be made even quicker, thus necessitating the methods with shorter solving time. Furthermore, uncertainty (i.e., the uncertainty in decision-making) still has a big room for improvement. The current method in solving uncertainty is still relying on simple math (i.e., average or centre of area). The ability to address the uncertainty using more advance technique will be able to produce a more reliable result, ensuring more accurate decision-making.

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8 Appendices

Appendix A (Questionnaire for pilot study in phase 1)

Pilot study

Page 1: Participants Information Sheet

The aim of this study is to **Investigate how appropriateness is each item in measuring its construct within circularity and sustainability criteria**. The items will be used to rank and evaluate the most suitable recycling alternative for an End-of-Life tyre (ELT).

The study is being conducted by Mr. Sir Yee Lee at Coventry University. You have been selected to take part in this questionnaire survey because you have been working closely in the Circular Economy and sustainability field, and have sufficient knowledge about the research topic, and are willing to provide the information for research. Your participation in the survey is entirely voluntary, and you can opt out at any stage by closing and exiting the browser. If you are happy to take part, please answer the following questions in relation to the study, by ranking how appropriateness is each item in measuring its construct.

The survey should take approximately 10 minutes to complete. Your answers will be treated confidentially and the information you provide will be kept anonymous in our research outputs. Your data will be held securely with the password protected laptop. All data will be deleted by 31 December 2022. The project has been reviewed and approved through the formal Research Ethics procedure at Coventry University.

For further information, or if you have any queries, please contact the lead researcher Mr. Sir Yee Lee - email: lees116@uni.coventry.ac.uk. If you have any concerns that cannot be resolved through the lead researcher, please contact Jiayao Hu - email: ac5218@coventry.ac.uk. Thank you for taking the time to participate in this survey. Your help is very much appreciated.

By selecting "yes", indicate that you have read and understood the above information. You understand

that, because your answers will be anonymized, it will not be possible to withdraw them from the study once you have completed the survey. You agree to take part in this questionnaire survey and you consent your answers to be used as described. ✱ *Required*

- Yes
- No

Page 2: Definition of dimensions (constructs) within circularity

- **"Monetary"** indicate the indicator group associated with monetary term such as cost and profit.
- **"Energy and environment"** indicate the indicator group associated with energy and environmental pollution.
- **"Material"** indicate the indicator group associated with tangible material such as product weight and waste produced.
- **"Temporal"** indicate the indicator group associated with time, such as time to reach goal, lifetime of product.
- **"Efficiency"** indicate the indicator group associated with efficiency, such as recycling efficiency.

Page 3: Definition and rating of the appropriateness of items with monetary dimension

- **"Average cost of virgin material per kg"** is used as proxy indicator to reflect the scarcity of the material used in production. A higher cost indicate that a scarce resource is consumed in the production process, for example gold or rare earth metals.

- **"Average repairing price"** indicate the price to repair the damaged product. A repairing cost that is lower compared to cost of purchasing a new product would encourage the consumer to repair the product instead of buying a new product. This can extend the usage of a product before it is discarded as waste, ensuring that the material will be retained in the consumption cycle until it reach its designated end-of-life.

- **"Fraction of cost spent on CE technology to total cost of investments"** indicate the money spent on installing CE related technology, such as waste recycler, disassembly robot, alternative raw materials, etc. (see example: https://www.weforum.org/agenda/2017/09/new-tech-sustainable-circular-economy/). More money spent in these categories implies a company is more willing to participate in Circular Economy endeavour, by changing its operation and business model to incorporate CE related strategies.

- **"Fraction of cost spent on recyclable material to total cost of material"** indicate the money spent in purchasing End-Of-Life waste or recyclable product, which will be recycled and used to manufacture new product. More money spent in these categories implies a company is more willing to participate in Circular Economy endeavour, by bringing back the waste into the supply chain.

- **"Production cost per kg product"** indicate the cost of manufacturing a product which includes cost for energy, electricity, water as well as administration cost. A true circular supply chain generate its own energy and electricity, and reuse the resources such as water, keeping the production cost as low as possible.

- **"Profit OR saving per kg recyclable input consumed"** indicate the profit made by a recycler company in selling the recycled EOL post-consumer waste, or saving made by manufacturer when substituting virgin materials with recycled materials. A company that is having higher profit per unit waste implies more value had been added to the waste consumed, thus maximising the value of the waste.

In your opinion, how appropriate is each item in measuring the monetary dimension?
Notes: "1” indicates barely adequate and “7” indicates almost perfect.

Please don't select more than 1 answer(s) per row.

	1	2	3	4	5	6	7
Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐
Average repairing price	☐	☐	☐	☐	☐	☐	☐
Fraction of cost spent on CE technology to total cost of investments	☐	☐	☐	☐	☐	☐	☐
Fraction of cost spent on recyclable material to total cost of material	☐	☐	☐	☐	☐	☐	☐
Production cost per kg product	☐	☐	☐	☐	☐	☐	☐

Profit OR saving per kg recyclable input consumed	☐	☐	☐	☐	☐	☐	☐

Page 4: Definition and rating of the appropriateness of items with energy and environment dimension

- **"Fraction of energy generated using renewable sources"** indicate the energy generated within the company on site and not purchased from energy providers. Generation of energy onsite negate the needs to purchase energy from power stations that usually rely on non-renewable resources such as coal, fossil fuels, uranium, etc. Generation of energy using renewable energy sources such as solar, wind, tidal, biomass, etc is much better than generation of energy using non-renewable energy sources. A true circular economy harvest raw material only from the waste stream, and use only renewable energy (purchased or generated on-site) in all operational and logistical activities.

- **"Fraction of energy loss"** indicate the energy loss in operation such as energy dissipated in unit operation or energy loss in buildings. Lower energy loss in a company indicate efficient use of the energy resources. A supply chain in circular economy will have negligible energy leakage to the surroundings.

- **"Fraction of energy purchased from renewable sources"** indicate the amount of energy utilised in the company that is obtained from renewable energy sources such as solar, wind, tidal, biomass, etc. Higher utilisation of renewable energy negate the needs to fire up costly and polluting power stations, and reduce reliance on non-renewable resources such as coal, fossil fuels, uranium, etc. A true circular economy harvest raw material only from the waste stream, and use only renewable energy in all operational and logistical activities.

- **"Total GHG produced per kg product"** indicate the overall impact imparted on to the environment by the processes carried out in the company. Carbon footprint, which measure greenhouse gas (GHG) is one of the widely used environmental indicator. GHG includes carbon dioxide and methane, which cause global warming that lead to extinction of animal species and climate changes. Lower environmental impact ensure sound human health and environment wellbeing. A supply chain in the true circular economy will impart negligible environmental impact to the surroundings.

- **"Total energy consumed per kg product"** indicate the total energy required to manufacture a unit kg product. A high energy required to produce a product, can be used as proxy indicator to show the low efficiency production process or poorly designed production technology, which should be improved such that the energy consumption is lowered.

- **"Total energy generated per kg product"** indicate the energy generated within the company on site and not purchased from energy providers. A supply chain in true circular economy would generate its own energy on-site to be used in all operational and logistical activities.

In your opinion, how appropriate is each item in measuring the energy and environment dimension? Notes: "1” indicates barely adequate and “7” indicates almost perfect.

Please don't select more than 1 answer(s) per row.

	1	2	3	4	5	6	7
Fraction of energy generated using renewable sources	☐	☐	☐	☐	☐	☐	☐
Fraction of energy loss	☐	☐	☐	☐	☐	☐	☐
Fraction of energy purchased from renewable sources	☐	☐	☐	☐	☐	☐	☐
Total GHG produced per kg product	☐	☐	☐	☐	☐	☐	☐

Total energy consumed per kg product	☐	☐	☐	☐	☐	☐	☐
Total energy generated per kg product	☐	☐	☐	☐	☐	☐	☐

Page 5: Definition and rating of the appropriateness of items with material dimension

- **"Fraction of recycler output to original supply chain"** indicate the fraction of recycler output that being fed into original supply chain (upcycling) instead of foreign supply chain (downcycling). It is often thought that the quality of the waste are best preserved when it is being recycled into original supply chain, while deteriorate when recycled into foreign supply chain.

- **"Fraction of recycled material used per kg product"** indicate the fraction of product constitute of recycled material. A manufacturing company who utilise more recycled materials in the manufacturing of its product are deemed to align more closely to circular economy, by cutting down virgin resources consumption and promoting re-utilisation of waste as substitute of the virgin resources.

- **"Fraction of waste recycled internally"** indicate the amount of waste water and solid waste that are generated in the company and being recycled internally. Higher amount of waste water and solid waste recycled internally indicate the tendency of the company to embrace circular economy, by bringing back the waste it created and re-utilise it.

- **"Total weight of unrecoverable waste per kg product"** indicate the weight of waste including solid, liquid and gas that are not being recovered and emitted to the surrounding landfill, sewer and air. A high value of unrecoverable waste emitted signifying the inefficiency of a company in utilising its material resources and unmotivated in reutilising the waste as resources. A company in the circular economy must minimise its emission leakage to least possible, by transforming the waste into either technical or biological nutrient to other company.

In your opinion, how appropriate is each item in measuring the material dimension? Notes: "1” indicates barely adequate and “7” indicates almost perfect.

Please don't select more than 1 answer(s) per row.

	1	2	3	4	5	6	7
Fraction of recycler output to original supply chain	☐	☐	☐	☐	☐	☐	☐
Fraction of recycled material used per kg product	☐	☐	☐	☐	☐	☐	☐
Fraction of waste recycled internally	☐	☐	☐	☐	☐	☐	☐
Total weight of unrecoverable waste per kg product	☐	☐	☐	☐	☐	☐	☐

Page 6: Definition and rating of the appropriateness of items with temporal dimension

- **"Lifetime of product"** indicate the expected life time of a product until it reach its end-of-life. A longer lifetime indicate that the resources would remain in the consumption cycle for a longer time, retaining its value as well as reducing the demand for new resources required to manufacture a new product to replace that product.
- **"Time to reach CE goal "** indicate the time planned to reach any CE goal, for example time planned to reach 90% recycling rate of waste water and etc. Time to reach CE goal can be used as proxy indicator to show the commitment of a company to participate in CE or invest in CE technology, which could drastically shorten the time to reach CE goal.

In your opinion, how appropriate is each item in measuring the temporal dimension? Notes: "1" indicates barely adequate and "7" indicates almost perfect.

Please don't select more than 1 answer(s) per row.

	1	2	3	4	5	6	7
Lifetime of product	☐	☐	☐	☐	☐	☐	☐
Time to reach CE goal	☐	☐	☐	☐	☐	☐	☐

Page 7: Definition and rating of the appropriateness of items with efficiency dimension

- **"Collection efficiency"** indicate the efficiency of process in collecting EOL post-consumer products (for instance if a coating needs to be removed from a material before recycling then there will be a mass loss and waste generation). Higher efficiency implies more materials are retained in the consumption cycle and will not be discarded as waste.

- **"Modularity of product design"** indicate the extent of modularity of product, where higher modularity improve the possibilities of the product to be upgraded and refurbish, replacing any worn parts. High modularity also ensure the product can be easily disassemble at the EOL, so that it can be easily broken down into its constituent components and to be reuse or recycled.

- **"Recyclability"** indicate the fraction of the product that is recyclable. Not all parts of the product are recyclable. Higher percentage of recyclability implies more parts in the product can be recycled, and can be retained in the consumption cycle and not be discarded as waste.

- **"Recycling efficiency"** indicate the efficiency of recycler to recycle the end-of-life post-consumer products. Higher recycling efficiency implies more end-of-life product are successfully recycled, and will be retained in the consumption cycle and less material will be discarded as waste.

- **"Rental-ability"** indicate the ability of the product to be rented or leased to another consumers by consumer during its use phase, to increase its usage so that its uses can be maximised, at the same time reduce the needs of a consumer to own a product, thus decreasing the demand for more virgin resources to manufacture more products. Option to rent a product to consumers by a manufacturer also change the ownership of the product to the manufacturer, thus ensuring that the end-of-life post-consumer products will be returned back to the manufacturer and be treated accordingly.

In your opinion, how appropriate is each item in measuring the efficiency dimension?
Notes: "1" indicates barely adequate and "7" indicates almost perfect.

Please don't select more than 1 answer(s) per row.

	1	2	3	4	5	6	7
Collection efficiency	☐	☐	☐	☐	☐	☐	☐
Modularity of product design	☐	☐	☐	☐	☐	☐	☐
Recyclability of product	☐	☐	☐	☐	☐	☐	☐
Recycling efficiency of recycler	☐	☐	☐	☐	☐	☐	☐
Rental-ability	☐	☐	☐	☐	☐	☐	☐

Page 8: Definition of dimensions (constructs) within sustainability

- **"Economy"** indicate the indicator group associated with monetary term such as cost and profit.
- **"Environment"** indicate the indicator group associated with environmental such as waste emission and resources consumption.
- **"Social"** indicate the indicator group associated with wellbeing of society such as job creation, workers health and safety, injuries rate etc.

Page 9: Definition and rating of the appropriateness of items with economy dimension

- **"Operational cost"** indicate the money spent to sustain daily operations, such as cost to purchase raw material, energy, water, logistics and maintenances. Operational cost, as one of the key component in economical sustainability, must be considered along with environmental and societal aspect to ensure financial viability and feasibility of a business.

- **"Capital cost"** indicate the overhead cost spent on equipment, land and setup of company or plants. Capital cost, as one of the key component in economical sustainability, must be considered along with environmental and societal aspect to ensure financial viability and feasibility of a business.

- **"Net profit"** indicate the profit made after considering the sales, subsidies deducting all the costs. Net profit, as one of the key component in economical sustainability, must be considered along with environmental and societal aspect to ensure financial viability and feasibility of a business.

In your opinion, how appropriate is each item in measuring the economy dimension?
Notes: "1” indicates barely adequate and “7” indicates almost perfect.

Please don't select more than 1 answer(s) per row.

	1	2	3	4	5	6	7
Operational cost	☐	☐	☐	☐	☐	☐	☐
Capital cost	☐	☐	☐	☐	☐	☐	☐
Net profit	☐	☐	☐	☐	☐	☐	☐

Page 10: Definition and rating of the appropriateness of items with environment dimension

- **"Gas emission"** indicate the gaseous waste such as greenhouse gas (GHG), ozone depletant and PM10. GHG includes carbon dioxide and methane, which cause global warming that lead to extinction of animal species and climate changes. Ozone depletants such as chloro-fluro-carbon which damage the ozone layer and causes over-exposure of UV rays that would be detrimental to human health. Particulate matter (PM) less than 10 micron emitted along with gaseous waste will pollute the air and causes respiratory tract problems. Lower gaseous emission ensure sound human health and environment wellbeing.

- **"Resources consumption"** indicate the resources such as water, energy, materials and land consumed by the business. Over-consumption of resources surpassing the regeneration rate causes resources scarcity and supply risk, which lead to escalating price of commodities. Over consumption of certain resources such as land could also causes land erosion, over consumption of energy, water and raw materials worsens climate changes and increases air pollution. Low resources consumption ensure sound human health and environment wellbeing.

- **"Acidification and eutrophication potential"** indicate the extent of gaseous emission in the supply chain activities that would causes water, air and soil acidification, which destroy aquatic food chains and causes land infertility, eventually reducing food supply. Eutrophication causes algae blooming, which disrupt the natural habitat of lake and causes extinction of aquatic animal in the affected lake. Low acidification and eutrophication potential ensure sound human health and environment wellbeing.

- **"Renewable energy generation"** indicate a business move away from utilising energy generated from limited resources such as fossil fuel which causes severe air pollution. Renewable energy rely on energy generated from unlimited resources such as wind, water and solar with smaller environmental impact. Renewable energy generation serve as indicator demonstrating the potential of a company in supply chain to tackle environmental issue.

In your opinion, how appropriate is each item in measuring the environment dimension?
Notes: "1" indicates barely adequate and "7" indicates almost perfect.

Please don't select more than 1 answer(s) per row.

	1	2	3	4	5	6	7
Gas emission	☐	☐	☐	☐	☐	☐	☐
Resources consumption	☐	☐	☐	☐	☐	☐	☐
Acidification and eutrophication potential	☐	☐	☐	☐	☐	☐	☐
Renewable energy generation	☐	☐	☐	☐	☐	☐	☐

Page 11: Definition and rating of the appropriateness of items with social dimension

- **"Job creation"** indicate the number of jobs created by the establishment of the system. Higher job created able to minimise unemployment rate, and thus minimise unwanted social condition such as homeless, robbery and crime rate.

- **"Working hours and wages"** indicate the working-hours required to sustain the business, and taking into account the minimum wage in the country and average wage in the sector. Higher wages implies a good social conditioning.

- **"Workers health and safety"** are measured using the frequency of injuries or sick leaves taken by employees, to reflect the health and safety condition in the working environment. Low frequency of injuries and sick leaves implies a safe condition that is suitable to work.

- **"Child labour"** include forced labour and debt bondage (to pay off debts incurred by parents). Employing a child labour can be dangerous and harmful to the child, and can violate the child's freedom and human rights. A socially sustainable business should decouple from the unethical practice of employing a child labour.

- **"Local citizen participation"** indicate the involvement and supports of the local citizen in the business' projects, such as attending town hall meetings and community-led projects. Ideally, the local citizen would involve and support the business and not obstructing the siting of the company based on perception of noise, hygiene, safety, handling, transport and land space requirements.

In your opinion, how appropriate is each item in measuring the social dimension? Notes: "1” indicates barely adequate and “7” indicates almost perfect.

Please don't select more than 1 answer(s) per row.

	1	2	3	4	5	6	7
Job creation	☐	☐	☐	☐	☐	☐	☐
Working hours and wages	☐	☐	☐	☐	☐	☐	☐
Workers health and safety	☐	☐	☐	☐	☐	☐	☐
Child labor	☐	☐	☐	☐	☐	☐	☐
Local citizen participation	☐	☐	☐	☐	☐	☐	☐

Page 12: Final page

Thank you for taking the time to complete this questionnaire. If you have any queries please do not hesitate to contact Mr. Sir Yee Lee by telephoning +4407926214092 or emailing lees116@uni.coventry.ac.uk

Appendix B (Questionnaire for phase 1)

Investigate the relative importance of dimensions and items within circularity and sustainability criteria, for recycling alternative ranking

Page 1: Participants Information Sheet

The aim of this study is to **investigate the relative importance of dimension and items within circularity and sustainability criteria**. The relative index will be used to rank and evaluate the recycling alternative for an End-of-Life tyre (ELT).

The study is being conducted by Mr. Sir Yee Lee at Coventry University. You have been selected to take part in this questionnaire survey because you have been working closely in both the Circular Economy and sustainability field and have sufficient knowledge about the research topic, and are willing to provide the information for research. Your participation in the survey is entirely voluntary, and you can opt out at any stage by closing and exiting the browser. If you are happy to take part, please answer the following questions in relation to the study, by ranking the relative importance of dimensions and items. Your answers will help us to better understand the relative importance of components necessary to rank and evaluate the most suitable recycling alternative for an ELT.

The survey should take approximately 30 minutes (+10 minutes) to complete. Your answers will be treated confidentially and the information you provide will be kept anonymous in our research outputs. Your data will be held securely with the password protected laptop. All data will be deleted by 31 December 2021. The project has been reviewed and approved through the formal Research Ethics procedure at Coventry University.

For further information, or if you have any queries, please contact the lead researcher Mr. Sir Yee Lee - email: lees116@uni.coventry.ac.uk. If you have any concerns that cannot be resolved through the lead researcher, please contact Jiayao Hu - email: ac5218@coventry.ac.uk. Thank you for taking the time to participate in this survey. Your help is very much appreciated.

By selecting "yes", indicate that you have read and understood the above information. You understand that, because your answers will be anonymized, it will not be possible to withdraw them from the study once you have completed the survey. You agree to take part in this questionnaire survey and you consent your answers to be used as described. ✱ *Required*

- ○ Yes
- ○ No

Page 2: Instructions

The questionnaire is divided into two parts.

- **Part 1** will require you to select the profile of the institute or company that you work in.
- **Part 2** will require you to rank the relative importance of each indicator over one another.

- Note: A rank closer to left-hand-side (LHS) indicate the indicator group in LHS is more important than the indicator group in RHS and vice versa. A rank of "1" indicate both indicator groups are equally important.

- Example: A rank of 9 is chosen, and is closer to indicator A, signify that indicator A is extremely more important compared to indicator B.

Indicator A	9	7	5	3	1	3	5	7	9	Indicator B

- Example: A rank of 1 is chosen, signify that indicator C and indicator D is equally important.

Indicator C	9	7	5	3	1	3	5	7	9	Indicator D

- Example: A rank of 3 is chosen, and is closer to indicator F, signify that indicator F is moderately more important compared to indicator E.

Indicator E	9	7	5	3	1	3	5	7	9	Indicator F

Page 3: Part 1: Characteristics of your institute or company

Please select the sector you work in:

Please write down the name of the institute or company you work in (optional): *Optional*

Please select your position in your institute or company

- ◌ Professor
- ◌ Associate professor
- ◌ Assistant professor
- ◌ Manager
- ◌ Board member

Page 4: Part 2: Rank the relative importance of each dimension over one another.

- **"Monetary"** indicates the dimension associated with monetary terms such as cost and profit.
- **"Energy and environment"** indicates the dimension associated with energy and environmental pollution.
- **"Material"** indicates the dimension associated with tangible material such as product weight and waste produced.
- **"Temporal"** indicates the dimension associated with time, such as time to reach goal, lifetime of product.
- **"Efficiency"** indicates the dimension associated with efficiency, such as recycling efficiency.

- Note: A rank closer to left-hand-side (LHS) indicate the indicator group in LHS is more important than the indicator group in RHS and vice versa. A rank of "1" indicate both indicator groups are equally important.

In your opinion, which dimension is more important and can best reflect the circularity of a recycling alternative?

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	
Monetary	☐	☐	☐	☐	☐	☐	☐	☐	☐	Energy and environment
Monetary	☐	☐	☐	☐	☐	☐	☐	☐	☐	Material
Monetary	☐	☐	☐	☐	☐	☐	☐	☐	☐	Temporal
Monetary	☐	☐	☐	☐	☐	☐	☐	☐	☐	Efficiency
Energy and environment	☐	☐	☐	☐	☐	☐	☐	☐	☐	Material
Energy and environment	☐	☐	☐	☐	☐	☐	☐	☐	☐	Temporal
Energy and environment	☐	☐	☐	☐	☐	☐	☐	☐	☐	Efficiency
Material	☐	☐	☐	☐	☐	☐	☐	☐	☐	Temporal
Material	☐	☐	☐	☐	☐	☐	☐	☐	☐	Efficiency
Temporal	☐	☐	☐	☐	☐	☐	☐	☐	☐	Efficiency

Page 5: Rank the relative importance of each item over one another within monetary dimension

- **"Average cost of virgin material per kg"** is used as proxy indicator to reflect the scarcity of the material used in production. A higher cost indicates that a scarce resource is consumed in the production process, for example gold or rare earth metals.

- **"Average repairing price"** indicates the price to repair the damaged product. A repairing cost that is lower compared to cost of purchasing a new product would encourage the consumer to repair the product instead of buying a new product. This can extend the usage of a product before it is discarded as waste, ensuring that the material will be retained in the consumption cycle until it reaches its designated EOL.

- **"Fraction of cost spent on CE technology to total cost of investments"** indicates the money spent on installing CE related technology, such as waste recycler, disassembly robot, alternative raw materials, etc. (see examples from world economic forum: https://www.weforum.org/agenda/2017/09/new-tech-sustainable-circular-economy/). More money spent in these categories implies a company is more willing to participate in circular economy endeavour, by changing its operation and business model to incorporate CE related strategies.

- **"Fraction of cost spent on recyclable material to total cost of material"** indicates the money spent in purchasing EOL waste or recyclable product, which will be recycled and used to manufacture new products. More money spent in this category implies a company is more willing to participate in circular economy endeavour, by bringing back the waste into the supply chain.

- **"Production cost per kg product"** indicates the cost of manufacturing a product which includes the cost for energy, electricity, water as well as administration cost. A true circular supply chain generates its own energy and electricity, and reuses the resources such as water, keeping the production cost as low as possible.

- **"Profit OR saving per kg recyclable input consumed"** indicates the profit made by a recycler company in selling the recycled EOL post-consumer waste or saving made by manufacturer when substituting virgin materials with recycled materials. A company that is having higher profit per unit waste implies more value had been added to the waste consumed, thus maximising the value of the waste.

- Note: A rank closer to left-hand-side (LHS) indicate the indicator group in LHS is more important than the inidcator group in RHS and vice versa. A rank of "1" indicate both indicator groups are equally important.

In your opinion, within the ***"monetary"*** dimension, which item is more important and can best reflect the circularity of a recycling alternative?

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	
Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐	☐	☐	Average repairing price

Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of cost spent on CE technology to total cost of investments
Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of cost spent on recyclable material to total cost of material
Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐	☐	☐	Production cost per kg product
Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐	☐	☐	Profit OR saving per kg recyclable input consumed
Average repairing price	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of cost spent on CE technology to total cost of investments
Average repairing price	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of cost spent on recyclable material to total cost of material
Average repairing price	☐	☐	☐	☐	☐	☐	☐	☐	☐	Production cost per kg product
Average repairing price	☐	☐	☐	☐	☐	☐	☐	☐	☐	Profit OR saving per kg recyclable input consumed

Fraction of cost spent on CE technology to total cost of investments	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of cost spent on recyclable material to total cost of material
Fraction of cost spent on CE technology to total cost of investments	☐	☐	☐	☐	☐	☐	☐	☐	☐	Production cost per kg product
Fraction of cost spent on CE technology to total cost of investments	☐	☐	☐	☐	☐	☐	☐	☐	☐	Profit OR saving per kg recyclable input consumed
Fraction of cost spent on recyclable material to total cost of material	☐	☐	☐	☐	☐	☐	☐	☐	☐	Production cost per kg product
Fraction of cost spent on recyclable material to total cost of material	☐	☐	☐	☐	☐	☐	☐	☐	☐	Profit OR saving per kg recyclable input consumed
Production cost per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Profit OR saving per kg recyclable input consumed

Page 6: Rank the relative importance of each item over one another within energy and environment dimension

- **"Fraction of energy generated using renewable sources"** indicates the energy generated within the company on-site and not purchased from energy providers. Generation of energy on site negates the need to purchase energy from power stations that usually rely on non-renewable resources such as coal, fossil fuels, uranium, etc. Generation of energy using renewable energy sources such as solar, wind, tidal, biomass, etc is much better than generation of energy using non-renewable energy resources. A true circular economy harvests raw material only from the waste stream and uses only renewable energy (purchased or generated on-site) in all operational and logistical activities.

- **"Fraction of energy loss"** indicates the energy loss in operation such as energy dissipated in unit operation or energy loss in buildings. Lower energy loss in a company indicates an efficient use of the energy resources. A supply chain in circular economy will have negligible energy leakage to the surroundings.

- **"Fraction of energy purchased from renewable sources"** indicates the amount of energy utilised in the company that is obtained from renewable energy sources such as solar, wind, tidal, biomass, etc. Higher utilisation of renewable energy negates the needs to fire up costly and polluting power stations and reduces reliance on non-renewable resources. A true circular economy harvests raw material only from the waste streams and uses only renewable energy in all operational and logistical activities.

- **"Total GHG produced per kg product"** indicates the overall impact imparted on to the environment by the processes carried out in the company. Carbon footprint, which measures greenhouse gas (GHG), is one of the widely used environmental indicators. GHG includes carbon dioxide and methane, which cause global warming leading to extinction of animal species and climate changes. Lower environmental impact ensures sound human health and environment wellbeing. A supply chain in the true circular economy will impart negligible environmental impact to the surroundings.

- **"Total energy consumed per kg product"** indicates the total energy required to manufacture a unit (kg) of product. A high energy required to produce a product can be used as a proxy indicator to show the low efficiency production process or poorly designed production technology, which should be improved such that the energy consumption is lowered.

- **"Total energy generated per kg product"** indicates the energy generated within the company on-site and not purchased from energy providers. A supply chain in a true circular economy will generate its own energy on-site to be used in all operational and logistical activities.

- Note: A rank closer to left-hand-side (LHS) indicate the indicator group in LHS is more important than the indicator group in RHS and vice versa. A rank of "1" indicate both indicator groups are equally important.

In your opinion, within the ***"energy and environment"*** dimension, which item is more important and can best reflect the circularity of a recycling alternative?

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	

Fraction of energy generated using renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of energy loss
Fraction of energy generated using renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of energy purchased from renewable sources
Fraction of energy generated using renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total GHG produced per kg product
Fraction of energy generated using renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total energy consumed per kg product
Fraction of energy generated using renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total energy generated per kg product
Fraction of energy loss	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of energy purchased from renewable sources
Fraction of energy loss	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total GHG produced per kg product
Fraction of energy loss	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total energy consumed per kg product
Fraction of energy loss	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total energy generated per kg product

Fraction of energy purchased from renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total GHG produced per kg product
Fraction of energy purchased from renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total energy consumed per kg product
Fraction of energy purchased from renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total energy generated per kg product
Total GHG produced per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total energy consumed per kg product
Total GHG produced per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total energy generated per kg product
Total energy consumed per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total energy generated per kg product

Page 7: Rank the relative importance of each item over one another within material dimension

- **"Fraction of recycler output to original supply chain"** indicates the fraction of recycler output that is being fed into original supply chain (upcycling) instead of foreign supply chain (downcycling). It is often thought that the quality of the waste is best preserved when it is being recycled into the original supply chain, and it deteriorates when recycled into the foreign supply chain.

- **"Fraction of recycled material used per kg product"** indicates the fraction of product constituted of recycled material. A manufacturing company who utilises more recycled materials in the manufacturing of its product is deemed to be aligned more closely to CE, by cutting down virgin resources consumption and promoting re-utilisation of waste as a substitute of the virgin resources.

- **"Fraction of waste recycled internally"** indicates the amount of wastewater and solid waste that are generated in the company and being recycled internally. Higher amount of wastewater and solid waste recycled internally indicates the tendency of the company to embrace CE, by retaining the waste created and re-utilising it.

- **"Total weight of unrecoverable waste per kg product"** indicates the weight of waste including solid, liquid and gas that are not being recovered and emitted to surrounding landfill, sewer and air. A high value of unrecoverable waste emitted signifies the inefficiency of a company in utilising its material resources and unmotivated in reutilising the waste as resources. A company practises CE must minimise its emission leakage as much as possible, by transforming waste into either technical or biological nutrient that can be returned to the surroundings.

- Note: A rank closer to left-hand-side (LHS) indicate the indicator group in LHS is more important than the inidcator group in RHS and vice versa. A rank of "1" indicate both indicator groups are equally important.

In your opinion, within the ***"material"*** dimension, which item is more important and can best reflect the circularity of a recycling alternative?

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	
Fraction of recycler output to original supply chain	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of recycled material used per kg product
Fraction of recycler output to original supply chain	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of waste recycled internally

Fraction of recycler output to original supply chain	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total weight of unrecoverable waste per kg product
Fraction of recycled material used per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of waste recycled internally
Fraction of recycled material used per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total weight of unrecoverable waste per kg product
Fraction of waste recycled internally	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total weight of unrecoverable waste per kg product

Page 8: Rank the relative importance of each item over one another within temporal dimension

- **"Lifetime of product"** indicates the expected lifetime of a product until it reaches its end-of-life. A longer lifetime indicates the product would remain in the consumption cycle for a longer time, retaining its value as well as reducing the demand for new resources required to manufacture a new product to replace that product.

- **"Time to reach CE goal "** indicates the time planned to reach any CE goal, for example the time planned to reach 90% recycling rate of wastewater. Time to reach CE goal can be used as a proxy indicator to show the commitment of a company practising CE or invest in CE technology, which could drastically shorten the time to reach CE goal.

- Note: A rank closer to left-hand-side (LHS) indicate the indicator group in LHS is more important than the inidcator group in RHS and vice versa. A rank of "1" indicate both indicator groups are equally important.

In your opinion, within the ***"temporal"*** dimension, which item is more important and can best reflect the circularity of a recycling alternative?

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	
Lifetime of product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Time to reach CE goal

Page 9: Rank the relative importance of each item over one another within efficiency dimension

- **"Collection efficiency"** indicates the efficiency of process in collecting and dissembling EOL post-consumer products (for instance if a coating needs to be removed from the material before recycling then there will be a mass loss and waste generation). Higher efficiency implies more materials are retained in the consumption cycle and will not be discarded as waste.

- **"Modularity of product design"** indicates the extent of modularity of a product, where higher modularity increases the possibility of the product to be upgraded and refurbished, replacing any worn parts. High modularity also ensures the product can be easily disassembled at EOL, so that it can be easily broken down into constituent components to be reused or recycled, reducing disassembly time.

- **"Recyclability"** indicates the fraction of the product that is recyclable. Not all parts of the product are recyclable. Higher percentage of recyclability implies more parts in the product can be recycled, and can be retained in the consumption cycle and not be discarded as waste.

- **"Recycling efficiency"** indicates the efficiency of recycler to recycle the end-of-life post-consumer products. Higher recycling efficiency implies more end-of-life products are successfully recycled and will be retained in the consumption cycle and less material will be discarded as waste.

- **"Rental-ability"** indicates the ability of the product to be rented or leased to another consumers, so that its uses can be maximised, and at the same time, reducing the need of a consumer to own a product, thus decreasing the demand for more virgin resources to manufacture more products. Option to rent a product to consumers by a manufacturer also changes the ownership of the product to the manufacturer, ensuring that the end-of-life post-consumer products will be returned to the manufacturer and be treated accordingly.

- Note: A rank closer to left-hand-side (LHS) indicate the indicator group in LHS is more important than the indicator group in RHS and vice versa. A rank of "1" indicate both indicator groups are equally important.

In your opinion, within the *"efficiency"* dimension, which item is more important and can best reflect the circularity of a recycling alternative?

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	
Collection efficiency	☐	☐	☐	☐	☐	☐	☐	☐	☐	Modularity of product design
Collection efficiency	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recyclability of product
Collection efficiency	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recycling efficiency of recycler

Collection efficiency	☐	☐	☐	☐	☐	☐	☐	☐	☐	Rental-ability
Modularity of product design	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recyclability of product
Modularity of product design	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recycling efficiency of recycler
Modularity of product design	☐	☐	☐	☐	☐	☐	☐	☐	☐	Rental-ability
Recyclability of product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recycling efficiency of recycler
Recyclability of product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Rental-ability
Recycling efficiency of recycler	☐	☐	☐	☐	☐	☐	☐	☐	☐	Rental-ability

Page 10: Rank the relative importance of each item over one another within monetary and energy and environment dimension

In your opinion, within the *"monetary"* and *"energy and environment"* dimension, which item is more important and can best reflect the circularity of a recycling alternative? Note: The explanation of each item remains the same as shown in the previous pages.

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	
Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of energy generated using renewable sources
Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of energy loss
Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of energy purchased from renewable sources
Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total GHG produced per kg product
Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total energy consumed per kg product
Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total energy generated per kg product
Average repairing price	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of energy generated using renewable sources
Average repairing price	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of energy loss

Average repairing price	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of energy purchased from renewable sources
Average repairing price	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total GHG produced per kg product
Average repairing price	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total energy consumed per kg product
Average repairing price	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total energy generated per kg product
Fraction of cost spent on CE technology to total cost of investments	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of energy generated using renewable sources
Fraction of cost spent on CE technology to total cost of investments	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of energy loss
Fraction of cost spent on CE technology to total cost of investments	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of energy purchased from renewable sources
Fraction of cost spent on CE technology to total cost of investments	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total GHG produced per kg product
Fraction of cost spent on CE technology to total cost of investments	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total energy consumed per kg product

Fraction of cost spent on CE technology to total cost of investments	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total energy generated per kg product
Fraction of cost spent on recyclable material to total cost of material	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of energy generated using renewable sources
Fraction of cost spent on recyclable material to total cost of material	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of energy loss
Fraction of cost spent on recyclable material to total cost of material	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of energy purchased from renewable sources
Fraction of cost spent on recyclable material to total cost of material	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total GHG produced per kg product
Fraction of cost spent on recyclable material to total cost of material	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total energy consumed per kg product
Fraction of cost spent on recyclable material to total cost of material	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total energy generated per kg product
Production cost per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of energy generated using renewable sources
Production cost per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of energy loss

Production cost per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of energy purchased from renewable sources
Production cost per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total GHG produced per kg product
Production cost per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total energy consumed per kg product
Production cost per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total energy generated per kg product
Profit OR saving per kg recyclable input consumed	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of energy generated using renewable sources
Profit OR saving per kg recyclable input consumed	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of energy loss
Profit OR saving per kg recyclable input consumed	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of energy purchased from renewable sources
Profit OR saving per kg recyclable input consumed	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total GHG produced per kg product
Profit OR saving per kg recyclable input consumed	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total energy consumed per kg product

Profit OR saving per kg recyclable input consumed	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total energy generated per kg product

Page 11: Rank the relative importance of each item over one another within monetary and material dimension

In your opinion, within the *"monetary"* and *"material"* dimension, which item is more important and can best reflect the circularity of a recycling alternative? Note: The explanation of each item remains the same as shown in the previous pages.

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	
Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of recycler output to original supply chain
Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of recycled material used per kg product
Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of waste recycled internally
Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total weight of unrecoverable waste per kg product
Average repairing price	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of recycler output to original supply chain
Average repairing price	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of recycled material used per kg product
Average repairing price	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of waste recycled internally
Average repairing price	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total weight of unrecoverable waste per kg product

Fraction of cost spent on CE technology to total cost of investments	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of recycler output to original supply chain
Fraction of cost spent on CE technology to total cost of investments	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of recycled material used per kg product
Fraction of cost spent on CE technology to total cost of investments	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of waste recycled internally
Fraction of cost spent on CE technology to total cost of investments	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total weight of unrecoverable waste per kg product
Fraction of cost spent on recyclable material to total cost of material	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of recycler output to original supply chain
Fraction of cost spent on recyclable material to total cost of material	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of recycled material used per kg product
Fraction of cost spent on recyclable material to total cost of material	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of waste recycled internally
Fraction of cost spent on recyclable material to total cost of material	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total weight of unrecoverable waste per kg product

Production cost per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of recycler output to original supply chain
Production cost per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of recycled material used per kg product
Production cost per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of waste recycled internally
Production cost per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total weight of unrecoverable waste per kg product
Profit OR saving per kg recyclable input consumed	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of recycler output to original supply chain
Profit OR saving per kg recyclable input consumed	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of recycled material used per kg product
Profit OR saving per kg recyclable input consumed	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of waste recycled internally
Profit OR saving per kg recyclable input consumed	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total weight of unrecoverable waste per kg product

Page 12: Rank the relative importance of each item over one another within monetary and temporal dimension

In your opinion, within the *"monetary"* and *"temporal"* dimension, which item is more important and can best reflect the circularity of a recycling alternative? Note: The explanation of each item remains the same as shown in the previous pages.

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	
Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐	☐	☐	Lifetime of product
Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐	☐	☐	Time to reach CE goal
Average repairing price	☐	☐	☐	☐	☐	☐	☐	☐	☐	Lifetime of product
Average repairing price	☐	☐	☐	☐	☐	☐	☐	☐	☐	Time to reach CE goal
Fraction of cost spent on CE technology to total cost of investments	☐	☐	☐	☐	☐	☐	☐	☐	☐	Lifetime of product
Fraction of cost spent on CE technology to total cost of investments	☐	☐	☐	☐	☐	☐	☐	☐	☐	Time to reach CE goal
Fraction of cost spent on recyclable material to total cost of material	☐	☐	☐	☐	☐	☐	☐	☐	☐	Lifetime of product
Fraction of cost spent on recyclable material to total cost of material	☐	☐	☐	☐	☐	☐	☐	☐	☐	Time to reach CE goal

Production cost per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Lifetime of product
Production cost per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Time to reach CE goal
Profit OR saving per kg recyclable input consumed	☐	☐	☐	☐	☐	☐	☐	☐	☐	Lifetime of product
Profit OR saving per kg recyclable input consumed	☐	☐	☐	☐	☐	☐	☐	☐	☐	Time to reach CE goal

Page 13: Rank the relative importance of each item over one another within monetary and efficiency dimension

In your opinion, within the *"monetary"* and *"efficiency"* dimension, which item is more important and can best reflect the circularity of a recycling alternative? Note: The explanation of each item remains the same as shown in the previous pages.

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	
Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐	☐	☐	Collection efficiency
Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐	☐	☐	Modularity of product design
Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recyclability of product
Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recycling efficiency of recycler
Average cost of virgin material per kg	☐	☐	☐	☐	☐	☐	☐	☐	☐	Rental-ability
Average repairing price	☐	☐	☐	☐	☐	☐	☐	☐	☐	Collection efficiency
Average repairing price	☐	☐	☐	☐	☐	☐	☐	☐	☐	Modularity of product design
Average repairing price	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recyclability of product
Average repairing price	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recycling efficiency of recycler
Average repairing price	☐	☐	☐	☐	☐	☐	☐	☐	☐	Rental-ability

Fraction of cost spent on CE technology to total cost of investments	☐	☐	☐	☐	☐	☐	☐	☐	☐	Collection efficiency
Fraction of cost spent on CE technology to total cost of investments	☐	☐	☐	☐	☐	☐	☐	☐	☐	Modularity of product design
Fraction of cost spent on CE technology to total cost of investments	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recyclability of product
Fraction of cost spent on CE technology to total cost of investments	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recycling efficiency of recycler
Fraction of cost spent on CE technology to total cost of investments	☐	☐	☐	☐	☐	☐	☐	☐	☐	Rental-ability
Fraction of cost spent on recyclable material to total cost of material	☐	☐	☐	☐	☐	☐	☐	☐	☐	Collection efficiency
Fraction of cost spent on recyclable material to total cost of material	☐	☐	☐	☐	☐	☐	☐	☐	☐	Modularity of product design
Fraction of cost spent on recyclable material to total cost of material	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recyclability of product

Fraction of cost spent on recyclable material to total cost of material	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recycling efficiency of recycler
Fraction of cost spent on recyclable material to total cost of material	☐	☐	☐	☐	☐	☐	☐	☐	☐	Rental-ability
Production cost per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Collection efficiency
Production cost per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Modularity of product design
Production cost per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recyclability of product
Production cost per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recycling efficiency of recycler
Production cost per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Rental-ability
Profit OR saving per kg recyclable input consumed	☐	☐	☐	☐	☐	☐	☐	☐	☐	Collection efficiency
Profit OR saving per kg recyclable input consumed	☐	☐	☐	☐	☐	☐	☐	☐	☐	Modularity of product design
Profit OR saving per kg recyclable input consumed	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recyclability of product
Profit OR saving per kg recyclable input consumed	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recycling efficiency of recycler

Profit OR saving per kg recyclable input consumed	☐	☐	☐	☐	☐	☐	☐	☐	☐	Rental-ability

Page 14: Rank the relative importance of each item over one another within energy and environment and material dimension

In your opinion, within the *"energy and environment"* and *"material"* dimension, which item is more important and can best reflect the circularity of a recycling alternative? Note: The explanation of each item remains the same as shown in the previous pages.

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	
Fraction of energy generated using renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of recycler output to original supply chain
Fraction of energy generated using renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of recycled material used per kg product
Fraction of energy generated using renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of waste recycled internally
Fraction of energy generated using renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total weight of unrecoverable waste per kg product
Fraction of energy loss	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of recycler output to original supply chain
Fraction of energy loss	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of recycled material used per kg product
Fraction of energy loss	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of waste recycled internally

Fraction of energy loss	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total weight of unrecoverable waste per kg product
Fraction of energy purchased from renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of recycler output to original supply chain
Fraction of energy purchased from renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of recycled material used per kg product
Fraction of energy purchased from renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of waste recycled internally
Fraction of energy purchased from renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total weight of unrecoverable waste per kg product
Total GHG produced per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of recycler output to original supply chain
Total GHG produced per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of recycled material used per kg product
Total GHG produced per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Fraction of waste recycled internally
Total GHG produced per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Total weight of unrecoverable waste per kg product

Total energy consumed per kg product										Fraction of recycler output to original supply chain
Total energy consumed per kg product										Fraction of recycled material used per kg product
Total energy consumed per kg product										Fraction of waste recycled internally
Total energy consumed per kg product										Total weight of unrecoverable waste per kg product
Total energy generated per kg product										Fraction of recycler output to original supply chain
Total energy generated per kg product										Fraction of recycled material used per kg product
Total energy generated per kg product										Fraction of waste recycled internally
Total energy generated per kg product										Total weight of unrecoverable waste per kg product

Page 15: Rank the relative importance of each item over one another within energy and environment and temporal dimension

In your opinion, within the *"energy and environment"* and *"temporal"* dimension, which item is more important and can best reflect the circularity of a recycling alternative? Note: The explanation of each item remains the same as shown in the previous pages.

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	
Fraction of energy generated using renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Lifetime of product
Fraction of energy generated using renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Time to reach CE goal
Fraction of energy loss	☐	☐	☐	☐	☐	☐	☐	☐	☐	Lifetime of product
Fraction of energy loss	☐	☐	☐	☐	☐	☐	☐	☐	☐	Time to reach CE goal
Fraction of energy purchased from renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Lifetime of product
Fraction of energy purchased from renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Time to reach CE goal
Total GHG produced per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Lifetime of product
Total GHG produced per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Time to reach CE goal

Total energy consumed per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Lifetime of product
Total energy consumed per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Time to reach CE goal
Total energy generated per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Lifetime of product
Total energy generated per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Time to reach CE goal

Page 16: Rank the relative importance of each item over one another within energy and environment and efficiency dimension

In your opinion, within the *"energy and environment"* and *"efficiency"* dimension, which item is more important and can best reflect the circularity of a recycling alternative? Note: The explanation of each item remains the same as shown in the previous pages.

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	
Fraction of energy generated using renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Collection efficiency
Fraction of energy generated using renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Modularity of product design
Fraction of energy generated using renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recyclability of product
Fraction of energy generated using renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recycling efficiency of recycler
Fraction of energy generated using renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Rental-ability
Fraction of energy loss	☐	☐	☐	☐	☐	☐	☐	☐	☐	Collection efficiency
Fraction of energy loss	☐	☐	☐	☐	☐	☐	☐	☐	☐	Modularity of product design
Fraction of energy loss	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recyclability of product
Fraction of energy loss	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recycling efficiency of recycler

Fraction of energy loss	☐	☐	☐	☐	☐	☐	☐	☐	☐	Rental-ability
Fraction of energy purchased from renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Collection efficiency
Fraction of energy purchased from renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Modularity of product design
Fraction of energy purchased from renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recyclability of product
Fraction of energy purchased from renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recycling efficiency of recycler
Fraction of energy purchased from renewable sources	☐	☐	☐	☐	☐	☐	☐	☐	☐	Rental-ability
Total GHG produced per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Collection efficiency
Total GHG produced per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Modularity of product design
Total GHG produced per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recyclability of product
Total GHG produced per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recycling efficiency of recycler
Total GHG produced per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Rental-ability
Total energy consumed per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Collection efficiency

Total energy consumed per kg product										Modularity of product design
Total energy consumed per kg product										Recyclability of product
Total energy consumed per kg product										Recycling efficiency of recycler
Total energy consumed per kg product										Rental-ability
Total energy generated per kg product										Collection efficiency
Total energy generated per kg product										Modularity of product design
Total energy generated per kg product										Recyclability of product
Total energy generated per kg product										Recycling efficiency of recycler
Total energy generated per kg product										Rental-ability

Page 17: Rank the relative importance of each item over one another within material and temporal dimension

In your opinion, within the *"material"* and *"temporal"* dimension, which item is more important and can best reflect the circularity of a recycling alternative? Note: The explanation of each item remains the same as shown in the previous pages.

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	
Fraction of recycler output to original supply chain	☐	☐	☐	☐	☐	☐	☐	☐	☐	Lifetime of product
Fraction of recycler output to original supply chain	☐	☐	☐	☐	☐	☐	☐	☐	☐	Time to reach CE goal
Fraction of recycled material used per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Lifetime of product
Fraction of recycled material used per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Time to reach CE goal
Fraction of waste recycled internally	☐	☐	☐	☐	☐	☐	☐	☐	☐	Lifetime of product
Fraction of waste recycled internally	☐	☐	☐	☐	☐	☐	☐	☐	☐	Time to reach CE goal
Total weight of unrecoverable waste per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Lifetime of product
Total weight of unrecoverable waste per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Time to reach CE goal

Page 18: Rank the relative importance of each item over one another within material and efficiency dimension

In your opinion, within the *"material"* and *"efficiency"* dimension, which item is more important and can best reflect the circularity of a recycling alternative? Note: The explanation of each item remains the same as shown in the previous pages.

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	
Fraction of recycler output to original supply chain	☐	☐	☐	☐	☐	☐	☐	☐	☐	Collection efficiency
Fraction of recycler output to original supply chain	☐	☐	☐	☐	☐	☐	☐	☐	☐	Modularity of product design
Fraction of recycler output to original supply chain	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recyclability of product
Fraction of recycler output to original supply chain	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recycling efficiency of recycler
Fraction of recycler output to original supply chain	☐	☐	☐	☐	☐	☐	☐	☐	☐	Rental-ability
Fraction of recycled material used per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Collection efficiency
Fraction of recycled material used per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Modularity of product design
Fraction of recycled material used per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recyclability of product

Fraction of recycled material used per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recycling efficiency of recycler
Fraction of recycled material used per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Rental-ability
Fraction of waste recycled internally	☐	☐	☐	☐	☐	☐	☐	☐	☐	Collection efficiency
Fraction of waste recycled internally	☐	☐	☐	☐	☐	☐	☐	☐	☐	Modularity of product design
Fraction of waste recycled internally	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recyclability of product
Fraction of waste recycled internally	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recycling efficiency of recycler
Fraction of waste recycled internally	☐	☐	☐	☐	☐	☐	☐	☐	☐	Rental-ability
Total weight of unrecoverable waste per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Collection efficiency
Total weight of unrecoverable waste per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Modularity of product design
Total weight of unrecoverable waste per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recyclability of product
Total weight of unrecoverable waste per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recycling efficiency of recycler

Total weight of unrecoverable waste per kg product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Rental-ability

Page 19: Rank the relative importance of each item over one another within temporal and efficiency dimension

In your opinion, within the *"temporal"* and *"efficiency"* dimension, which item is more important and can best reflect the circularity of a recycling alternative? Note: The explanation of each item remains the same as shown in the previous pages.

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	
Lifetime of product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Collection efficiency
Lifetime of product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Modularity of product design
Lifetime of product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recyclability of product
Lifetime of product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recycling efficiency of recycler
Lifetime of product	☐	☐	☐	☐	☐	☐	☐	☐	☐	Rental-ability
Time to reach CE goal	☐	☐	☐	☐	☐	☐	☐	☐	☐	Collection efficiency
Time to reach CE goal	☐	☐	☐	☐	☐	☐	☐	☐	☐	Modularity of product design
Time to reach CE goal	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recyclability of product
Time to reach CE goal	☐	☐	☐	☐	☐	☐	☐	☐	☐	Recycling efficiency of recycler
Time to reach CE goal	☐	☐	☐	☐	☐	☐	☐	☐	☐	Rental-ability

Page 20: Rank the relative importance of each dimension over one another.

- **"Economy"** indicates the dimension associated with monetary term such as cost and profit.
- **"Environment"** indicates the dimension associated with environmental such as waste emission and resources consumption.
- **"Social"** indicates the dimension associated with wellbeing of society such as job creation, workers health and safety, injuries rate etc.

- Note: A rank closer to left-hand-side (LHS) indicate the indicator group in LHS is more important than the indicator group in RHS and vice versa. A rank of "1" indicate both indicator groups are equally important.

In your opinion, which dimension is more important and can best reflect the sustainability of a recycling alternative?

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	
Economy	☐	☐	☐	☐	☐	☐	☐	☐	☐	Environment
Economy	☐	☐	☐	☐	☐	☐	☐	☐	☐	Social
Environment	☐	☐	☐	☐	☐	☐	☐	☐	☐	Social

Page 21: Rank the relative importance of each item over one another within economical dimension

- **"Operational cost"** indicates the money spent to sustain daily operations, such as cost to purchase raw material, energy, water, logistics and maintenance. Operational cost, as one of the key components in economical sustainability, must be considered along with environmental and societal aspects to ensure financial viability and feasibility of a business.

- **"Capital cost"** indicates the overhead cost spent on equipment, land and setup of company or plant. Capital cost, as one of the key components in economical sustainability, must be considered along with environmental and societal aspects to ensure financial viability and feasibility of a business.

- **"Net profit"** indicates the profit made after considering the sales, subsidies deducting all the costs. Net profit, as one of the key components in economical sustainability, must be considered along with environmental and societal aspects to ensure financial viability and feasibility of a business.

- Note: A rank closer to left-hand-side (LHS) indicate the indicator group in LHS is more important than the indicator group in RHS and vice versa. A rank of "1" indicate both indicator groups are equally important.

In your opinion, within the *"economy"* dimension, which item is more important and can best reflect the sustainability of a recycling alternative?

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	
Operational cost	☐	☐	☐	☐	☐	☐	☐	☐	☐	Capital cost
Operational cost	☐	☐	☐	☐	☐	☐	☐	☐	☐	Net profit
Capital cost	☐	☐	☐	☐	☐	☐	☐	☐	☐	Net profit

Page 22: Rank the relative importance of each item over one another within environmental dimension

- **"Gas emission"** indicates the gaseous waste such as greenhouse gas (GHG), ozone depletant and PM10. GHG includes carbon dioxide and methane, which cause global warming leading to extinction of animal species and climate changes. Ozone depletants such as chloro-fluro-carbon which damages the ozone layer and causes over-exposure of UV rays that would be detrimental to human health. Particulate matter (PM) less than 10 micron emitted along with gaseous waste will pollute the air and cause respiratory tract problems. Lower gaseous emission ensures sound human health and environment wellbeing.

- **"Resources consumption"** indicates the resources such as water, energy, materials and land consumed by the business. Over-consumption of resources surpassing the regeneration rate causes scarcity of resources and supply risks, which leads to escalating price of commodities. Over-consumption of certain resources such as land may also cause land erosion, and over-consumption of energy, water and raw materials may worsen climate change and increase air pollution. Low resources consumption ensures sound human health and environment wellbeing.

- **"Acidification and eutrophication potential"** indicates the extent of gaseous emission in the supply chain activities that would cause water, air and soil acidification, which will destroy aquatic food chains and cause land infertility, eventually reducing food supply. Eutrophication causes algae blooming, which disrupts the natural habitat of lake and causes extinction of aquatic animal in the affected lake. Low acidification and eutrophication potential ensure sound human health and environment wellbeing.

- **"Renewable energy generation"** indicates a business moving away from utilising energy generated from limited resources such as fossil fuel which causes severe air pollution to using renewable energy generated from unlimited resources such as wind, water and solar with smaller environmental impact. Renewable energy generation served as an indicator demonstrating the potential of a company in supply chain to tackle environmental issue.

- Note: A rank closer to left-hand-side (LHS) indicate the indicator group in LHS is more important than the indicator group in RHS and vice versa. A rank of "1" indicate both indicator groups are equally important.

In your opinion, within the *"environmental"* dimension, which item is more important and can best reflect the sustainability of a recycling alternative?

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	
Gas emission	☐	☐	☐	☐	☐	☐	☐	☐	☐	Resources consumption
Gas emission	☐	☐	☐	☐	☐	☐	☐	☐	☐	Acidification and eutrophication potential
Gas emission	☐	☐	☐	☐	☐	☐	☐	☐	☐	Renewable energy generation

Resources consumption	☐	☐	☐	☐	☐	☐	☐	☐	☐	Acidification and eutrophication potential
Resources consumption	☐	☐	☐	☐	☐	☐	☐	☐	☐	Renewable energy generation
Acidification and eutrophication potential	☐	☐	☐	☐	☐	☐	☐	☐	☐	Renewable energy generation

Page 23: Rank the relative importance of each item over one another within societal dimension

- **"Job creation"** indicates the number of jobs created by the establishment of the system. Higher number of job creation will minimise unemployment rate, thus minimising unfavourable social conditions like homelessness, robbery and high crime rate.

- **"Working hours and wages"** indicates the working hours required to sustain the business, considering the minimum wage in the country and average wage in the sector. Higher wages imply a good social condition.

- **"Workers health and safety"** is measured using the frequency of injuries or sick leaves taken by employees to reflect the health and safety standard in working environment. Low frequency of injuries and sick leaves imply safe working environment.

- **"Child labour"** includes forced labour and debt bondage (to pay off debts incurred by parents). Employing child labour can be dangerous and harmful to the child and violates the child's freedom and human rights. A socially sustainable business should decouple from the unethical practice of employing child labour.

- **"Local citizen participation"** indicates the involvement and support of local citizen in the business' projects, such as attending town hall meetings and be involved with community-led projects. Ideally, the local citizens will understand and support the business and not obstruct the siting of the company based on perception of noise, hygiene, safety, handling, transport and land space requirements.

- Note: A rank closer to left-hand-side (LHS) indicate the indicator group in LHS is more important than the inidcator group in RHS and vice versa. A rank of "1" indicate both indicator groups are equally important.

In your opinion, within the *"societal"* dimension, which item is more important and can best reflect the sustainability of a recycling alternative?

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	
Job creation	☐	☐	☐	☐	☐	☐	☐	☐	☐	Working hours and wages
Job creation	☐	☐	☐	☐	☐	☐	☐	☐	☐	Workers health and safety
Job creation	☐	☐	☐	☐	☐	☐	☐	☐	☐	Child labor
Job creation	☐	☐	☐	☐	☐	☐	☐	☐	☐	Local citizen participation

Working hours and wages	☐	☐	☐	☐	☐	☐	☐	☐	☐	Workers health and safety
Working hours and wages	☐	☐	☐	☐	☐	☐	☐	☐	☐	Child labor
Working hours and wages	☐	☐	☐	☐	☐	☐	☐	☐	☐	Local citizen participation
Workers health and safety	☐	☐	☐	☐	☐	☐	☐	☐	☐	Child labor
Workers health and safety	☐	☐	☐	☐	☐	☐	☐	☐	☐	Local citizen participation
Child labor	☐	☐	☐	☐	☐	☐	☐	☐	☐	Local citizen participation

Page 24: Rank the relative importance of each item over one another within economical and environmental dimension

In your opinion, within the *"economical"* and *"environmental"* dimension, which item is more important and can best reflect the sustainability of a recycling alternative? Note: The explanation of each item remains the same as shown in the previous pages.

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	
Operational cost										Gas emission
Operational cost										Resources consumption
Operational cost										Acidification and eutrophication potential
Operational cost										Renewable energy generation
Capital cost										Gas emission
Capital cost										Resources consumption
Capital cost										Acidification and eutrophication potential
Capital cost										Renewable energy generation
Net profit										Gas emission
Net profit										Resources consumption
Net profit										Acidification and eutrophication potential
Net profit										Renewable energy generation

Page 25: Rank the relative importance of each item over one another within economical and societal dimension

In your opinion, within the *"economical"* and *"societal"* dimension, which item is more important and can best reflect the sustainability of a recycling alternative? Note: The explanation of each item remains the same as shown in the previous pages.

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	
Operational cost	☐	☐	☐	☐	☐	☐	☐	☐	☐	Job creation
Operational cost	☐	☐	☐	☐	☐	☐	☐	☐	☐	Working hours and wages
Operational cost	☐	☐	☐	☐	☐	☐	☐	☐	☐	Workers health and safety
Operational cost	☐	☐	☐	☐	☐	☐	☐	☐	☐	Child labor
Operational cost	☐	☐	☐	☐	☐	☐	☐	☐	☐	Local citizen participation
Capital cost	☐	☐	☐	☐	☐	☐	☐	☐	☐	Job creation
Capital cost	☐	☐	☐	☐	☐	☐	☐	☐	☐	Working hours and wages
Capital cost	☐	☐	☐	☐	☐	☐	☐	☐	☐	Workers health and safety
Capital cost	☐	☐	☐	☐	☐	☐	☐	☐	☐	Child labor
Capital cost	☐	☐	☐	☐	☐	☐	☐	☐	☐	Local citizen participation
Net profit	☐	☐	☐	☐	☐	☐	☐	☐	☐	Job creation
Net profit	☐	☐	☐	☐	☐	☐	☐	☐	☐	Working hours and wages
Net profit	☐	☐	☐	☐	☐	☐	☐	☐	☐	Workers health and safety
Net profit	☐	☐	☐	☐	☐	☐	☐	☐	☐	Child labor
Net profit	☐	☐	☐	☐	☐	☐	☐	☐	☐	Local citizen participation

Page 26: Rank the relative importance of each item over one another within environmental and societal dimension

In your opinion, within the *"environmental"* and *"societal"* dimension, which item is more important and can best reflect the sustainability of a recycling alternative? Note: The explanation of each item remains the same as shown in the previous pages.

Please don't select more than 1 answer(s) per row.

	9	7	5	3	1	3	5	7	9	
Gas emission	☐	☐	☐	☐	☐	☐	☐	☐	☐	Job creation
Gas emission	☐	☐	☐	☐	☐	☐	☐	☐	☐	Working hours and wages
Gas emission	☐	☐	☐	☐	☐	☐	☐	☐	☐	Workers health and safety
Gas emission	☐	☐	☐	☐	☐	☐	☐	☐	☐	Child labor
Gas emission	☐	☐	☐	☐	☐	☐	☐	☐	☐	Local citizen participation
Resources consumption	☐	☐	☐	☐	☐	☐	☐	☐	☐	Job creation
Resources consumption	☐	☐	☐	☐	☐	☐	☐	☐	☐	Working hours and wages
Resources consumption	☐	☐	☐	☐	☐	☐	☐	☐	☐	Workers health and safety
Resources consumption	☐	☐	☐	☐	☐	☐	☐	☐	☐	Child labor
Resources consumption	☐	☐	☐	☐	☐	☐	☐	☐	☐	Local citizen participation
Acidification and eutrophication potential	☐	☐	☐	☐	☐	☐	☐	☐	☐	Job creation
Acidification and eutrophication potential	☐	☐	☐	☐	☐	☐	☐	☐	☐	Working hours and wages
Acidification and eutrophication potential	☐	☐	☐	☐	☐	☐	☐	☐	☐	Workers health and safety

Acidification and eutrophication potential	☐	☐	☐	☐	☐	☐	☐	☐	☐	Child labor
Acidification and eutrophication potential	☐	☐	☐	☐	☐	☐	☐	☐	☐	Local citizen participation
Renewable energy generation	☐	☐	☐	☐	☐	☐	☐	☐	☐	Job creation
Renewable energy generation	☐	☐	☐	☐	☐	☐	☐	☐	☐	Working hours and wages
Renewable energy generation	☐	☐	☐	☐	☐	☐	☐	☐	☐	Workers health and safety
Renewable energy generation	☐	☐	☐	☐	☐	☐	☐	☐	☐	Child labor
Renewable energy generation	☐	☐	☐	☐	☐	☐	☐	☐	☐	Local citizen participation

Page 27: Final page

Thank you for taking the time to complete this questionnaire. If you have any queries please do not hesitate to contact Mr. Sir Yee Lee by telephoning +4407926214092 or emailing lees116@uni.coventry.ac.uk

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Key for selection options

2 - Please select the sector you work in:

Educational Sector
Non-educational Sector

Appendix C (Questionnaire for phase 2)

EOL alternative rating under CE and sustainability criteria - TDA

Start of Block: Default Question Block

i The aim of this study is to rank and evaluate the most suitable recycling alternative for an End-of-Life tyre (ELT).

The study is being conducted by Mr. Sir Yee Lee at Coventry University. You have been selected to take part in this questionnaire survey because you have been working closely in the industry and have sufficient knowledge about the research topic (Circular economy and sustainability field) and are willing to provide the information for research. Your participation in the survey is entirely voluntary, and you can opt out at any stage by closing and exiting the browser. If you are happy to take part, please answer the following questions in relation to the study, by rating the EOL recycling alternatives under various criteria. Your answers will help us to better understand how to rank and evaluate the recycling alternatives and revealing the relationship between circularity and sustainability. The survey should take approximately 20 minutes (+10 minutes) to complete. Your answers will be treated confidentially and the information you provide will be kept anonymous in our research outputs. Your data will be held securely with the password protected laptop. All data will be deleted by 31 December 2021. The project has been reviewed and approved through the formal Research Ethics procedure at Coventry University. For further information or if you have any queries, please contact the lead researcher Mr. Sir Yee Lee - email: lees116@uni.coventry.ac.uk. If you have any concerns that cannot be resolved through the lead researcher, please contact Jiayao Hu - email: ac5218@coventry.ac.uk. Thank you for taking the time to participate in this survey. Your help is very much appreciated.

- O I indicate that I have read and understood the above information. I understand that, because my answers will be anonymised, it will not be possible to withdraw them from the study once I have completed the survey. I agree to take part in this questionnaire survey and I confirm that I am aged 18 or over. I consent my answers to be used as described. **N/B: PLEASE CLICK THIS BOX TO PROCEED TO NEXT PAGE**

Page Break

ii The questionnaire is divided into two parts.   Part 1 requires you to describe the company that you are working in.
Part 2a requires you to rate the recycling alternatives under **Circularity** criteria.
Part 2b requires you to rate the recycling alternativesunder **Sustainability** criteria.

Page Break

Part 1: Please describe the company that you are working in.
(*please select the suitable range from the dropdown boxes below*)

Company size	O 201 - 500 employees	O 501 - 1,000 employees	O 1,001 - 5,000 employees	O 5,001 - 10,000 employees	O 10,000 + employees
Annual gross sales or revenus	O less than $0.25 million	O $0.25 million - $29 million	O $30 million - $59 million	O $60 million - $99 million	O $100 million or over

Q2 Monthly output of EOL tyres (kg):
(*please enter the amount in the box given below)*

____

Q3 Which EOL alternative is involved for the EOL tyre that your company have collected? (Which supply chain the EOL tyre enter into?)

(*please click on the relevant image(s) displayed below*)

- ☐ **Tire-to-tire recycling**
- ☐ **Tire-to-synthetic turf recycling**
- ☐ **Tire-to-sports surface recycling**
- ☐ **Tire-to-asphalts recycling**
- ☐ **Tire-to-moulded objects recycling**
- ☐ **Tire-to-cement recycling**
- ☐ **Tire-to-tire derived aggregate recycling**
- ☐ **Tire-to-pyrolysis char recycling**
- ☐ **Tire-to-foundries recycling**

Page Break

Q4 Please specify the demand (annual sales figure) for the ELT (tonne) for each of the selected recycling alternative:
(please enter the amount in the box given)
_______ ${TYPE/ChoiceDescription/1} Tire-to-tire recycling is selected
_______ ${TYPE/ChoiceDescription/2} Tire-to-synthetic turf recycling is selected
_______ ${TYPE/ChoiceDescription/3} Tire-to-sports surface recycling is selected
_______ ${TYPE/ChoiceDescription/4} Tire-to-asphalts recycling is selected
_______ ${TYPE/ChoiceDescription/5} Tire-to-moulded objects recycling is selected
_______ ${TYPE/ChoiceDescription/6} Tire-to-cement recycling is selected
_______ ${TYPE/ChoiceDescription/8} Tire-to-tire derived aggregate recycling is selected
_______ ${TYPE/ChoiceDescription/7} Tire-to-pyrolysis char recycling is selected
_______ ${TYPE/ChoiceDescription/9} Tire-to-foundries recycling is selected

Page Break

iii Part 2a: You are required to rate the recycling alternative under **Circularity** criteria using 7-point Likert scale as below:

Rating	Implication
1	Very Low
2	Low
3	Medium Low
4	Medium
5	Medium High
6	High
7	Very High

Page Break

Instruction:
Please rate the EOL strategy alternatives according to the **"Average cost of virgin materials"**. This criterion is used as proxy indicator to reflect the scarcity of the material used in production. A higher cost indicate that a scarce resource is consumed in the production process, for example gold or rare earth metals.

Data required:
Cost of all virgin materials required to manufacture a unit product

Unit:
$ per kg product manufactured

Aspiration:
indicates **low** average cost of virgin materials, means **better** Circularity
indicates **high** average cost of virgin materials, means **worst** Circularity

(*please rate the alternatives using the 7 point- Likert scale*)

${TYPE/ChoiceDescription/1} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/2} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/3} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/4} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/5} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/6} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/8} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/7} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/9} ☆ ☆ ☆ ☆ ☆ ☆ ☆

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Average repairing price"**.This criterion indicates the price to repair the damaged product. A repairing cost that is lower compared to cost of purchasing a new product would encourage the consumer to repair the product instead of buying a new product. This can extend the usage of a product before it is discarded as waste, ensuring that the material will be retained in the consumption cycle until it reaches its designated EOL.

Data required:
Price to repair a unit product

Unit:
$ per unit product manufactured

Aspiration:
indicates **low** average repairing price, means **better** CE performance
indicates **high** average repairing price, means **worst** CE performance

(*please rate the alternatives using the 7 point- Likert scale*)

${TYPE/ChoiceDescription/1}

${TYPE/ChoiceDescription/2}

${TYPE/ChoiceDescription/3}

${TYPE/ChoiceDescription/4}

${TYPE/ChoiceDescription/5}

${TYPE/ChoiceDescription6/}

${TYPE/ChoiceDescription/8}

${TYPE/ChoiceDescription/7}

${TYPE/ChoiceDescription/9}

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Fraction of cost spent on CE technology to total cost of investments"**. This criterion indicates the money spent on installing CE related technology, such as waste recycler, disassembly robot, alternative raw materials, etc. (see example: https://www.weforum.org/agenda/2017/09/new-tech-sustainable-circular-economy/). More money spent in these categories implies a company is more willing to participate in Circular Economy endeavour, by changing its operation and business model to incorporate CE related strategies.

Data required:
Cost of CE technology or equipments, total cost of investments.

Unit:
% ($ per $)

Aspiration:
indicates **low** cost spent on CE technology, means **worst** CE performance
indicates **high** cost spent on CE technology, means **better** CE performance

(please rate the alternatives using the 7 point- Likert scale)
${TYPE/ChoiceDescription/1} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/2} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/3} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/4} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/5} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/6} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/8} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/7} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/9} ☆ ☆ ☆ ☆ ☆ ☆ ☆

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Fraction of cost spent on recyclable material to total cost of material"**.This criterion indicates the money spent in purchasing EOLe waste or recyclable product, which will be recycled and used to manufacture new product. More money spent in these categories implies a company is more willing to participate in Circular Economy endeavour, by bringing back the waste into the supply chain.

Data required:
Cost of recyclable materials per unit product, Cost of all materials per unit product

Unit:
% ($ per $)

Aspiration:
indicates **low** cost spent on recyclable materials, means **worst** CE performance
indicates **high** cost spent on recyclable materials, means **better** CE performance

(*please rate the alternatives using the 7 point- Likert scale*)

${TYPE/ChoiceDescription/1}
${TYPE/ChoiceDescription/2}
${TYPE/ChoiceDescription/3}
${TYPE/ChoiceDescription/4}
${TYPE/ChoiceDescription/5}
${TYPE/ChoiceDescription/6}
${TYPE/ChoiceDescription/8}
${TYPE/ChoiceDescription/7}
${TYPE/ChoiceDescription/9}

Page Break

Instruction:

Please rate the recycling alternatives according to the **"Production cost per kg product"**.This criterion indicates the cost of manufacturing a product which includes cost for energy, electricity, water as well as administration cost. A true circular supply chain generate its own energy and electricity, and reuse the resources such as water, keeping the production cost as low as possible.

Data required:

Cost of manufacturing, Mileage cost of logistics

Unit:

$ per kg product manufactured

Aspiration:

indicates **low** production cost, means **better** CE performance

indicates **high** production cost, means **worst** CE performance

(*please rate the alternatives using the 7 point- Likert scale*)

${TYPE/ChoiceDescription/1}

${TYPE/ChoiceDescription/2}

${TYPE/ChoiceDescription/3}

${TYPE/ChoiceDescription/4}

${TYPE/ChoiceDescription/5}

${TYPE/ChoiceDescription/6}

${TYPE/ChoiceDescription/8}

${TYPE/ChoiceDescription/7}

${TYPE/ChoiceDescription/9}

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Profit OR savings per kg recyclable input consumed"**. This criterion indicates the profit made by a recycler company in selling the recycled EOL post-consumer waste, or saving smade by manufacturer when substituting virgin materials with recycled materials. A company that is having higher profit per unit waste implies more value had been added to the waste consumed, thus maximising the value of the waste.

Data required:
Profit made in selling recycled EOL tyre, savings made when recycled materials are used, total amount of recyclable materials consumed

Unit:
$ per kg recyclable input

Aspiration:
indicates **low** profit or savings,means **worst** CE performance
indicates **high** profit or savings, means **better** CE performance

(please rate the alternatives using the 7 point- Likert scale)

${TYPE/ChoiceDescription/1}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/2}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/3}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/4}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/5}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/6}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/8}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/7}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/9}	☆	☆	☆	☆	☆	☆	☆

Page Break

Instruction:

Please rate the recycling alternatives according to the **"Fraction of energy generated using renewable resources"**. This criterion indicates the energy generated within the company on-site and not purchased from energy providers. Generation of energy onsite negate the need to purchase energy from power stations that usually rely on non-renewable resources such as coal, fossil fuels, uranium, etc. Generation of energy using renewable energy sources such as solar, wind, tidal, biomass, etc is much better than generation of energy using non-renewable energy resources. A true circular economy harvests raw material only from the waste stream, and uses only renewable energy (purchased or generated on-site) in all operational and logistical activities.

Data required:

Energy generated using renewable resources, Energy generated using non-renewable resources

Unit:

% (Joule per Joule)

Aspiration:

indicates **low** energy generated using renewable resources, means **worst** CE performance

indicates **high e**nergy generated using renewable resources, means **better** CE performance

(please rate the alternatives using the 7 point- Likert scale)

${TYPE/ChoiceDescription/1} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/2} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/3} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/4} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/5} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/6} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/8} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/7} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/9} ☆ ☆ ☆ ☆ ☆ ☆ ☆

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Fraction of energy loss"**. This criterion indicates the energy loss in operation such as energy dissipated in unit operation or energy loss in buildings. Lower energy loss in a company indicate efficient use of the energy resources. A supply chain in circular economy will have negligible energy leakage to the surroundings.

Data required:
Energy input, Energy actually consumed

Unit:
% (Joule per joule)

Aspiration:
indicates **low** energy loss, means **better** CE performance
indicates **high** energy loss, means **worst** CE performance

(please rate the alternatives using the 7 point- Likert scale)

${TYPE/ChoiceDescription/1}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/2}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/3}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/4}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/5}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/6}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/8}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/7}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/9}	☆	☆	☆	☆	☆	☆	☆

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Fraction of energy purchased from renewable resources"**. This criterion indicates the amount of energy utilised in the company that is obtained from renewable energy sources such as solar, wind, tidal, biomass, etc. Higher utilisation of renewable energy negate the needs to fire up costly and polluting power stations and reduce reliance on non-renewable resources such as coal, fossil fuels, uranium, etc. A true circular economy harvests raw material only from the waste streams and uses only renewable energy in all operational and logistical activities.

Data required:
Energy purchased from renewable resources, Energy purchased from non-renewable resources.

Unit:
% (joule per joule)

Aspiration:
indicates **low** fraction of energy purchased from renewable resources, means **worst** CE performance
indicates **high** fraction of energy purchased from renewable resources, means **better** CE performance

(please rate the alternatives using the 7 point- Likert scale)
${TYPE/ChoiceDescription/1} ☆ ☆ ☆ ☆ ☆ ☆ ☆
${TYPE/ChoiceDescription/2} ☆ ☆ ☆ ☆ ☆ ☆ ☆
${TYPE/ChoiceDescription/3} ☆ ☆ ☆ ☆ ☆ ☆ ☆
${TYPE/ChoiceDescription/4} ☆ ☆ ☆ ☆ ☆ ☆ ☆
${TYPE/ChoiceDescription/5} ☆ ☆ ☆ ☆ ☆ ☆ ☆
${TYPE/ChoiceDescription/6} ☆ ☆ ☆ ☆ ☆ ☆ ☆
${TYPE/ChoiceDescription/8} ☆ ☆ ☆ ☆ ☆ ☆ ☆
${TYPE/ChoiceDescription/7} ☆ ☆ ☆ ☆ ☆ ☆ ☆
${TYPE/ChoiceDescription/9} ☆ ☆ ☆ ☆ ☆ ☆ ☆

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Total GHG produced per kg product"**. This criterion indicates the overall impact imparted on to the environment by the processes carried out in the company. Carbon footprint, which measure greenhouse gas (GHG) is one of the widely used environmental indicator. GHG includes carbon dioxide and methane, which cause global warming leading to extinction of animal species and climate changes. Lower environmental impact ensures sound human health and environment wellbeing. A supply chain in the true circular economy will impart negligible environmental impact to the surroundings.

Data required:
Amount of GHG produced in production and logistics, amount of product produced.

Unit:
Tonne per kg product manufactured

Aspiration:
indicates **low** total GHG produced, means **better** CE performance
indicates **high** high GHG produced, means **worst** CE performance

(please rate the alternatives using the 7 point- Likert scale)

${TYPE/ChoiceDescription/1}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/2}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/3}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/4}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/5}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/6}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/8}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/7}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/9}	☆	☆	☆	☆	☆	☆	☆

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Total energy consumed per kg product"**. This criterion indicates the total energy required to manufacture a unit (kg) of product. A high energy required to produce a product, can be used as proxy indicator to show the low efficiency production process or poorly designed production technology, which should be improved such that the energy consumption is lowered.

Data required:
Total energy consumed, Total amount of product produced

Unit:
Joule per kg product manufactured

Aspiration:
indicates **low** energy consumption, means **better** CE performance
indicates **high** energy consumption, means **worst** CE performance

(*please rate the alternatives using the 7 point- Likert scale*)

${TYPE/ChoiceDescription/1}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/2}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/3}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/4}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/5}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/6}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/8}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/7}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/9}	☆	☆	☆	☆	☆	☆	☆

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Total energy generated per kg product"**. This criterion indicates the energy generated within the company on-site and not purchased from energy providers. A supply chain in true circular economy would generate its own energy on-site to be used in all operational and logistical activities.

Data required:
Total energy generated on-site, Total amount of porduct produced

Unit:
Joule per kg product manufactured

Aspiration:
indicates **low** energy generated,means **worst** CE performance
indicates **high** energy generated, means **better** CE performance

(*please rate the alternatives using the 7 point- Likert scale*)
${TYPE/ChoiceDescription/1}
${TYPE/ChoiceDescription/2}
${TYPE/ChoiceDescription/3}
${TYPE/ChoiceDescription/4}
${TYPE/ChoiceDescription/5}
${TYPE/ChoiceDescription/6}
${TYPE/ChoiceDescription/8}
${TYPE/ChoiceDescription/7}
${TYPE/ChoiceDescription/9}

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Fraction of recycler output to original supply chain"**. This criterion indicates the fraction of recycler output that is being fed into original supply chain (upcycling) instead of foreign supply chain (downcycling). It is often thought that the quality of the waste is best preserved when it is being recycled into original supply chain, while it deteriorates when recycled into foreign supply chain.

Data required:
Total amount of recycler output, Amount of recycler output fed into original supply chain.

Unit:
% (kg per kg)

Aspiration:
indicates **low** fraction to original supply chain, means **worst** CE performance
indicates **high** fraction to original supply chain, means **better** CE performance

(please rate the alternatives using the 7 point- Likert scale)

${TYPE/ChoiceDescription/1} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/2} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/3} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/4} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/5} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/6} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/8} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/7} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/9} ☆ ☆ ☆ ☆ ☆ ☆ ☆

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Fraction of recycled material used per kg product"**. This criterion indicates the fraction of product constitute of recycled material. A manufacturing company who utilise more recycled materials in the manufacturing of its product are deemed to align more closely to circular economy, by cutting down virgin resources consumption and promoting re-utilisation of waste as substitute of the virgin resources.

Data required:
Amount of recycled material used to manufacture a unit product, Amount of virgin material used to manufacture a unit product.

Unit:
% (kg per kg)

Aspiration:
indicates **low** fraction of recycled materials used,means **worst** CE performance
indicates **high** fraction of recycled materials used, means **better** CE performance

(please rate the alternatives using the 7 point- Likert scale)

${TYPE/ChoiceDescription/1} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/2} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/3} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/4} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/5} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/6} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/8} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/7} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/9} ☆ ☆ ☆ ☆ ☆ ☆ ☆

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Fraction of waste recycled internally "**. This criterion indicates the amount of waste water and solid waste that are generated in the company and being recycled internally. Higher amount of waste water and solid waste recycled internally indicate the tendency of the company to embrace circular economy, by retaining the waste created and re-utilising it.

Data required:
Amount of waste water recycled internally, Amount of waste solid recycled internally, Amount of waste water produced, Amount of waste solid produced.

Unit:
% (kg per kg)

Aspiration:
indicates **low** fraction of waste recycled internally, means **worst** CE performance
indicates **high** fraction of waste recycled internally, means **better** CE performance

(please rate the alternatives using the 7 point- Likert scale)

${TYPE/ChoiceDescription/1} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/2} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/3} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/4} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/5} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/6} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/8} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/7} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/9} ☆ ☆ ☆ ☆ ☆ ☆ ☆

Page Break

Instruction:

Please rate the recycling alternatives according to the **"Total weight of unrecoverable waste per kg product"**.This criterion indicates the weight of waste including solid, liquid and gas that are not being recovered and emitted to surrounding landfill, sewer and air. A high value of unrecoverable waste emitted signifies the inefficiency of a company in utilising its material resources and unmotivated in reutilising the waste as resources. A company in the circular economy must minimise its emission leakage as much as possible, by transforming waste into either technical or biological nutrient that can be returned to the surroundings.

Data required:

Amount of solid waste, amount of liquid waste, Amount of gaseous waste.

Unit:

Tonne per kg product manufactured

Aspiration:

indicates **low** weight of unrecoverable waste, means **better** CE performance
indicates **high** weight of unrecoverable waste, means **worst** CE performance

(please rate the alternatives using the 7 point- Likert scale)

${TYPE/ChoiceDescription/1}

${TYPE/ChoiceDescription/2}

${TYPE/ChoiceDescription/3}

${TYPE/ChoiceDescription/4}

${TYPE/ChoiceDescription/5}

${TYPE/ChoiceDescription/6}

${TYPE/ChoiceDescription/8}

${TYPE/ChoiceDescription/7}

${TYPE/ChoiceDescription/9}

Page Break

Instruction:

Please rate the recycling alternatives according to the **"Lifetime of product"**.This criterion indicates the expected life time of a product until it reaches its end-of-life. A longer lifetime indicates the product would remain in the consumption cycle for a longer time, retaining its value as well as reducing the demand for new resources required to manufacture a new product to replace that product.

Data required:

Lifetime of product

Unit:

Year per unit

Aspiration:

indicates **short** lifetime,means **worst** CE performance

indicates **long** lifetime, means **better** CE performance

(*please rate the alternatives using the 7 point- Likert scale*)

${TYPE/ChoiceDescription/1} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/2} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/3} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/4} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/5} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/6} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/8} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/7} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/9} ☆ ☆ ☆ ☆ ☆ ☆ ☆

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Time to reach CE goal"**. This criterion indicates the time planned to reach any CE goal, for example time planned to reach 90% recycling rate of waste water etc. Time to reach CE goal can be used as proxy indicator to show the commitment of a company to participate in CE or invest in CE technology, which could drastically shorten the time to reach CE goal.

Data required:
Time planned to reach any CE goal.

Unit:
Year

Aspiration:
indicates **short** time to reach CE goal, means **better** CE performance
indicates **long** time to reach CE goal, means **worst** CE performance

(please rate the alternatives using the 7 point- Likert scale)

${TYPE/ChoiceDescription/1}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/2}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/3}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/4}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/5}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/6}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/8}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/7}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/9}	☆	☆	☆	☆	☆	☆	☆

Page Break

Instruction:

Please rate the recycling alternatives according to the **"Collection efficiency"**. This criterion indicates the efficiency of process in collecting EOL post-consumer products (for instance if a coating needs to be removed from a material before recycling then there will be a mass loss and waste generation). Higher efficiency implies more materials are retained in the consumption cycle and will not be discarded as waste.

Data required:

Waste discarded when handling input EOL, Amount of input EOL

Unit:

% (kg per kg)

Aspiration:

indicates **low** collection efficiency, means **worst** CE performance

indicates **high** collection efficiency, means **better** CE performance

(*please rate the alternatives using the 7 point- Likert scale*)

${TYPE/ChoiceDescription/1}

${TYPE/ChoiceDescription/2}

${TYPE/ChoiceDescription/3}

${TYPE/ChoiceDescription/4}

${TYPE/ChoiceDescription/5}

${TYPE/ChoiceDescription/6}

${TYPE/ChoiceDescription/8}

${TYPE/ChoiceDescription/7}

${TYPE/ChoiceDescription/9}

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Modularity of product design"**. This criterion indicates the extent of modularity of product, where higher modularity improves the possibility of the product to be upgraded and refurbished, replacing any worn parts. High modularity also ensures the product can be easily disassemble at EOL, so that it can be easily broken down into its constituent components and to be reuse or recycled, reducing disassembly time.

Data required:
Modularity of product design

Unit:
%

Aspiration:
indicates **low** modularity, means **worst** CE performance
indicates **high** modularity, means **better** CE performance

(please rate the alternatives using the 7 point- Likert scale)

${TYPE/ChoiceDescription/1}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/2}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/3}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/4}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/5}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/6}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/8}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/7}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/9}	☆	☆	☆	☆	☆	☆	☆

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Recyclability"**. This criterion indicates the fraction of the product that is recyclable. Not all parts of the product are recyclable. Higher percentage of recyclability implies more parts in the product can be recycled, and can be retained in the consumption cycle and not be discarded as waste.

Data required:
Weight of parts that can be recycled, Total weight of product.

Unit:
% (kg per kg)

Aspiration:
indicates **low** recyclability, means **worst** CE performance
indicates **high** recyclability, means **better** CE performance

(please rate the alternatives using the 7 point- Likert scale)

${TYPE/ChoiceDescription/1}

${TYPE/ChoiceDescription/2}

${TYPE/ChoiceDescription/3}

${TYPE/ChoiceDescription/4}

${TYPE/ChoiceDescription/5}

${TYPE/ChoiceDescription/6}

${TYPE/ChoiceDescription/8}

${TYPE/ChoiceDescription/7}

${TYPE/ChoiceDescription/9}

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Recycling efficiency"**. This criterion indicates the efficiency of recycler to recycle the end-of-life post-consumer products. Higher recycling efficiency implies more end-of-life products are successfully recycled and will be retained in the consumption cycle and less material will be discarded as waste.

Data required:
Waste of recycler input, Waste of recycler output

Unit:
% (kg per kg)

Aspiration:
indicates **low** recycling efficiency,means **worst** CE performance
indicates **high** recycling efficiency, means **better** CE performance

(please rate the alternatives using the 7 point- Likert scale)

${TYPE/ChoiceDescription/1}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/2}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/3}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/4}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/5}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/6}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/8}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/7}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/9}	☆	☆	☆	☆	☆	☆	☆

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Rental-ability"**. This criterion indicates the ability of the product to be rented or leased to another consumers by consumer during its use phase, to increase its usage so that its uses can be maximised, at the same time reduce the needs of a consumer to own a product, thus decreasing the demand for more virgin resources to manufacture more products. Option to rent a product to consumers by a manufacturer also change the ownership of the product to the manufacturer, thus ensuring that the end-of-life post-consumer products will be returned back to the manufacturer and be treated accordingly.

Data required:
Rentability (Yes or No)

Unit:
Null

Aspiration:
indicates product **cannot** be rented, means **worst** CE performance
indicates product **can** be rented, means **better** CE performance

(please rate the alternatives using the 7 point- Likert scale)
${TYPE/ChoiceDescription/1}

${TYPE/ChoiceDescription/2}

${TYPE/ChoiceDescription/3}

${TYPE/ChoiceDescription/4}

${TYPE/ChoiceDescription/5}

${TYPE/ChoiceDescription/6}

${TYPE/ChoiceDescription/8}

${TYPE/ChoiceDescription/7}

${TYPE/ChoiceDescription/9}

Page Break

Sus Part 2b: You are required to rate the recycling alternatives under **sustainability** criteria using 7-point Likert scale as below:

Rating	Implication
1	Very Low
2	Low
3	Medium Low
4	Medium
5	Medium High
6	High
7	Very High

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Operational cost"**. This criterion indicates the money spent to sustain daily operation, such as cost to purchase raw material, energy, water, logistics and maintenance. Operational cost, as one of the key components in economical sustainability, must be considered along with environmental and societal aspect to ensure financial viability and feasibility of a business.

Data required:
Cost of all operations required to manufacture a unit kg product, amount of product manufactured

Unit:
$ per kg product manufactured

Aspiration:
indicates **low** operational cost, means **better** sustainability performance
indicates **high** operational cost, means **worst** sustainability performance

(*please rate the alternatives using the 7 point- Likert scale*)

${TYPE/ChoiceDescription/1} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/2} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/3} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/4} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/5} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/6} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/8} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/7} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/9} ☆ ☆ ☆ ☆ ☆ ☆ ☆

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Capital cost"**. This criterion indicates the overhead cost spent on equipment, land and setup of company or plants. Capital cost, as one of the key components in economical sustainability, must be considered along with environmental and societal aspect to ensure financial viability and feasibility of a business.

Data required:
Cost spent on equipment, land and setup of company or plants, amount of product manufactured

Unit:
$ per kg product manufactured

Aspiration:
indicates **low** capital cost, means **better** sustainability performance
indicates **high** capital cost, means **worst** sustainability performance

(please rate the alternatives using the 7 point- Likert scale)

${TYPE/ChoiceDescription/1}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/2}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/3}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/4}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/5}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/6}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/8}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/7}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/9}	☆	☆	☆	☆	☆	☆	☆

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Net profit"**. This criterion indicates the profit made after considering the sales, subsidies deducting all the costs. Net profit, as one of the key components in economical sustainability, must be considered along with environmental and societal aspect to ensure financial viability and feasibility of a business.

Data required:
Net profit, amount of product manufactured

Unit:
$ per kg product manufactured

Aspiration:
indicates **low** net profit, means **worst** sustainability performance
indicates **high** net profit, means **better** sustainability performance

(*please rate the alternatives using the 7 point- Likert scale*)
${TYPE/ChoiceDescription/1} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/2} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/3} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/4} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/5} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/6} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/8} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/7} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/9} ☆ ☆ ☆ ☆ ☆ ☆ ☆

Page Break

Instruction:

Please rate the recycling alternatives according to the **"Gas emmision"**. This criterion indicates the gaseous waste such as greenhouse gas (GHG), ozone depletant and PM10. GHG includes carbon dioxide and methane, which cause global warming leading to extinction of animal species and climate changes. Ozone depletants such as chloro-fluro-carbon which damages the ozone layer and causes over-exposure of UV rays that would be detrimental to human health. Particulate matter (PM) less than 10 micron emitted along with gaseous waste will pollute the air and causes respiratory tract problems. Lower gaseous emission ensures sound human health and environment wellbeing.

Data required:

GHG emmision, amount of product manufactured

Unit:

tonne per kg product manufactured

Aspiration:

indicates **low** gas emmision, means **better** sustainability performance

indicates **high** gas emmision, means **worst** sustainability performance

(please rate the alternatives using the 7 point- Likert scale)

${TYPE/ChoiceDescription/1}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/2}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/3}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/4}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/5}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/6}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/8}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/7}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/9}	☆	☆	☆	☆	☆	☆	☆

Page Break

Instruction:

Please rate the recycling alternatives according to the **"Resources consumption"**. This criterion indicates the resources such as water, energy, materials and land consumed by the business. Over-consumption of resources surpassing the regeneration rate causes scarcity of resources and supply risks, which leads to escalating price of commodities. Over consumption of certain resources such as land could also cause land erosion, over consumption of energy, water and raw materials worsen climate change and increases air pollution. Low resources consumption ensures sound human health and environment wellbeing.

Data required:

weight of water+ energy+ materials+ land consumed, amount of product manufactured

Unit:

tonne per kg product manufactured

Aspiration:

indicates **low** resources consumption, means **better** sustainability performance
indicates **high** resources consumption, means **worst** sustainability performance

(please rate the alternatives using the 7 point- Likert scale)

${TYPE/ChoiceDescription/1}

${TYPE/ChoiceDescription/2}

${TYPE/ChoiceDescription/3}

${TYPE/ChoiceDescription/4}

${TYPE/ChoiceDescription/5}

${TYPE/ChoiceDescription/6}

${TYPE/ChoiceDescription/8}

${TYPE/ChoiceDescription/7}

${TYPE/ChoiceDescription/9}

Page Break

Instruction:

Please rate the recycling alternatives according to the **"Acidification and eutrophication potential"**. This criterion indicates the extent of gaseous emission in the supply chain activities that would cause water, air and soil acidification, which will destroy aquatic food chains and cause land infertility, eventually reducing food supply. Eutrophication causes algae blooming, which disrupt the natural habitat of lake and causes extinction of aquatic animal in the affected lake. Low acidification and eutrophication potential ensure sound human health and environment wellbeing.

Data required:

Acidic gas emmision potential

Unit:

% acidity

Aspiration:

indicates **low** acidification and eutrophication potential, means **better** sustainability performance

indicates **high** acidification and eutrophication potential, means **worst** sustainability performance

(please rate the alternatives using the 7 point- Likert scale)

${TYPE/ChoiceDescription/1}

${TYPE/ChoiceDescription/2}

${TYPE/ChoiceDescription/3}

${TYPE/ChoiceDescription/4}

${TYPE/ChoiceDescription/5}

${TYPE/ChoiceDescription/6}

${TYPE/ChoiceDescription/8}

${TYPE/ChoiceDescription/7}

${TYPE/ChoiceDescription/9}

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Renewable energy generation"**. This criterion indicates a business moves away from utilising energy generated from limited resources such as fossil fuel which causes severe air pollution to using renewable energy generated from unlimited resources such as wind, water and solar with smaller environmental impact. Renewable energy generation serve as indicator demonstrating the potential of a company in supply chain to tackle environmental issue.

Data required:
Energy generated from renewable resources, amount of product manufactured

Unit:
joule per kg product manufactured

Aspiration:
indicates **low** renewable energy generation, means **worst** sustainability performance
indicates **high** renewable energy generation, means **better** sustainability performance

(please rate the alternatives using the 7 point- Likert scale)

${TYPE/ChoiceDescription/1}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/2}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/3}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/4}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/5}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/6}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/8}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/7}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/9}	☆	☆	☆	☆	☆	☆	☆

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Job creation"**. This criterion indicates the number of jobs created by the establishment of the system. Higher number of job creation will minimise unemployment rate, thus minimise unfavourable social condition such as homelessness, robbery and high crime rate.

Data required:
Number of jobs created, amount of product manufactured

Unit:
jobs per kg product manufactured

Aspiration:
indicates **low** number of jobs created, means **worst** sustainability performance
indicates **high** number of jobs created, means **better** sustainability performance

(*please rate the alternatives using the 7 point- Likert scale*)

${TYPE/ChoiceDescription/1} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/2} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/3} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/4} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/5} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/6} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/8} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/7} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/9} ☆ ☆ ☆ ☆ ☆ ☆ ☆

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Working hours and wages"**. This criterion indicates the working-hours required to sustain the business, considering the minimum wage in the country and average wage in the sector. Higher wages imply a good social conditioning.

Data required:
Average wages

Unit:
$ per hour

Aspiration:
indicates **low** working hours and wages,means **worst** sustainability performance
indicates **high** working hours and wages, means **better** sustainability performance

(*please rate the alternatives using the 7 point- Likert scale*)

${TYPE/ChoiceDescription/1}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/2}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/3}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/4}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/5}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/6}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/8}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/7}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/9}	☆	☆	☆	☆	☆	☆	☆

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Workers health and safety"**.This criterion is measured using the frequency of injuries or sick leaves taken by employees to reflect the health and safety standard in a working environment. Low frequency of injuries and sick leaves implies a safe working environment.

Data required:
Frequency of injuries, frequency of sick leaves

Unit:
Number per year

Aspiration:
indicates **low** frequency of health and safety issue, means **better** sustainability performance
indicates **high** frequency of health and safety issue, means **worst** sustainability performance

(please rate the alternatives using the 7 point- Likert scale)

${TYPE/ChoiceDescription/1} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/2} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/3} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/4} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/5} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/6} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/8} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/7} ☆ ☆ ☆ ☆ ☆ ☆ ☆

${TYPE/ChoiceDescription/9} ☆ ☆ ☆ ☆ ☆ ☆ ☆

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Child labor"**.This criterion includes forced labour and debt bondage (to pay off debts incurred by parents). Employing child labour can be dangerous and harmful to the child and can violate the child's freedom and human rights. A socially sustainable business should decouple from the unethical practice of employing child labour.

Data required:
Number of child labor, amount of product manufactured

Unit:
Number per kg product manufactured

Aspiration:
indicates **low** number of child labor, means **better** sustainability performance
indicates **high** number of child labor, means **worst** sustainability performance

(please rate the alternatives using the 7 point- Likert scale)

${TYPE/ChoiceDescription/1}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/2}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/3}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/4}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/5}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/6}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/8}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/7}	☆	☆	☆	☆	☆	☆	☆
${TYPE/ChoiceDescription/9}	☆	☆	☆	☆	☆	☆	☆

Page Break

Instruction:
Please rate the recycling alternatives according to the **"Local citizen participation"**.This criterion indicates the involvement and support of local citizen in the business' projects, such as attending town hall meetings and be involved with community-led projects. Ideally, the local citizen will understand and support the business and not obstructing the siting of the company based on perception of noise, hygiene, safety, handling, transport and land space requirements.

Data required:
Participation (Yes or No)

Unit:
Null

Aspiration:
indicates **No** participation,means **worst** sustainability performance
indicates **presence** of participation, means **better** sustainability performance

(please rate the alternatives using the 7 point- Likert scale)
${TYPE/ChoiceDescription/1}

${TYPE/ChoiceDescription/2}

${TYPE/ChoiceDescription/3}

${TYPE/ChoiceDescription/4}

${TYPE/ChoiceDescription/5}

${TYPE/ChoiceDescription/6}

${TYPE/ChoiceDescription/8}

${TYPE/ChoiceDescription/7}

${TYPE/ChoiceDescription/9}

Page Break

end Thankyou for your time in providing information for this research. For further information or if you have any queries, please contact the lead researcher Mr. Sir Yee Lee - email: lees116@uni.coventry.ac.uk. If you have any concerns that cannot be resolved through the lead researcher, please contact Jiayao Hu - email: ac5218@coventry.ac.uk. Thank you for taking the time to participate in this survey. Your help is very much appreciated.

End of Block: Default Question Block

Appendix D (NSGA-II code for Phase 3)

```
clc;
clear;
close all;

%% Problem Definition

CostFunction=@(x) MOP(x);      % Cost Function

nVar=5;             % Number of Decision Variables

VarSize=[1 nVar];   % Size of Decision Variables Matrix

VarMin=-0;          % Lower Bound of Variables
VarMax= 278000;         % Upper Bound of Variables

% Number of Objective Functions
nObj=numel(CostFunction(unifrnd(VarMin,VarMax,VarSize)));


%% NSGA-II Parameters

MaxIt=100;      % Maximum Number of Iterations

nPop=50;        % Population Size

pCrossover=0.7;                         % Crossover Percentage
nCrossover=2*round(pCrossover*nPop/2);  % Number of Parents (Offsprings)

pMutation=0.4;                          % Mutation Percentage
nMutation=round(pMutation*nPop);        % Number of Mutants

mu=0.02;                    % Mutation Rate

sigma=0.1*(VarMax-VarMin);  % Mutation Step Size


%% Initialization

empty_individual.Position=[];
empty_individual.Cost=[];
empty_individual.Rank=[];
empty_individual.DominationSet=[];
empty_individual.DominatedCount=[];
empty_individual.CrowdingDistance=[];

pop=repmat(empty_individual,nPop,1);

for i=1:nPop

    pop(i).Position=unifrnd(VarMin,VarMax,VarSize);

    pop(i).Cost=CostFunction(pop(i).Position);

end
```

```
% Non-Dominated Sorting
[pop, F]=NonDominatedSorting(pop);

% Calculate Crowding Distance
pop=CalcCrowdingDistance(pop,F);

% Sort Population
[pop, F]=SortPopulation(pop);


%% NSGA-II Main Loop

for it=1:MaxIt

    % Crossover
    popc=repmat(empty_individual,nCrossover/2,2);
    for k=1:nCrossover/2

        i1=randi([1 nPop]);
        p1=pop(i1);

        i2=randi([1 nPop]);
        p2=pop(i2);

        [popc(k,1).Position, popc(k,2).Position]=Crossover(p1.Position,p2.Position);

        popc(k,1).Cost=CostFunction(popc(k,1).Position);
        popc(k,2).Cost=CostFunction(popc(k,2).Position);

    end
    popc=popc(:);

    % Mutation
    popm=repmat(empty_individual,nMutation,1);
    for k=1:nMutation

        i=randi([1 nPop]);
        p=pop(i);

        popm(k).Position=Mutate(p.Position,mu,sigma);

        popm(k).Cost=CostFunction(popm(k).Position);

    end

    % Merge
    pop=[pop
         popc
         popm]; %#ok

    % Non-Dominated Sorting
    [pop, F]=NonDominatedSorting(pop);
```

```
    % Calculate Crowding Distance
    pop=CalcCrowdingDistance(pop,F);

    % Sort Population
    pop=SortPopulation(pop);

    % Truncate
    pop=pop(1:nPop);

    % Non-Dominated Sorting
    [pop, F]=NonDominatedSorting(pop);

    % Calculate Crowding Distance
    pop=CalcCrowdingDistance(pop,F);

    % Sort Population
    [pop, F]=SortPopulation(pop);

    % Store F1
    F1=pop(F{1});

    % Show Iteration Information
    disp(['Iteration ' num2str(it) ': Number of F1 Members = ' num2str(numel(F1))]);

    % Plot F1 Costs
    figure(1);
    PlotCosts(F1);
    pause(0.01);

end

%% Results
```

function pop=CalcCrowdingDistance(pop,F)

```
    nF=numel(F);

    for k=1:nF

        Costs=[pop(F{k}).Cost];

        nObj=size(Costs,1);

        n=numel(F{k});

        d=zeros(n,nObj);

        for j=1:nObj

            [cj, so]=sort(Costs(j,:));

            d(so(1),j)=inf;
```

```
        for i=2:n-1

            d(so(i),j)=abs(cj(i+1)-cj(i-1))/abs(cj(1)-cj(end));

        end

        d(so(end),j)=inf;

    end


    for i=1:n

        pop(F{k}(i)).CrowdingDistance=sum(d(i,:));

    end

end


end
```

function [y1, y2]=Crossover(x1,x2)

```
    alpha=rand(size(x1));

    y1=alpha.*x1+(1-alpha).*x2;
    y2=alpha.*x2+(1-alpha).*x1;

end
```

function b=Dominates(x,y)

```
    if isstruct(x)
        x=x.Cost;
    end

    if isstruct(y)
        y=y.Cost;
    end

    b=all(x<=y) && any(x<y);

end
```

function z=MOP(x)

```
z1= 0.2966*X(1)+0.2614*X(2)+0.1977*X(3)+0.0982*X(4)+0.1461*X(5)
z2= 0.2026*X(1)+0.2413*X(2)+0.2816*X(3)+0.1372*X(4)+0.1372*X(5)
```

```
            c(1,1) =x(1)-369603;
            c(1,2)=-x(2)-369603;
            c(1,3)=-x(3)-369603;
            c(1,4)=-x(4)-326000;
            c(1,5)=-x(5)-9000;
            c(1,6)=-x(1)+x(2)+x(3)+x(4)+x(5)-278000;
            err=(c>0).*c;

    z=[z1 z2]';

end
```

function y=Mutate(x,mu,sigma)

```
    nVar=numel(x);

    nMu=ceil(mu*nVar);

    j=randsample(nVar,nMu);
    if numel(sigma)>1
        sigma = sigma(j);
    end

    y=x;

    y(j)=x(j)+sigma.*randn(size(j));

end
```

function [pop, F]=NonDominatedSorting(pop)

```
    nPop=numel(pop);

    for i=1:nPop
        pop(i).DominationSet=[];
        pop(i).DominatedCount=0;
    end

    F{1}=[];

    for i=1:nPop
        for j=i+1:nPop
            p=pop(i);
            q=pop(j);

            if Dominates(p,q)
                p.DominationSet=[p.DominationSet j];
                q.DominatedCount=q.DominatedCount+1;
            end

            if Dominates(q.Cost,p.Cost)
                q.DominationSet=[q.DominationSet i];
```

```
            p.DominatedCount=p.DominatedCount+1;
        end

        pop(i)=p;
        pop(j)=q;
    end

    if pop(i).DominatedCount==0
        F{1}=[F{1} i];
        pop(i).Rank=1;
    end
end

k=1;

while true

    Q=[];

    for i=F{k}
        p=pop(i);

        for j=p.DominationSet
            q=pop(j);

            q.DominatedCount=q.DominatedCount-1;

            if q.DominatedCount==0
                Q=[Q j]; %#ok
                q.Rank=k+1;
            end

            pop(j)=q;
        end
    end

    if isempty(Q)
        break;
    end

    F{k+1}=Q; %#ok

    k=k+1;

end


end
```

function PlotCosts(pop)

```
    Costs=[pop.Cost];
```

```
    plot(Costs(1,:),Costs(2,:),'r*','MarkerSize',8);
    xlabel('1^{st} Objective');
    ylabel('2^{nd} Objective');
    title('Non-dominated Solutions (F_{1})');
    grid on;

end
```

function [pop, F]=SortPopulation(pop)

```
    % Sort Based on Crowding Distance
    [~, CDSO]=sort([pop.CrowdingDistance],'descend');
    pop=pop(CDSO);

    % Sort Based on Rank
    [~, RSO]=sort([pop.Rank]);
    pop=pop(RSO);

    % Update Fronts
    Ranks=[pop.Rank];
    MaxRank=max(Ranks);
    F=cell(MaxRank,1);
    for r=1:MaxRank
        F{r}=find(Ranks==r);
    end

end
```

Appendix E (Interview protocol for phase 4)

Opening script (consent forms have been collected prior to starting the opening script).

Thank you for meeting with me today! The purpose of this interview is to explore the discrepancies between the modelling results and the actual business. This includes identifying the barriers that obstruct the company from the attempt towards achieving the optimum result shown in the modelling and the enablers that would improve this situation.

As a participant in this study, I consider you to be an expert on this topic and would like to understand your thoughts in regard to the questions I am going to ask. I will be recording this interview with this device (shows the recorder). After our interview is over, I will make a transcript of what you said, but I will replace your name, as well as those of anyone you mention and any places you mention, so that nothing can be traced. I will be the only one who has access to this data and will keep it locked away and safe until it is time to erase the data entirely.

If you want to stop participating in this interview or not respond to any specific questions for any reason, you may do so any time. Before we begin, do you have any questions? [Answers any question until the participants are satisfied and ready to begin].

This interview is expected to take about 60 minutes. Are you willing to start the interview and be recorded right now? [Wait for responses and begin recording]. Okay, I've started the recording. Can you affirm, for the recording, that you understand and assent to having your words to be recorded in this interview? [Wait for responses]. Thank you! Let's begin with the first question.

Table 1: Interview questions.

<table>
<tr><th>Questions</th><th>Rationale</th><th>Probes/ Follow-up questions</th></tr>
<tr><td>1) Can you please share your organisation background with me?</td><td>Ice-breaker and collection of general information about the company.</td><td rowspan="9">1. You mentioned [prior statement]. Can you please elaborate further?
2. I was interested in what you said about [prior statement]. Can you please tell me a specific story from that experience that illustrates this point?
3. How so/In what way?
4. What do you mean?</td></tr>
<tr><td>2) Can you please share with me the contextual situation in ELT recycling industry? What are the main drivers behind the recycling alternative selection?</td><td rowspan="8">To answer research question 4 in identifying barriers towards application of model output. These questions seek to explain the discrepancies between the modelling results and the actual business. This is critical as it does not only outline the possible hindrance towards accepting circularity practices, but also disclose the drivers that will motivate circularity and sustainable practices in the ELT recycling industry.</td></tr>
<tr><td>3) What are the practical criteria and measurements used in guiding the recycling outlet selection?</td></tr>
<tr><td>4) Why A4- Tyre-to-cement is currently selected over other recycling outlets as a major outlet?</td></tr>
<tr><td>5) What could be the reasons that stop you from applying the solution provided by the model?</td></tr>
<tr><td>6) What are the key challenges to take sustainability & CE indicators in outlet selection?</td></tr>
<tr><td>7) Can you please share with me your company’s attitude towards circularity and sustainability?</td></tr>
<tr><td>8) A1- Tyre-to-synthetic turf and A3- Tyre-to-moulded objects seem to be the best choice in terms of CE and sustainability, why are they not being selected as major recycling outlets?</td></tr>
<tr><td>9) What are the potential techniques to overcome the barriers?</td></tr>
</table>

Closing script:

That concludes our time. Thank you all for your participation in this interview! The results will help us to understand more about the barriers as well as enablers that would promote circular and sustainable practices in the ELT recycling industry. [Preview any other tasks that the participant will be asked to do]. Do you have any questions for me before you go? Thank you very much! This research will not be possible without your participation!

Appendix F (Questionnaire result from phase 1 pertaining to circularity dimension)

Table 1: Relative importance of each dimension within CE criteria for DM 1

DM 1	C_1	C_2	C_3	C_4	C_5
C_1	1	7	5	7	3
C_2	1/7	1	1/7	7	1/9
C_3	1/5	1/5	1	7	5
C_4	1/7	1/7	1/7	1	1/7
C_5	1/3	9	1/5	7	1

Table 2: Relative importance of each dimension within CE criteria for DM 2.

DM 2	C_1	C_2	C_3	C_4	C_5
C_1	1	1/7	1/9	5	5
C_2	7	1	7	7	7
C_3	9	9	1	7	7
C_4	1/5	1/7	1/7	1	1/7
C_5	1/5	1/7	1/7	7	1

Table 3:: Relative importance of each dimension within CE criteria for DM 3.

DM 3	C_1	C_2	C_3	C_4	C_5
C_1	1	1/5	5	5	1/5
C_2	5	1	5	7	7
C_3	1/5	1/5	1	1/5	1/7
C_4	1/5	1/7	5	1	1
C_5	5	1/7	7	1	1

Table 4: Relative importance of each dimension within CE criteria for DM 4

DM 4	C_1	C_2	C_3	C_4	C_5
C_1	1	1/5	1/3	1/3	1/5
C_2	5	1	5	5	5
C_3	3	3	1	1/3	1/3
C_4	3	1/5	3	1	1
C_5	5	1/5	3	1	1

Table 5: Relative importance of each dimension within CE criteria for DM 5

DM 5	C_1	C_2	C_3	C_4	C_5
C_1	1	1/7	7	7	1/9
C_2	7	1	7	9	9
C_3	1/7	1/7	1	5	1/7
C_4	1/7	1/9	1/5	1	1/9
C_5	9	1/9	7	9	1

Table 6: Relative importance of each dimension within CE criteria for DM 6

DM 6	C_1	C_2	C_3	C_4	C_5
C_1	1	1/9	1/9	1	1/5
C_2	9	1	1/9	9	1
C_3	9	9	1	9	5
C_4	1	1/9	1/9	1	1/7
C_5	5	1	1/5	7	1

Table 7: Relative importance of each dimension within CE criteria for DM 7

DM 7	C_1	C_2	C_3	C_4	C_5
C_1	1	5	7	7	7
C_2	1/5	1	7	7	1/5
C_3	1/7	1/7	1	1/5	1/5
C_4	1/7	1/7	5	1	1/5
C_5	1/7	5	5	5	1

Table 8: Relative importance of each dimension within CE criteria for DM 8

DM 8	C_1	C_2	C_3	C_4	C_5
C_1	1	7	9	7	3
C_2	1/7	1	1/5	1/5	1/7
C_3	1/9	1/9	1	1/5	1/7
C_4	1/7	5	5	1	1/7
C_5	1/3	7	7	7	1

Table 9: Relative importance of each dimension within CE criteria for DM 9

DM 9	C_1	C_2	C_3	C_4	C_5
C_1	1	1/3	1/3	1/3	1
C_2	3	1	1/5	1/5	5
C_3	3	3	1	1	5
C_4	3	5	1	1	5
C_5	1	1/5	1/5	1/5	1

Table 10: Relative importance of each dimension within CE criteria for DM 10

DM 10	C_1	C_2	C_3	C_4	C_5
C_1	1	7	7	9	5
C_2	1/7	1	1	5	5
C_3	1/7	1/7	1	5	1/3
C_4	1/9	1/5	1/5	1	1/5
C_5	1/5	1/5	3	5	1

Table 11: Relative importance of each dimension within CE criteria for DM 11

DM 11	C_1	C_2	C_3	C_4	C_5
C_1	1	5	5	1/5	1
C_2	1/5	1	5	1/5	1/7
C_3	1/5	1/5	1	7	1/7
C_4	5	5	1/7	1	1/7
C_5	1	7	7	7	1

Table 12:: Relative importance of each dimension within CE criteria for DM 12

DM 12	C_1	C_2	C_3	C_4	C_5
C_1	1	3	3	3	1
C_2	1/3	1	5	5	1
C_3	1/3	1/3	1	3	1/5
C_4	1/3	1/5	1/3	1	1/3
C_5	1	1	5	3	1

Table 13: Relative importance of each dimension within CE criteria for DM 13

DM 13	C_1	C_2	C_3	C_4	C_5
C_1	1	5	3	5	5
C_2	1/5	1	1/3	1/3	1
C_3	1/3	1/3	1	1/3	3
C_4	1/5	3	3	1	5
C_5	1/5	1	1/3	1/5	1

Table 15: Relative importance of each dimension within CE criteria for DM 14

DM 14	C_1	C_2	C_3	C_4	C_5
C_1	1	5	5	5	5
C_2	1/5	1	1	1	1/9
C_3	1/5	1/5	1	1	1/9
C_4	1/5	1	1	1	1/5
C_5	1/5	9	9	5	1

Table 17: Relative importance of each dimension within CE criteria for DM 15

DM 15	C_1	C_2	C_3	C_4	C_5
C_1	1	1	3	5	3
C_2	1	1	5	9	5
C_3	1/3	1/3	1	7	5
C_4	1/5	1/9	1/7	1	1/7
C_5	1/3	1/5	1/5	7	1

Table 14: Relative importance of each dimension within CE criteria for DM 16

DM 16	C_1	C_2	C_3	C_4	C_5
C_1	1	1	1	1	1
C_2	1	1	1/3	3	3
C_3	1	1	1	3	3
C_4	1	1/3	1/3	1	1/3
C_5	1	1/3	1/3	3	1

Table 16: Relative importance of each dimension within CE criteria for DM 17

DM 17	C_1	C_2	C_3	C_4	C_5
C_1	1	1/5	1	1/5	7
C_2	5	1	1/7	9	5
C_3	1	1	1	9	5
C_4	5	1/9	1/9	1	1/3
C_5	1/7	1/5	1/5	3	1

Table 18: Relative importance of each dimension within CE criteria for DM 18

DM 18	C_1	C_2	C_3	C_4	C_5
C_1	1	5	7	5	5
C_2	1/5	1	5	3	7
C_3	1/7	1/7	1	7	5
C_4	1/5	1/3	1/7	1	5
C_5	1/5	1/7	1/5	1/5	1

Appendix G (Questionnaire result from phase 1 pertaining to circularity item)

Table 1: Relative importance of each item within CE criteria for DM 1.

DM 1	C_{1a}	C_{1b}	C_{1c}	C_{1d}	C_{1e}	C_{1f}	C_{2a}	C_{2b}	C_{2c}	C_{2d}	C_{2e}	C_{2f}	C_{3a}	C_{3b}	C_{3c}	C_{3d}	C_{4a}	C_{4b}	C_{5a}	C_{5b}	C_{5c}	C_{5d}	C_{5e}
C_{1a}	1	7	7	9	1/7	1/7	7	7	5	1/7	1	7	3	3	1	5	7	9	3	7	7	3	9
C_{1b}	1/7	1	1/9	1/7	1/7	1/7	1/3	1/3	1/3	1/9	1/9	1/9	1/3	1/3	1/3	1/3	1/3	1/5	1/3	1/3	3	1/3	1
C_{1c}	1/7	9	1	1/7	1/9	1/9	1/3	3	5	1/9	1/9	1/3	1/3	1/3	1/3	1/3	7	9	1/3	3	3	3	1
C_{1d}	1/9	7	7	1	1/7	1/7	3	7	1/3	1/7	1/7	1/7	5	5	5	5	7	9	1/5	1/5	3	3	3
C_{1e}	7	7	9	7	1	1/7	7	7	7	7	7	7	9	9	9	9	7	9	7	7	7	7	7
C_{1f}	7	7	9	7	7	1	9	9	9	9	9	9	9	9	9	9	7	9	9	9	9	9	9
C_{2a}	1/7	3	3	1/3	1/7	1/9	1	7	1/7	1/7	1/7	1/7	3	1/3	1/3	3	1/3	3	1/5	1/5	1/3	1/5	1
C_{2b}	1/7	3	1/3	1/7	1/7	1/9	1/7	1	1/9	1/9	1/9	1/9	1/7	1/7	1/7	1/7	1	1	1/7	1/7	1/7	1/7	1
C_{2c}	1/5	3	1/5	3	1/7	1/9	7	9	1	1/9	1/9	1/9	3	3	3	3	7	7	1/3	3	1/3	1/5	3
C_{2d}	7	9	9	7	1/7	1/9	7	9	9	1	9	9	7	7	7	7	9	9	7	7	7	7	7
C_{2e}	1	9	9	7	1/7	1/9	7	9	9	1/9	1	9	9	9	9	9	9	9	7	7	7	7	7
C_{2f}	1/7	9	3	7	1/7	1/9	7	9	9	1/9	1/9	1	9	9	9	9	3	3	1/7	1/7	1/7	1/7	1
C_{3a}	1/3	3	3	1/5	1/9	1/9	1/3	7	1/3	1/7	1/9	1/9	1	9	7	7	1	3	1/5	1/5	1/5	1/5	3
C_{3b}	1/3	3	3	1/5	1/9	1/9	3	7	1/3	1/7	1/9	1/9	1/9	1	5	5	1	5	1/5	1/5	1/5	1/5	3
C_{3c}	1	3	3	1/5	1/9	1/9	3	7	1/3	1/7	1/9	1/9	1/7	1/5	1	7	1	9	1/5	1/5	1/5	1/5	3
C_{3d}	1/5	3	3	1/5	1/9	1/9	1/3	7	1/3	1/7	1/9	1/9	1/7	1/5	1/7	1	1	3	1/5	1/5	1/5	1/5	3
C_{4a}	1/7	3	1/7	1/7	1/7	1/7	3	1	1/7	1/9	1/9	1/3	1	1	1	1	1	7	1/9	1/9	1/9	1/9	7
C_{4b}	1/9	5	1/9	1/9	1/9	1/9	1/3	1	1/7	1/9	1/9	1/3	1/3	1/5	1/9	1/3	1/7	1	1/9	1	1/9	1/9	1/9
C_{5a}	1/3	3	3	5	1/7	1/9	5	7	3	1/7	1/7	7	5	5	5	5	9	9	1	7	7	7	7
C_{5b}	1/7	3	1/3	5	1/7	1/9	5	7	1/3	1/7	1/7	7	5	5	5	5	9	1	1/7	1	9	1	7
C_{5c}	1/7	1/3	1/3	1/3	1/7	1/9	3	7	3	1/7	1/7	7	5	5	5	5	9	9	1/7	1/9	1	1/5	7
C_{5d}	1/3	3	1/3	1/3	1/7	1/9	5	7	5	1/7	1/7	7	5	5	5	5	9	9	1/7	1	5	1	7
C_{5e}	1/9	1	1	1/3	1/7	1/9	1	1	1/3	1/7	1/7	1	1/3	1/3	1/3	1/3	1/7	9	1/7	1/7	1/7	1/7	1

Table 2: Relative importance of each item within CE criteria for DM 2.

DM 2	C_{1a}	C_{1b}	C_{1c}	C_{1d}	C_{1e}	C_{1f}	C_{2a}	C_{2b}	C_{2c}	C_{2d}	C_{2e}	C_{2f}	C_{3a}	C_{3b}	C_{3c}	C_{3d}	C_{4a}	C_{4b}	C_{5a}	C_{5b}	C_{5c}	C_{5d}	C_{5e}
C_{1a}	1	1/7	1/9	1/9	1/7	1/9	1/7	1	1/5	1/7	1/3	1/5	1/3	1/7	1/7	1/7	5	5	5	3	1/7	1/5	1/7
C_{1b}	7	1	1/7	1/7	5	1/7	1/5	1/3	1/3	1/7	1/7	1/7	1/3	1/7	1/7	1/7	5	5	5	1/3	1/7	1/5	1/7
C_{1c}	9	7	1	1	7	3	1/3	5	5	1	7	3	3	7	1	3	7	9	7	5	1/5	1	1/5
C_{1d}	9	7	1	1	7	5	1	3	1/3	1/7	1/3	1/7	3	1	1	3	9	9	3	3	5	3	5
C_{1e}	7	1/5	1/7	1/7	1	1/7	1/7	1/5	1/7	1/9	1/9	1/9	1	1/5	1/5	1/5	5	5	3	1/3	1/5	1/3	1/5
C_{1f}	9	7	1/3	1/5	7	1	1	5	5	3	3	1	3	1/3	1/3	1/3	7	7	7	5	1/5	1	1/5
C_{2a}	7	5	3	1	7	1	1	5	7	7	7	1	3	1/5	1/5	1/3	5	5	7	5	1/7	1/5	1/7
C_{2b}	1	3	1/5	1/3	5	1/5	1/5	1	1/7	1/7	1/7	1/7	1/3	1/7	1/7	1/5	3	1/3	3	1/5	1/7	1/5	1/7
C_{2c}	5	3	1/5	3	7	1/5	1/7	7	1	1/5	1/5	1/5	3	1/5	1/5	1/3	5	5	3	1/3	1/7	1	1/7
C_{2d}	7	7	1	7	9	1/3	1/7	7	5	1	5	1/5	3	1	1	3	7	7	7	5	1	5	1
C_{2e}	3	7	1/7	3	9	1/3	1/7	7	5	1/5	1	1/5	3	1/3	1/3	1/3	7	7	5	3	1/5	1	1/5
C_{2f}	5	7	1/3	7	9	1	1	7	5	5	5	1	1	1/5	1/5	1/3	7	7	5	1	1/5	1/3	1/5
C_{3a}	3	3	1/3	1/3	1	1/3	1/3	3	1/3	1/3	1/3	1	1	1/5	1/7	1/7	1/3	1	3	1	1/7	1/5	1/7
C_{3b}	7	7	1/7	1	5	3	5	7	5	1	3	5	5	1	1	1/7	9	9	5	3	1	5	1
C_{3c}	7	7	1	1	5	3	5	7	5	1	3	5	7	1	1	1/7	9	9	7	3	1	3	1
C_{3d}	7	7	1/3	1/3	5	3	3	5	3	1/3	3	3	7	7	7	1	7	7	3	1	1/5	1	1/5
C_{4a}	1/5	1/5	1/7	1/9	1/5	1/7	1/5	1/3	1/5	1/7	1/7	1/7	3	1/9	1/9	1/7	1	1/7	1	1/3	1/7	1/3	1/7
C_{4b}	1/5	1/5	1/9	1/9	1/5	1/7	1/5	3	1/5	1/7	1/7	1/7	1	1/9	1/9	1/7	7	1	1	1/3	1/7	1/3	1/7
C_{5a}	1/5	1/5	1/7	1/3	1/3	1/7	1/7	1/3	1/3	1/7	1/5	1/5	1/3	1/5	1/7	1/3	1	1	1	1/5	1/9	1/9	1/9
C_{5b}	1/3	3	1/5	1/3	3	1/5	1/5	5	3	1/5	1/3	1	1	1/3	1/3	1	3	3	5	1	1/9	1/9	1/9
C_{5c}	7	7	5	1/5	5	5	7	7	7	1	5	5	7	1	1	5	7	7	9	9	1	7	3
C_{5d}	5	5	1	1/3	3	1	5	5	1	1/5	1	3	5	1/5	1/3	1	3	3	9	9	1/7	1	1/5
C_{5e}	7	7	5	1/5	5	5	7	7	7	1	5	5	7	1	1	5	7	7	9	9	1/3	5	1

Table 3: Relative importance of each item within CE criteria for DM 3.

DM 3	C_{1a}	C_{1b}	C_{1c}	C_{1d}	C_{1e}	C_{1f}	C_{2a}	C_{2b}	C_{2c}	C_{2d}	C_{2e}	C_{2f}	C_{3a}	C_{3b}	C_{3c}	C_{3d}	C_{4a}	C_{4b}	C_{5a}	C_{5b}	C_{5c}	C_{5d}	C_{5e}
C_{1a}	1	1/7	1/7	1/7	1/3	1/7	1/7	1	1/3	1/3	1/7	1/5	1/5	1/7	1/5	1/3	1/7	1/7	1/5	1/7	1/7	1/7	1/3
C_{1b}	7	1	1/5	1/7	1	1/7	1/7	1/3	1/5	1/5	1/7	1/3	1/7	1/7	1/5	1/5	1/7	1/7	3	1/7	1/7	1/7	1
C_{1c}	7	5	1	1	7	1/3	5	5	5	5	5	7	5	5	5	7	3	3	7	7	7	7	7
C_{1d}	7	7	1	1	7	1	3	5	5	5	5	5	5	5	5	7	1	1/3	7	1/3	3	5	7
C_{1e}	3	1	1/7	1/7	1	1/5	1/5	3	1/5	1/5	1/5	1/5	1/5	1/7	1/5	1/3	1/5	1/5	1	1/7	1/5	1/7	1/3
C_{1f}	7	7	3	1	5	1	5	7	7	7	5	7	7	7	7	5	7	5	7	7	5	3	7
C_{2a}	7	7	1/5	1/3	5	1/5	1	9	7	7	3	7	7	7	7	7	5	5	7	1/5	7	3	7
C_{2b}	1	3	1/5	1/5	1/3	1/7	1/9	1	1/9	1/3	1/7	1/7	1	1/5	1	1/3	1/5	1/5	1/3	1/7	1/5	1/7	1
C_{2c}	3	5	1/5	1/5	5	1/7	1/7	9	1	3	1/7	3	1/5	1/3	3	5	1/5	1/5	5	1/5	1/5	1/5	1
C_{2d}	3	5	1/5	1/5	5	1/7	1/7	3	1/3	1	1/7	1	5	3	3	5	1	1	5	1/5	5	1/5	5
C_{2e}	7	7	1/5	1/5	5	1/5	1/3	7	7	7	1	5	5	1/3	1/3	3	1/7	1/5	3	1/5	1/5	1/5	1
C_{2f}	5	3	1/7	1/5	5	1/7	1/7	7	1/3	1	1/5	1	5	1/7	1/5	3	1/7	1/7	3	1/3	3	1/3	3
C_{3a}	5	7	1/5	1/5	5	1/7	1/7	1	5	1/5	1/5	1/5	1	1/5	3	3	1/5	1/5	5	1/5	1/5	1/7	3
C_{3b}	7	7	1/5	1/5	7	1/7	1/7	5	3	1/3	3	7	5	1	7	7	1/5	1/5	5	1/3	5	5	5
C_{3c}	5	5	1/5	1/5	5	1/7	1/7	1	1/3	1/3	3	5	1/3	1/7	1	1	1/5	1	5	1/5	3	1/5	3
C_{3d}	3	5	1/7	1/7	3	1/5	1/7	3	1/5	1/5	1/3	1/3	1/3	1/7	1	1	1/5	1/7	3	1/7	1/7	1/7	1
C_{4a}	7	7	1/3	1	5	1/7	1/5	5	5	1	7	7	5	5	5	5	1	3	7	3	3	5	7
C_{4b}	7	7	1/3	3	5	1/5	1/5	5	5	1	5	7	5	5	1	7	1/3	1	7	1/3	5	1/3	5
C_{5a}	5	1/3	1/7	1/7	1	1/7	1/7	3	1/5	1/5	1/3	1/3	1/5	1/5	1/5	1/3	1/7	1/7	1	1/7	1/7	1/7	1/5
C_{5b}	7	7	1/7	3	7	1/7	5	7	5	5	5	3	5	3	5	7	1/3	3	7	1	5	5	7
C_{5c}	7	7	1/7	1/3	5	1/5	1/7	5	5	1/5	5	1/3	5	1/5	1/3	7	1/3	1/5	7	1/5	1	1/3	1
C_{5d}	7	7	1/7	1/5	7	1/3	1/3	7	5	5	5	3	7	1/5	5	7	1/5	3	7	1/5	3	1	3
C_{5e}	3	1	1/7	1/7	3	1/7	1/7	1	1	1/5	1	1/3	1/3	1/5	1/3	1	1/7	1/5	5	1/7	1	1/3	1

Table 4: Relative importance of each item within CE criteria for DM 4.

DM 4	C_{1a}	C_{1b}	C_{1c}	C_{1d}	C_{1e}	C_{1f}	C_{2a}	C_{2b}	C_{2c}	C_{2d}	C_{2e}	C_{2f}	C_{3a}	C_{3b}	C_{3c}	C_{3d}	C_{4a}	C_{4b}	C_{5a}	C_{5b}	C_{5c}	C_{5d}	C_{5e}
C_{1a}	1	1/3	1/5	1/3	1	1/3	1/3	1	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	5	3	1/3	3
C_{1b}	3	1	1/3	1/3	3	1/3	1/5	3	3	1/3	3	1/3	1/3	1/3	1/3	1/3	5	5	1/3	1/3	1/5	1/3	5
C_{1c}	5	3	1	5	3	3	3	5	5	3	1/3	3	5	3	1/3	1/3	5	3	1/3	1/3	1	1/3	5
C_{1d}	3	3	1/5	1	3	3	5	3	1/3	1	3	3	1/3	1/3	1/3	1	1	3	3	3	1/3	1/3	3
C_{1e}	1	1/3	1/3	1/3	1	1/3	1/3	1	1/3	1/3	1	1	1/3	1/5	1/5	1/3	1/3	1/3	1/3	1/3	1/3	3	1/3
C_{1f}	3	3	1/3	1/3	3	1	1/3	3	3	3	5	3	1/3	1/3	5	3	5	5	1	3	1/3	1/3	3
C_{2a}	3	5	1/3	1/5	3	3	1	5	3	3	1	3	3	5	1/3	1/3	3	3	1/3	3	1/5	1/5	3
C_{2b}	1	1/3	1/5	1/3	1	1/3	1/5	1	1/3	1/3	1/3	1/3	1/3	1/5	1/5	1/5	1/3	1/3	1/3	1/3	1/3	1/5	1
C_{2c}	3	1/3	1/5	3	3	1/3	1/3	3	1	1/3	3	3	1/5	1/3	3	1/3	5	5	3	3	3	1/3	3
C_{2d}	3	3	1/3	1	3	1/3	1/3	3	3	1	3	3	1/3	1/3	1/3	1/3	3	1/5	1/3	3	1/3	1/3	3
C_{2e}	3	1/3	3	1/3	1	1/5	1	3	1/3	1/3	1	3	1/3	1/3	1/3	1/3	1/3	1/5	1/3	1	1/3	3	3
C_{2f}	3	3	1/3	1/3	1	1/3	1/3	3	1/3	1/3	1/3	1	5	1/3	1/3	1/3	1/5	1/3	1/3	1/5	1/3	1/5	5
C_{3a}	3	3	1/5	3	3	3	1/3	3	5	3	3	1/5	1	1/3	1/3	1	1/3	1	1/3	5	1	5	5
C_{3b}	3	3	1/3	3	5	3	1/5	5	3	3	3	3	3	1	1/3	1/3	3	1/3	3	3	1/3	1	5
C_{3c}	3	3	3	3	5	1/5	3	5	1/3	3	3	3	3	3	1	3	5	1/3	1/3	3	3	1/3	3
C_{3d}	3	3	3	1	3	1/3	3	5	3	3	3	3	1	3	1/3	1	3	5	3	3	3	1/3	3
C_{4a}	3	1/5	1/5	1	3	1/5	1/3	3	1/5	1/3	3	5	3	1/3	1/5	1/3	1	7	1/3	1/3	1/3	1/3	5
C_{4b}	3	1/5	1/3	1/3	3	1/5	1/3	3	1/5	5	5	3	1	3	3	1/5	1/7	1	5	1/3	1/3	1/3	5
C_{5a}	3	3	3	1/3	3	1	3	3	1/3	3	3	3	3	1/3	3	1/3	3	1/5	1	3	1	1/3	5
C_{5b}	1/5	3	3	1/3	3	1/3	1/3	3	1/3	1/3	1	5	1/5	1/3	1/3	1/3	3	3	1/3	1	1/3	1/3	5
C_{5c}	1/3	5	1	3	3	3	5	3	1/3	3	3	3	1	3	1/3	1/3	3	3	1	3	1	3	5
C_{5d}	3	3	3	3	1/3	3	5	5	3	3	1/3	5	1/5	1	3	3	3	3	3	3	1/3	1	5
C_{5e}	1/3	1/5	1/5	1/3	3	1/3	1/3	1	1/3	1/3	1/3	1/5	1/5	1/5	1/3	1/3	1/5	1/5	1/5	1/5	1/5	1/5	1

Table 5: Relative importance of each item within CE criteria for DM 5.

DM 5	C_{1a}	C_{1b}	C_{1c}	C_{1d}	C_{1e}	C_{1f}	C_{2a}	C_{2b}	C_{2c}	C_{2d}	C_{2e}	C_{2f}	C_{3a}	C_{3b}	C_{3c}	C_{3d}	C_{4a}	C_{4b}	C_{5a}	C_{5b}	C_{5c}	C_{5d}	C_{5e}
C_{1a}	1	1/9	1/9	1/9	1/9	1/9	1/9	1/7	1/7	1/9	1/9	1/9	1/7	1/9	1/7	1/7	1/9	1/5	1/9	1/7	1/9	1/5	1/5
C_{1b}	9	1	9	9	9	9	5	1/7	1/7	1/9	1/9	1/9	1/5	1/7	1/3	1/7	1/9	5	1/9	1/9	1/9	1/5	1/7
C_{1c}	9	1/9	1	1/7	7	7	1/7	1/5	1/5	1/9	1/9	1/9	1/7	1/9	1/5	1/9	1/9	1	1/9	1/9	1/9	1/7	1/7
C_{1d}	9	1/9	7	1	7	1/7	1/9	1/7	1	1/9	1/9	1/9	1/7	1/5	1	1/9	1/9	1/3	1/9	1/9	1/9	1/7	1/7
C_{1e}	9	1/9	1/7	1/7	1	1/7	1	1/9	1/5	1/9	1/9	1/5	1/7	1/9	1/7	1/9	1/9	1/5	1/9	1/9	1/9	1/7	1/7
C_{1f}	9	1/9	1/7	7	7	1	1/5	1/7	1/5	1/9	1/9	1/9	1/7	1/9	1/7	1/9	1/9	1/5	1/9	1/9	1/9	1/9	1/5
C_{2a}	9	1/5	7	9	1	5	1	1/5	3	1/9	1/9	1/9	1/5	1/5	1/7	1/7	1/7	5	1/9	1/7	1/7	1/5	1/5
C_{2b}	7	7	5	7	9	7	5	1	5	1/7	1/7	7	1/7	1/7	1/7	1/7	1/9	5	1/9	1/9	1/9	1/5	1/5
C_{2c}	7	7	5	1	5	5	1/3	1/5	1	1/9	1/5	5	1/7	1/7	1/5	1/9	1/9	1	1/9	1/9	1/9	1/7	1/5
C_{2d}	9	9	9	9	9	9	9	7	9	1	7	7	9	9	9	9	1/9	9	9	9	9	9	9
C_{2e}	9	9	9	9	9	9	9	7	5	1/7	1	9	9	9	9	9	3	7	5	5	5	5	5
C_{2f}	9	9	9	9	5	9	9	1/7	1/5	1/7	1/9	1	9	9	9	9	1/7	1	1/9	1	1/9	1/5	1/5
C_{3a}	7	5	7	7	7	7	5	7	7	1/9	1/9	1/9	1	1/9	1/9	1/7	1/9	3	1/7	1/7	1/7	1/5	1/5
C_{3b}	9	7	9	5	9	9	5	7	7	1/9	1/9	1/9	9	1	9	9	1/9	5	1/7	1/7	1/7	1/7	1/5
C_{3c}	7	3	5	1	7	7	7	7	5	1/9	1/9	1/9	9	1/9	1	1/5	1/9	1	1/7	1/7	1/7	1/9	1/5
C_{3d}	7	7	9	9	9	9	7	7	9	1/9	1/9	1/9	7	1/9	5	1	1/9	3	1/7	1/7	1/7	5	5
C_{4a}	9	9	9	9	9	9	7	9	9	9	1/3	7	9	9	9	9	1	7	3	3	3	7	7
C_{4b}	5	1/5	1	3	5	5	1/5	1/5	1	1/9	1/7	1	1/3	1/5	1	1/3	1/7	1	1/7	1/7	1/7	1/7	1
C_{5a}	9	9	9	9	9	9	9	9	9	1/9	1/5	9	7	7	7	7	1/3	7	1	1/9	1/5	7	1/3
C_{5b}	7	9	9	9	9	9	7	9	9	1/9	1/5	1	7	7	7	7	1/3	7	9	1	1/7	9	1
C_{5c}	9	9	9	9	9	9	7	9	9	1/9	1/5	9	7	7	7	7	1/3	7	5	7	1	7	1/7
C_{5d}	5	5	7	7	7	9	5	5	7	1/9	1/5	5	5	7	9	1/5	1/7	7	1/7	1/9	1/7	1	1/7
C_{5e}	5	7	7	7	7	5	5	5	5	1/9	1/5	5	5	5	5	1/5	1/7	1	3	1	7	7	1

Table 6: Relative importance of each item within CE criteria for DM 6.

DM 6	C_{1a}	C_{1b}	C_{1c}	C_{1d}	C_{1e}	C_{1f}	C_{2a}	C_{2b}	C_{2c}	C_{2d}	C_{2e}	C_{2f}	C_{3a}	C_{3b}	C_{3c}	C_{3d}	C_{4a}	C_{4b}	C_{5a}	C_{5b}	C_{5c}	C_{5d}	C_{5e}
C_{1a}	1	1	3	3	1	1	1	1	1	1	1	1	1/3	1/3	1/3	1/3	1	1	1/3	1/3	1/3	1/3	1/3
C_{1b}	1	1	1	1	1	1	1	1	1	1	1	1	1/3	1/3	1/3	1/3	1	1	1/3	1/3	1/3	1/3	1/3
C_{1c}	1/3	1	1	1/3	1	1	1	1	1	1	1	1	1/3	1/3	1/3	1/3	1	1	1/3	1/3	1/3	1/3	1/3
C_{1d}	1/3	1	3	1	1	1	1	1	1	1	1	1	1/3	1/3	1/3	1/3	1	1	1/3	1/3	1/3	1/3	1/3
C_{1e}	1	1	1	1	1	1	1	1	1	1	1	1	1/3	1/3	1/3	1/3	1	1	1/3	1/3	1/3	1/3	1/3
C_{1f}	1	1	1	1	1	1	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1	1	1/3	1/3	1/3	1/3	1/3
C_{2a}	1	1	1	1	1	3	1	1/3	1/3	1/3	1/3	1/3	1	1	1	1	3	3	1	1	1	1	1
C_{2b}	1	1	1	1	1	3	3	1	1	1/3	1/3	1/3	1	1	1	1	3	3	1	1	1	1	1
C_{2c}	1	1	1	1	1	3	3	1	1	1/3	1/3	1/3	1	1	1	1	3	3	1	1	1	1	1
C_{2d}	1	1	1	1	1	3	3	3	3	1	1	1	1	1	1	1	3	3	1	1	1	1	1
C_{2e}	1	1	1	1	1	3	3	3	3	1	1	1	1	1	1	1	3	3	1	1	1	1	1
C_{2f}	1	1	1	1	1	3	3	3	3	1	1	1	1	1	1	1	3	3	1	1	1	1	1
C_{3a}	3	3	3	3	3	3	1	1	1	1	1	1	1	1	1	1	5	5	1	3	1	1	1
C_{3b}	3	3	3	3	3	3	1	1	1	1	1	1	1	1	1	1	5	5	1	1	1	1	1
C_{3c}	3	3	3	3	3	3	1	1	1	1	1	1	1	1	1	1	5	5	1	1	1	1	1
C_{3d}	3	3	3	3	3	3	1	1	1	1	1	1	1	1	1	1	5	5	1	1	1	1	1
C_{4a}	1	1	1	1	1	1	1/3	1/3	1/3	1/3	1/3	1/3	1/5	1/5	1/5	1/5	1	1	1/3	1/3	1/3	1/3	1/3
C_{4b}	1	1	1	1	1	1	1/3	1/3	1/3	1/3	1/3	1/3	1/5	1/5	1/5	1/5	1	1	1/3	1/3	1/3	1/3	1/3
C_{5a}	3	3	3	3	3	3	1	1	1	1	1	1	1	1	1	1	3	3	1	1	1	1	1
C_{5b}	3	3	3	3	3	3	1	1	1	1	1	1	1/3	1	1	1	3	3	1	1	1/3	1/3	1/3
C_{5c}	3	3	3	3	3	3	1	1	1	1	1	1	1	1	1	1	3	3	1	3	1	1	1
C_{5d}	3	3	3	3	3	3	1	1	1	1	1	1	1	1	1	1	3	3	1	3	1	1	1
C_{5e}	3	3	3	3	3	3	1	1	1	1	1	1	1	1	1	1	3	3	1	3	1	1	1

Table 7: Relative importance of each item within CE criteria for DM 7.

DM 7	C_{1a}	C_{1b}	C_{1c}	C_{1d}	C_{1e}	C_{1f}	C_{2a}	C_{2b}	C_{2c}	C_{2d}	C_{2e}	C_{2f}	C_{3a}	C_{3b}	C_{3c}	C_{3d}	C_{4a}	C_{4b}	C_{5a}	C_{5b}	C_{5c}	C_{5d}	C_{5e}
C_{1a}	1	9	9	9	9	9	1/3	3	1/5	3	5	1/3	3	1/3	1	5	1/9	3	3	1/5	3	1	3
C_{1b}	1/9	1	5	7	5	7	3	1/3	5	1/5	1	1	3	1/3	3	1/3	1/3	5	1/5	5	1/5	1/3	3
C_{1c}	1/9	1/5	1	1/5	1/5	1/5	1/5	1	7	1/3	1/5	1/5	1	3	1/3	7	1/9	1/5	1/3	3	1/3	3	1/3
C_{1d}	1/9	1/7	5	1	5	1/5	5	1	1/3	1/5	1	3	1/5	5	1	1	1/9	5	1/5	3	1/3	1/3	1
C_{1e}	1/9	1/5	5	1/5	1	5	1/5	1/5	3	1	1/7	1/7	1/3	3	1/5	1	1/9	1/3	3	1/3	1/3	3	1
C_{1f}	1/9	1/7	5	5	1/5	1	1	3	1/3	1	3	1/3	5	7	1/3	1	1/9	1	1	3	1/3	1	1
C_{2a}	3	1/3	5	1/5	5	1	1	1	1	1/5	1/5	1/5	1	3	1/3	7	1/9	3	3	1/3	1	5	1/5
C_{2b}	1/3	3	1	1	5	1/3	1	1	1/3	1/3	3	1/3	1/3	3	1/3	1	1/9	1/3	1/5	1/5	1	5	1/3
C_{2c}	5	1/5	1/7	3	1/3	3	1	3	1	1	1/7	1/7	3	5	1/5	1	1/9	5	5	1/3	1/5	3	5
C_{2d}	1/3	5	3	5	1	1	5	3	1	1	1/7	1/7	1	5	1/3	1	1/9	1/3	1/3	1/5	1/5	3	5
C_{2e}	1/5	1	5	1	7	1/3	5	1/3	7	7	1	1/7	3	1	1/3	3	1/9	3	5	7	1/5	1	1
C_{2f}	3	1	5	1/3	7	3	5	3	7	7	7	1	1	3	1/3	1	1/9	1/3	3	5	1/5	1/7	1/3
C_{3a}	1/3	1/3	1	5	3	1/5	1	3	1/3	1	1/3	1	1	1/7	1/5	5	1/9	3	1/3	1/5	3	1	3
C_{3b}	3	3	1/3	1/5	1/3	1/7	1/3	1/3	1/5	1/5	1	1/3	7	1	1/3	3	1/9	1/3	1	1	1/3	3	1/5
C_{3c}	1	1/3	3	1	5	3	3	3	5	3	3	3	5	3	1	3	1/9	1/3	3	1/5	3	1/3	1/3
C_{3d}	1/5	3	1/7	1	1	1	1/7	1	1	1	1/3	1	1/5	1/3	1/3	1	1/9	1/5	3	3	1	1/3	1/5
C_{4a}	9	3	9	9	9	9	9	9	9	9	9	9	9	9	9	9	1	9	9	9	9	9	9
C_{4b}	1/3	1/5	5	1/5	3	1	1/3	3	1/5	3	1/3	3	1/3	3	3	5	1/9	1	1/3	1/3	1/3	1/5	1/5
C_{5a}	1/3	5	3	5	1/3	1	1/3	5	1/5	3	1/5	1/3	3	1	1/3	1/3	1/9	3	1	1/3	1/3	1/3	1
C_{5b}	5	1/5	1/3	1/3	3	1/3	3	5	3	5	1/7	1/5	5	1	5	1/3	1/9	3	3	1	1	1	1/3
C_{5c}	1/3	5	3	3	3	3	1	1	5	5	5	5	1/3	3	1/3	1	1/9	3	3	1	1	3	3
C_{5d}	1	3	1/3	3	1/3	1	1/5	1/5	1/3	1/3	1	7	1	1/3	3	3	1/9	5	3	1	1/3	1	3
C_{5e}	1/3	1/3	3	1	1	1	5	3	1/5	1/5	1	3	1/3	5	3	5	1/9	5	1	3	1/3	1/3	1

Table 8: Relative importance of each item within CE criteria for DM 8.

DM 8	C_{1a}	C_{1b}	C_{1c}	C_{1d}	C_{1e}	C_{1f}	C_{2a}	C_{2b}	C_{2c}	C_{2d}	C_{2e}	C_{2f}	C_{3a}	C_{3b}	C_{3c}	C_{3d}	C_{4a}	C_{4b}	C_{5a}	C_{5b}	C_{5c}	C_{5d}	C_{5e}
C_{1a}	1	1/7	5	1/9	1/7	1/9	7	7	5	3	5	5	1/5	1/5	1/7	1/3	1/7	5	5	7	1/7	1/7	5
C_{1b}	7	1	7	1/7	5	1/7	1/5	3	1/3	1/7	5	5	1/5	1/3	1/5	1/3	1/7	5	1/7	5	1/5	1/5	5
C_{1c}	1/5	1/7	1	1/7	3	1/7	3	5	1/5	1/5	5	5	1/7	1/3	1/3	5	1/7	5	1/7	5	1/5	1/7	5
C_{1d}	9	7	7	1	7	1	7	7	3	5	5	3	5	5	3	3	1/7	5	5	5	5	1/7	7
C_{1e}	7	1/5	1/3	1/7	1	1/7	1/5	1/5	1/7	1/5	1/5	1/3	3	1/5	1/5	1/7	1/5	1/3	1/7	5	1/7	1/7	5
C_{1f}	9	7	7	1	7	1	1/5	7	3	5	5	3	1/7	1/7	5	5	1/5	5	1/7	5	1/7	3	3
C_{2a}	1/7	5	1/3	1/7	5	5	1	7	7	5	7	5	5	5	3	3	1/7	5	1/5	7	1/5	1/7	5
C_{2b}	1/7	1/3	1/5	1/7	5	1/7	1/7	1	1/7	1/7	1/7	1/5	1/5	1/5	1/5	1/5	1/7	5	1/5	5	1/5	1/7	7
C_{2c}	1/5	3	5	1/3	7	1/3	1/7	7	1	1/5	5	7	1/3	5	5	7	5	5	5	5	5	3	7
C_{2d}	1/3	7	5	1/5	5	1/5	1/5	7	5	1	7	7	3	3	3	3	5	5	3	7	3	1/3	5
C_{2e}	1/5	1/5	1/5	1/5	5	1/5	1/7	7	1/5	1/7	1	5	1/5	1/7	1/5	1/3	5	7	1/7	3	1/5	1/5	5
C_{2f}	1/5	1/5	1/5	1/3	3	1/3	1/5	5	1/7	1/7	1/5	1	3	5	1/5	3	1/7	5	1/5	5	1/5	1/5	5
C_{3a}	5	5	7	1/5	1/3	7	1/5	5	3	1/3	5	1/3	1	1/7	1/7	7	1/7	5	1/5	7	1/5	1/5	5
C_{3b}	5	3	3	1/5	5	7	1/5	5	1/5	1/3	7	1/5	7	1	7	7	1/5	7	1/5	5	1/5	5	5
C_{3c}	7	5	3	1/3	5	1/5	1/3	5	1/5	1/3	5	5	7	1/7	1	7	1/7	5	5	5	5	1/5	5
C_{3d}	3	3	1/5	1/3	7	1/5	1/3	5	1/7	1/3	3	1/3	1/7	1/7	1/7	1	1/5	3	1/5	3	1/3	1/3	5
C_{4a}	7	7	7	7	5	5	7	7	1/5	1/5	1/5	7	7	5	7	5	1	5	3	7	1/5	5	7
C_{4b}	1/5	1/5	1/5	1/5	3	1/5	1/5	1/5	1/5	1/5	1/7	1/5	1/5	1/7	1/5	1/3	1/5	1	1/5	1	1/5	1/5	5
C_{5a}	1/5	7	7	1/5	7	7	5	5	1/5	1/3	7	5	5	5	1/5	5	1/3	5	1	7	5	5	7
C_{5b}	1/7	1/5	1/5	1/5	1/5	1/5	1/7	1/5	1/5	1/7	1/3	1/5	1/7	1/5	1/5	1/3	1/7	1	1/7	1	1/7	1/7	7
C_{5c}	7	5	5	1/5	7	7	5	5	1/5	1/3	5	5	5	5	1/5	3	5	5	1/5	7	1	5	7
C_{5d}	7	5	7	7	7	1/3	7	7	1/3	3	5	5	5	1/5	5	3	1/5	5	1/5	7	1/5	1	7
C_{5e}	1/5	1/5	1/5	1/7	1/5	1/3	1/5	1/7	1/7	1/5	1/5	1/5	1/5	1/5	1/5	1/5	1/7	1/5	1/7	1/7	1/7	1/7	1

Table 9: Relative importance of each item within CE criteria for DM 9.

DM 9	C_{1a}	C_{1b}	C_{1c}	C_{1d}	C_{1e}	C_{1f}	C_{2a}	C_{2b}	C_{2c}	C_{2d}	C_{2e}	C_{2f}	C_{3a}	C_{3b}	C_{3c}	C_{3d}	C_{4a}	C_{4b}	C_{5a}	C_{5b}	C_{5c}	C_{5d}	C_{5e}
C_{1a}	1	3	3	1	7	1/7	7	5	1	1/7	3	3	5	1/5	5	5	1/5	3	1/3	1/7	1/7	1/5	7
C_{1b}	1/3	1	5	3	5	1/7	5	3	1/3	1/7	1/3	5	1/3	1/5	7	5	1/9	5	1	1/7	1/7	1/5	3
C_{1c}	1/3	1/5	1	1/3	5	1/7	3	1/3	1/7	1/9	1/3	5	1/5	1/9	3	1/5	1/9	5	1/3	1/7	1/7	1/3	1
C_{1d}	1	1/3	3	1	5	1/7	7	7	1	1/5	3	5	1/3	1/7	5	1/5	1/7	7	5	1/7	1/7	1/5	3
C_{1e}	1/7	1/5	1/5	1/5	1	1/9	1/3	1/5	1/9	1/9	3	5	1/3	1/7	3	1/3	1/9	1/5	1/5	1	1/7	1/3	1
C_{1f}	7	7	7	7	9	1	7	7	3	1	5	7	7	1	9	7	1/3	7	5	5	5	5	7
C_{2a}	1/7	1/5	1/3	1/7	3	1/7	1	1/5	1/9	1/9	1/9	1/5	1/5	1/7	1/3	1/7	1/9	1/3	1	1/5	1/7	1/9	1/5
C_{2b}	1/5	1/3	3	1/7	5	1/7	5	1	1/5	1/7	1/3	7	1/7	1/7	3	1/5	1/9	1	1/3	1/7	1/9	1/7	1/3
C_{2c}	1	3	7	1	9	1/3	9	5	1	1/7	1/5	5	1/3	1/5	3	1/5	1/5	7	1/3	1/7	1/9	1/7	1
C_{2d}	7	7	9	5	9	1	9	7	7	1	7	9	9	7	9	7	1/5	9	7	1	1	5	7
C_{2e}	1/3	3	3	1/3	1/3	1/5	9	3	5	1/7	1	7	1/5	1/9	1	1	1/9	1	1/7	1/9	1/3	1/9	1/3
C_{2f}	1/3	1/5	1/5	1/5	1/5	1/7	5	1/7	1/5	1/9	1/7	1	3	1/7	1/5	1/7	1/9	1/3	1/9	1/9	1/9	1/9	1/5
C_{3a}	1/5	3	5	3	3	1/7	5	7	3	1/9	5	1/3	1	1/5	7	1/5	1/7	3	5	1/9	1/9	1/5	1/5
C_{3b}	5	5	9	7	7	1	7	7	5	1/7	9	7	5	1	7	5	1	7	9	5	7	7	9
C_{3c}	1/5	1/7	1/3	1/5	1/3	1/9	3	1/3	1/3	1/9	1	5	1/7	1/7	1	1/5	1/9	1	1	1/5	1/9	1/7	1/3
C_{3d}	1/5	1/5	5	5	3	1/7	7	5	5	1/7	1	7	5	1/5	5	1	1/9	5	1/3	1/9	1/9	1/5	1
C_{4a}	5	9	9	7	9	3	9	9	5	5	9	9	7	1	9	9	1	9	9	5	5	3	9
C_{4b}	1/3	1/5	1/5	1/7	5	1/7	3	1	1/7	1/9	1	3	1/3	1/7	1	1/5	1/9	1	1	1/9	1/9	1/5	1/3
C_{5a}	3	1	3	1/5	5	1/5	1	3	3	1/7	7	9	1/5	1/9	1	3	1/9	1	1	1/5	1/9	1/7	1/3
C_{5b}	7	7	7	7	1	1/5	5	7	7	1	9	9	9	1/5	5	9	1/5	9	5	1	1/5	7	5
C_{5c}	7	7	7	7	7	1/5	7	9	9	1	3	9	9	1/7	9	9	1/5	9	9	5	1	7	9
C_{5d}	5	5	3	5	3	1/5	9	7	7	1/5	9	9	5	1/7	7	5	1/3	5	7	1/7	1/7	1	9
C_{5e}	1/7	1/3	1	1/3	1	1/7	5	3	1	1/7	3	5	5	1/9	3	1	1/9	3	3	1/5	1/9	1/9	1

Table 10: Relative importance of each item within CE criteria for DM 10.

DM 10	C_{1a}	C_{1b}	C_{1c}	C_{1d}	C_{1e}	C_{1f}	C_{2a}	C_{2b}	C_{2c}	C_{2d}	C_{2e}	C_{2f}	C_{3a}	C_{3b}	C_{3c}	C_{3d}	C_{4a}	C_{4b}	C_{5a}	C_{5b}	C_{5c}	C_{5d}	C_{5e}
C_{1a}	1	1/5	1/5	1/7	1	1/5	1/5	1/3	1/7	1/9	1/7	1/7	1/5	1/5	1/5	1/5	1/3	1/5	1/3	1/5	1/5	1/5	1/5
C_{1b}	5	1	1/7	1/3	5	1/5	1/3	1/3	1/3	1/9	1/5	1/5	1/3	1/3	3	1/5	1/3	1/3	1	1/3	1/3	1/3	1/3
C_{1c}	5	7	1	3	5	3	5	5	5	1/5	1	1	5	3	7	3	3	3	3	1	1	1	1
C_{1d}	7	3	1/3	1	5	3	3	3	3	1/7	1	3	1	1	5	1/3	5	3	1	1	1	1	1
C_{1e}	1	1/5	1/5	1/5	1	1/3	1/3	1/3	1/5	1/7	1/3	1/3	1/5	1/5	1	1/5	1/3	1/3	1/3	1/3	1/3	1/3	1/3
C_{1f}	5	5	1/3	1/3	3	1	1	1	1/3	1/7	3	3	1/3	1/5	5	1/5	1/3	1/3	3	1	1/3	1/3	1/3
C_{2a}	5	3	1/5	1/3	3	1	1	5	3	1/7	1/7	1	1/3	1/5	3	1/3	1/3	1/3	1/5	1/5	1/5	1/5	1/5
C_{2b}	3	3	1/5	1/3	3	1	1/5	1	5	1/5	1/7	1/5	1/3	1/3	1	1/5	1/5	1/5	1/5	1/5	1/5	1/5	1/5
C_{2c}	7	3	1/5	1/3	5	3	1/3	1/5	1	1/7	1/7	3	1/5	1/5	1	1/5	1/5	1/5	1/5	1/5	1/5	1/5	1/5
C_{2d}	9	9	5	7	7	7	7	5	7	1	7	7	1	1	5	1	1/5	1	1/3	1/3	1/3	1/3	1/3
C_{2e}	7	5	1	1	3	1/3	7	7	7	1/7	1	1	1/5	1/5	3	1/3	1/5	1/5	1/5	1/5	1/5	1/5	1/5
C_{2f}	7	5	1	1/3	3	1/3	1	5	1/3	1/7	1	1	1/3	1/3	3	1/3	1/5	1/5	1/5	1/5	1/5	1/5	1/5
C_{3a}	5	3	1/5	1	5	3	3	3	5	1	5	3	1	1/7	7	7	1	3	3	1	1	1	1
C_{3b}	5	3	1/3	1	5	5	5	3	5	1	5	3	7	1	7	7	3	3	3	1	1	1	1
C_{3c}	5	1/3	1/7	1/5	1	1/5	1/3	1	1	1/5	1/3	1/3	1/7	1/7	1	1/5	1/3	1/3	1/5	1/5	1/5	1/5	1/5
C_{3d}	5	5	1/3	3	5	5	3	5	5	1	3	3	1/7	1/7	5	1	3	3	1	1	1	1	1
C_{4a}	3	3	1/3	1/5	3	3	3	5	5	5	5	5	1	1/3	3	1/3	1	3	3	1	1/5	1/5	1
C_{4b}	5	3	1/3	1/3	3	3	3	5	5	1	5	5	1/3	1/3	3	1/3	1/3	1	1/3	1	1/5	1/5	1
C_{5a}	3	1	1/3	1	3	1/3	5	5	5	3	5	5	1/3	1/3	5	1	1/3	3	1	1/5	1/5	1/5	1/7
C_{5b}	5	3	1	1	3	1	5	5	5	3	5	5	1	1	5	1	1	1	5	1	1/3	1/3	1/3
C_{5c}	5	3	1	1	3	3	5	5	5	3	5	5	1	1	5	1	5	5	5	3	1	3	1/3
C_{5d}	5	3	1	1	3	3	5	5	5	3	5	5	1	1	5	1	5	5	5	3	1/3	1	1/3
C_{5e}	5	3	1	1	3	3	5	5	5	3	5	5	1	1	5	1	1	1	7	3	3	3	1

Table 11: Relative importance of each item within CE criteria for DM 11.

DM 11	C_{1a}	C_{1b}	C_{1c}	C_{1d}	C_{1e}	C_{1f}	C_{2a}	C_{2b}	C_{2c}	C_{2d}	C_{2e}	C_{2f}	C_{3a}	C_{3b}	C_{3c}	C_{3d}	C_{4a}	C_{4b}	C_{5a}	C_{5b}	C_{5c}	C_{5d}	C_{5e}
C_{1a}	1	7	1/7	1/9	9	1/7	7	7	1/7	7	7	7	7	7	7	7	3	3	7	1/7	3	5	7
C_{1b}	1/7	1	1/7	1/7	7	1/7	1/7	3	1/7	1/7	1/7	1/7	1/3	1/3	1/3	1/3	1/3	1/3	1/5	1/3	1/5	1/5	1/5
C_{1c}	7	7	1	3	5	1/7	7	7	7	7	7	7	7	1/5	1/5	7	5	5	5	3	1/3	3	3
C_{1d}	9	7	1/3	1	5	5	7	7	7	7	7	7	7	7	7	7	5	5	5	5	3	5	5
C_{1e}	1/9	1/7	1/5	1/5	1	1/7	7	7	1/3	7	7	7	7	7	7	7	7	7	5	5	3	5	7
C_{1f}	7	7	7	1/5	7	1	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
C_{2a}	1/7	7	1/7	1/7	1/7	1/7	1	7	1/7	7	7	1/7	7	1/5	5	7	7	7	7	7	3	3	5
C_{2b}	1/7	1/3	1/7	1/7	1/7	1/7	1/7	1	1/7	1/7	1/7	1/7	1/3	1/3	1/3	1	1/7	1/7	1/5	1/5	1/5	1/5	1/3
C_{2c}	7	7	1/7	1/7	3	1/7	7	7	1	7	7	7	3	3	3	5	7	7	7	7	1/5	1/5	1/3
C_{2d}	1/7	7	1/7	1/7	1/7	1/7	1/7	7	1/7	1	7	7	5	1/3	5	5	3	3	1/5	5	1/5	1/5	3
C_{2e}	1/7	7	1/7	1/7	1/7	1/7	1/7	7	1/7	1/7	1	7	5	1/3	3	5	5	5	1/5	3	1/5	1/5	5
C_{2f}	1/7	7	1/7	1/7	1/7	1/7	7	7	1/7	1/7	1/7	1	1/3	1/5	3	3	3	3	1/5	1/3	1/5	1/5	1/3
C_{3a}	1/7	3	1/7	1/7	1/7	1/7	1/7	3	1/3	1/5	1/5	3	1	1/7	7	9	1/7	1/7	1/7	1/7	1/7	1/7	1/3
C_{3b}	1/7	3	5	1/7	1/7	1/7	5	3	1/3	3	3	5	7	1	5	9	3	3	5	3	1/5	3	3
C_{3c}	1/7	3	5	1/7	1/7	1/7	1/5	3	1/3	1/5	1/3	1/3	1/7	1/5	1	9	1/7	1/7	3	1/3	1/5	1/5	3
C_{3d}	1/7	3	1/7	1/7	1/7	1/7	1/7	1	1/5	1/5	1/5	1/3	1/9	1/9	1/9	1	3	3	1/5	1/5	1/5	1/5	3
C_{4a}	1/3	3	1/5	1/5	1/7	1/7	1/7	7	1/7	1/3	1/5	1/3	7	1/3	7	1/3	1	5	3	7	7	7	7
C_{4b}	1/3	3	1/5	1/5	1/7	1/7	1/7	7	1/7	1/3	1/5	1/3	7	1/3	7	1/3	1/5	1	7	7	7	7	7
C_{5a}	1/7	5	1/5	1/5	1/5	1/7	1/7	5	1/7	5	5	5	7	1/5	1/3	5	1/3	1/7	1	7	1/7	1/7	7
C_{5b}	7	3	1/3	1/5	1/5	1/7	1/7	5	1/7	1/5	1/3	3	7	1/3	3	5	1/7	1/7	1/7	1	1/7	1/7	7
C_{5c}	1/3	5	3	1/3	1/3	1/7	1/3	5	5	5	5	5	7	5	5	5	1/7	1/7	7	7	1	7	7
C_{5d}	1/5	5	1/3	1/5	1/5	1/7	1/3	5	5	5	5	5	7	1/3	5	5	1/7	1/7	7	7	1/7	1	7
C_{5e}	1/7	5	1/3	1/5	1/7	1/7	1/5	3	3	1/3	1/5	3	3	1/3	1/3	1/3	1/7	1/7	1/7	1/7	1/7	1/7	1

Table 12: Relative importance of each item within CE criteria for DM 12.

DM 12	C_{1a}	C_{1b}	C_{1c}	C_{1d}	C_{1e}	C_{1f}	C_{2a}	C_{2b}	C_{2c}	C_{2d}	C_{2e}	C_{2f}	C_{3a}	C_{3b}	C_{3c}	C_{3d}	C_{4a}	C_{4b}	C_{5a}	C_{5b}	C_{5c}	C_{5d}	C_{5e}
C_{1a}	1	1/9	1/9	1/9	1/3	1/9	3	3	3	1/5	3	3	5	5	5	9	9	9	9	7	3	9	9
C_{1b}	9	1	1/3	1/3	3	1	3	3	3	1/5	3	5	3	5	3	7	9	9	3	3	3	5	9
C_{1c}	9	3	1	3	1	1	7	7	3	1/3	7	9	7	7	7	9	9	9	5	5	1	7	7
C_{1d}	9	3	1/3	1	1/3	1/3	1/3	1	1	1/5	1/3	1	1	1	1/5	1	3	1	3	1	1	3	5
C_{1e}	3	1/3	1	3	1	1/3	5	7	7	3	5	9	9	9	9	9	9	9	9	9	5	9	9
C_{1f}	9	1	1	3	3	1	1	1	1	1/5	1	3	1	3	1	3	3	3	1	3	1	3	3
C_{2a}	1/3	1/3	1/7	3	1/5	1	1	3	1	1/5	1/5	1/5	3	3	3	5	3	3	3	1	1/7	3	3
C_{2b}	1/3	1/3	1/7	1	1/7	1	1/3	1	1	1/7	1/3	1/3	3	3	3	3	3	3	1	3	1/3	3	3
C_{2c}	1/3	1/3	1/3	1	1/7	1	1	1	1	1/9	1/9	1/9	3	3	3	3	3	3	3	5	3	3	5
C_{2d}	5	5	3	5	1/3	5	5	7	9	1	3	3	9	9	9	9	9	9	7	5	3	7	9
C_{2e}	1/3	1/3	1/7	3	1/5	1	5	3	9	1/3	1	3	5	5	5	5	3	1	3	1	1/5	3	3
C_{2f}	1/3	1/5	1/9	1	1/9	1/3	5	3	9	1/3	1/3	1	1	1	1	1	1	1	3	3	3	3	7
C_{3a}	1/5	1/3	1/7	1	1/9	1	1/3	1/3	1/3	1/9	1/5	1	1	1/3	1/3	1	1	1	1	1	1/7	1	1
C_{3b}	1/5	1/5	1/7	1	1/9	1/3	1/3	1/3	1/3	1/9	1/5	1	3	1	1	3	1	1	3	1	1/7	3	3
C_{3c}	1/5	1/3	1/7	5	1/9	1	1/3	1/3	1/3	1/9	1/5	1	3	1	1	3	1	1	1	1	1/5	1	1
C_{3d}	1/9	1/7	1/9	1	1/9	1/3	1/5	1/3	1/3	1/9	1/5	1	1	1/3	1/3	1	1	1	1	1	1/7	1	1
C_{4a}	1/9	1/9	1/9	1/3	1/9	1/3	1/3	1/3	1/3	1/9	1/3	1	1	1	1	1	1	9	1	1	1/7	1	3
C_{4b}	1/9	1/9	1/9	1	1/9	1/3	1/3	1/3	1/3	1/9	1	1	1	1	1	1	1/9	1	1	1	1	1	1
C_{5a}	1/9	1/3	1/5	1/3	1/9	1	1/3	1	1/3	1/7	1/3	1/3	1	1/3	1	1	1	1	1	1	1/9	1/7	1
C_{5b}	1/7	1/3	1/5	1	1/9	1/3	1	1/3	1/5	1/5	1	1/3	1	1	1	1	1	1	1	1	1/9	1/5	3
C_{5c}	1/3	1/3	1	1	1/5	1	7	3	1/3	1/3	5	1/3	7	7	5	7	7	1	9	9	1	9	9
C_{5d}	1/9	1/5	1/7	1/3	1/9	1/3	1/3	1/3	1/3	1/7	1/3	1/3	1	1/3	1	1	1	1	7	5	1/9	1	3
C_{5e}	1/9	1/9	1/7	1/5	1/9	1/3	1/3	1/3	1/5	1/9	1/3	1/7	1	1/3	1	1	1/3	1	1	1/3	1/9	1/3	1

Table 13: Relative importance of each item within CE criteria for DM 13.

DM 13	C_{1a}	C_{1b}	C_{1c}	C_{1d}	C_{1e}	C_{1f}	C_{2a}	C_{2b}	C_{2c}	C_{2d}	C_{2e}	C_{2f}	C_{3a}	C_{3b}	C_{3c}	C_{3d}	C_{4a}	C_{4b}	C_{5a}	C_{5b}	C_{5c}	C_{5d}	C_{5e}
C_{1a}	1	1/5	1	1	1/5	1/3	3	3	3	5	3	1	3	3	3	3	1/3	3	1	3	3	3	5
C_{1b}	5	1	3	3	3	3	1	1	1	3	1	1	3	1	1	3	1	3	1	3	1	1	3
C_{1c}	1	1/3	1	1	1/3	1/3	1/3	1/3	1/3	1	1/3	1/3	1/3	1/3	1/3	1/3	1/5	1	1/5	1	1/3	1	1
C_{1d}	1	1/3	1	1	1/5	1/3	1	1	1	3	1/3	1/3	1	1	1	1	1/3	3	1	3	1	1	3
C_{1e}	5	1/3	3	5	1	1	5	5	5	5	3	3	3	3	3	3	1	5	3	5	3	3	5
C_{1f}	3	1/3	3	3	1	1	3	3	3	3	1	1	3	3	3	3	1/3	3	1	3	1	3	3
C_{2a}	1/3	1	3	1	1/5	1/3	1	1/3	3	3	1/3	1/3	1	1	1	3	1/5	1	1	3	1	1	3
C_{2b}	1/3	1	3	1	1/5	1/3	3	1	1	1	1/3	1/3	1	1/3	1/3	1	1/5	1	1	1	1	1	3
C_{2c}	1/3	1	3	1	1/5	1/3	1/3	1	1	1	1/3	1/3	1	1	1	3	1/5	1	1/3	3	1	1	3
C_{2d}	1/5	1/3	1	1/3	1/5	1/3	1/3	1	1	1	1/3	1/3	1/3	1/3	1/3	1	1/7	1	1/3	1/3	1/3	1/3	1
C_{2e}	1/3	1	3	3	1/3	1	3	3	3	3	1	1	1	1	1	3	1/3	1	1	3	1	3	3
C_{2f}	1	1	3	3	1/3	1	3	3	3	3	1	1	1	1	1	3	1/3	1	1	5	3	3	5
C_{3a}	1/3	1/3	3	1	1/3	1/3	1	1	1	3	1	1	1	3	1/3	1	1/5	1	1/3	1	1/3	1	3
C_{3b}	1/3	1	3	1	1/3	1/3	1	3	1	3	1	1	1/3	1	1/3	1	1/5	1	1	3	1	1	3
C_{3c}	1/3	1	3	1	1/3	1/3	1	3	1	3	1	1	3	3	1	3	1/5	1	1	3	1	1	3
C_{3d}	1/3	1/3	3	1	1/3	1/3	1/3	1	1/3	1	1/3	1/3	1	1	1/3	1	1/5	1	1/3	1	1/3	1/3	1
C_{4a}	3	1	5	3	1	3	5	5	5	7	3	3	5	5	5	5	1	7	3	5	5	5	7
C_{4b}	1/3	1/3	1	1/3	1/5	1/3	1	1	1	1	1	1	1	1	1	1	1/7	1	1/3	1	1/3	1/3	1
C_{5a}	1	1	5	1	1/3	1	1	1	3	3	1	1	3	1	1	3	1/3	3	1	5	1	3	3
C_{5b}	1/3	1/3	1	1/3	1/5	1/3	1/3	1	1/3	3	1/3	1/5	1	1/3	1/3	1	1/5	1	1/5	1	1/3	1	3
C_{5c}	1/3	1	3	1	1/3	1	1	1	1	3	1	1/3	3	1	1	3	1/5	3	1	3	1	3	5
C_{5d}	1/3	1	1	1	1/3	1/3	1	1	1	3	1/3	1/3	1	1	1	3	1/5	3	1/3	1	1/3	1	3
C_{5e}	1/5	1/3	1	1/3	1/5	1/3	1/3	1/3	1/3	1	1/3	1/5	1/3	1/3	1/3	1	1/7	1	1/3	1/3	1/5	1/3	1

Table 14: Relative importance of each item within CE criteria for DM 14.

DM 14	C_{1a}	C_{1b}	C_{1c}	C_{1d}	C_{1e}	C_{1f}	C_{2a}	C_{2b}	C_{2c}	C_{2d}	C_{2e}	C_{2f}	C_{3a}	C_{3b}	C_{3c}	C_{3d}	C_{4a}	C_{4b}	C_{5a}	C_{5b}	C_{5c}	C_{5d}	C_{5e}
C_{1a}	1	1	1	1	1	1	9	1	9	9	1	9	9	9	9	9	1	9	9	9	9	9	1
C_{1b}	1	1	1	1	1	1	9	1	9	9	1	9	9	9	9	9	1	9	9	9	9	9	1
C_{1c}	1	1	1	1	1	1	9	1/9	5	5	1/9	7	1	1	1	1	1/9	9	1	1	1	1	1/9
C_{1d}	1	1	1	1	1	1	7	1/9	1	7	1/9	7	1	1	1	1	1/9	9	1	1	1	1	1/9
C_{1e}	1	1	1	1	1	1	9	5	9	9	5	9	9	9	9	9	1	9	9	9	9	9	9
C_{1f}	1	1	1	1	1	1	5	1	5	5	1/9	5	9	9	9	9	1/9	9	9	9	9	9	1
C_{2a}	1/9	1/9	1/9	1/7	1/9	1/5	1	1/7	1/9	1/5	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1	1/9	1/9	1/9	1/9	1/9
C_{2b}	1	1	9	9	1/5	1	7	1	9	9	1	9	1	1	1	1	1/9	1	9	9	9	9	9
C_{2c}	1/9	1/9	1/5	1	1/9	1/5	9	1/9	1	5	1/9	9	1/9	1/9	1/9	1/9	1/9	1	1/9	1/9	1/9	1/9	1/9
C_{2d}	1/9	1/9	1/5	1/7	1/9	1/5	5	1/9	1/5	1	1/7	5	1/9	1/9	1/9	1/9	1/9	1	1/9	1/9	1/9	1/9	1/9
C_{2e}	1	1	9	9	1/5	9	9	1	9	7	1	9	9	9	9	9	1	9	9	9	9	9	9
C_{2f}	1/9	1/9	1/7	1/7	1/9	1/5	9	1/9	1/9	1/5	1/9	1	9	9	9	9	1/9	1	1/9	1/9	1/9	1/9	1/9
C_{3a}	1/9	1/9	1	1	1/9	1/9	9	1	9	9	1/9	1/9	1	9	1/9	1/9	1/9	9	1	1	1	1	1/9
C_{3b}	1/9	1/9	1	1	1/9	1/9	9	1	9	9	1/9	1/9	1/9	1	1/9	1/9	1/9	9	1	1	1	1	1/9
C_{3c}	1/9	1/9	1	1	1/9	1/9	9	1	9	9	1/9	1/9	9	9	1	1/9	1/9	9	1	1	1	1	1/9
C_{3d}	1/9	1/9	1	1	1/9	1/9	9	1	9	9	1/9	1/9	9	9	9	1	1/9	9	1	1	1	1	1/9
C_{4a}	1	1	9	9	1	9	9	9	9	9	1	9	9	9	9	9	1	9	9	9	9	9	1
C_{4b}	1/9	1/9	1/9	1/9	1/9	1/9	1	1	1	1	1/9	1	1/9	1/9	1/9	1/9	1/9	1	1/9	1/9	1/9	1/9	1/9
C_{5a}	1/9	1/9	1	1	1/9	1/9	9	1/9	9	9	1/9	9	1	1	1	1	1/9	9	1	5	1/7	7	1/9
C_{5b}	1/9	1/9	1	1	1/9	1/9	9	1/9	9	9	1/9	9	1	1	1	1	1/9	9	1/5	1	1/9	1/9	1/9
C_{5c}	1/9	1/9	1	1	1/9	1/9	9	1/9	9	9	1/9	9	1	1	1	1	1/9	9	7	9	1	7	1/9
C_{5d}	1/9	1/9	1	1	1/9	1/9	9	1/9	9	9	1/9	9	1	1	1	1	1/9	9	1/7	9	1/7	1	1/9
C_{5e}	1	1	9	9	1/9	1	9	1/9	9	9	1/9	9	9	9	9	9	1	9	9	9	9	9	1

Table 15: Relative importance of each item within CE criteria for DM 15.

DM 15	C_{1a}	C_{1b}	C_{1c}	C_{1d}	C_{1e}	C_{1f}	C_{2a}	C_{2b}	C_{2c}	C_{2d}	C_{2e}	C_{2f}	C_{3a}	C_{3b}	C_{3c}	C_{3d}	C_{4a}	C_{4b}	C_{5a}	C_{5b}	C_{5c}	C_{5d}	C_{5e}
C_{1a}	1	1/7	1/7	1/7	1/7	1/7	1/7	1/7	1/7	1/9	1/7	1/7	1/5	1/5	1/5	1/5	5	1	1/5	1/5	1/5	1/5	1/5
C_{1b}	7	1	1/7	1/7	1/7	1/7	1/7	1/7	7	1/9	1/7	7	1/5	1/5	1/5	1/5	5	1	5	5	5	5	5
C_{1c}	7	7	1	7	7	1/7	7	7	7	1/3	7	5	1/5	1/5	1/5	5	5	1	5	5	5	5	5
C_{1d}	7	7	1/7	1	7	1/7	5	1	5	1/7	5	5	5	5	5	5	5	1	5	5	5	5	5
C_{1e}	7	7	1/7	1/7	1	1/7	1/5	1/5	1/5	1/7	1/7	5	1/5	1/5	1/5	5	5	1	5	5	5	5	5
C_{1f}	7	7	7	7	7	1	5	5	5	1/7	5	5	5	5	5	5	7	5	7	7	7	7	7
C_{2a}	7	7	1/7	1/5	5	1/5	1	1/7	3	1/9	1/7	1/7	1/5	1/5	1/5	1/5	3	7	5	5	5	5	5
C_{2b}	7	7	1/7	1	5	1/5	7	1	7	1/7	1/7	1/7	1/5	1/5	1/5	1/5	3	7	5	5	5	5	5
C_{2c}	7	1/7	1/7	1/5	5	1/5	1/3	1/7	1	1/7	1/7	1/7	1/5	1/5	1/5	1/5	3	7	5	5	5	5	5
C_{2d}	9	9	3	7	7	7	9	7	7	1	7	7	7	7	7	7	7	7	7	7	7	7	7
C_{2e}	7	7	1/7	1/5	7	1/5	7	7	7	1/7	1	7	1/5	1/5	1/5	1/5	3	7	5	5	5	5	5
C_{2f}	7	1/7	1/5	1/5	1/5	1/5	7	7	7	1/7	1/7	1	1/5	1/5	1/5	1/5	3	7	5	5	5	5	5
C_{3a}	5	5	5	1/5	5	1/5	5	5	5	1/7	5	5	1	1/7	1/7	1/7	3	5	5	5	5	5	5
C_{3b}	5	5	5	1/5	5	1/5	5	5	5	1/7	5	5	7	1	1/7	1/7	3	5	5	5	5	5	5
C_{3c}	5	5	5	1/5	5	1/5	5	5	5	1/7	5	5	7	7	1	1/7	3	5	5	5	5	5	5
C_{3d}	5	5	1/5	1/5	1/5	1/5	5	5	5	1/7	5	5	7	7	7	1	3	5	5	5	5	5	5
C_{4a}	1/5	1/5	1/5	1/5	1/5	1/7	1/3	1/3	1/3	1/7	1/3	1/3	1/3	1/3	1/3	1/3	1	1/7	3	3	3	3	3
C_{4b}	1	1	1	1	1	1/5	1/7	1/7	1/7	1/7	1/7	1/7	1/5	1/5	1/5	1/5	7	1	1/3	1/3	1/3	1/3	1/3
C_{5a}	5	1/5	1/5	1/5	1/5	1/7	1/5	1/5	1/5	1/7	1/5	1/5	1/5	1/5	1/5	1/5	1/3	3	1	1/7	1/7	1/7	1/7
C_{5b}	5	1/5	1/5	1/5	1/5	1/7	1/5	1/5	1/5	1/7	1/5	1/5	1/5	1/5	1/5	1/5	1/3	3	7	1	1/7	1/7	1/7
C_{5c}	5	1/5	1/5	1/5	1/5	1/7	1/5	1/5	1/5	1/7	1/5	1/5	1/5	1/5	1/5	1/5	1/3	3	7	7	1	7	7
C_{5d}	5	1/5	1/5	1/5	1/5	1/7	1/5	1/5	1/5	1/7	1/5	1/5	1/5	1/5	1/5	1/5	1/3	3	7	7	1/7	1	1/7
C_{5e}	5	1/5	1/5	1/5	1/5	1/7	1/5	1/5	1/5	1/7	1/5	1/5	1/5	1/5	1/5	1/5	1/3	3	7	7	1/7	7	1

Table 16: Relative importance of each item within CE criteria for DM 16.

DM 16	C_{1a}	C_{1b}	C_{1c}	C_{1d}	C_{1e}	C_{1f}	C_{2a}	C_{2b}	C_{2c}	C_{2d}	C_{2e}	C_{2f}	C_{3a}	C_{3b}	C_{3c}	C_{3d}	C_{4a}	C_{4b}	C_{5a}	C_{5b}	C_{5c}	C_{5d}	C_{5e}
C_{1a}	1	1/7	1/7	1/7	1/7	1/7	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3
C_{1b}	7	1	1	3	3	3	1	3	3	3	3	3	3	3	3	3	1/3	1/3	3	3	3	3	3
C_{1c}	7	1	1	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/5	1/5	1/3	1/3	1/3	1/3	1/7
C_{1d}	7	1/3	3	1	1/3	1/3	3	3	3	3	3	3	1/3	1/3	1/3	1/3	1/5	1/5	1/7	1/3	1/3	1/3	1/5
C_{1e}	7	1/3	3	3	1	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/5	1/5	1/5	1/5	1	1	1/5	1/5	1/5	1/5	1/5
C_{1f}	7	1/3	3	3	3	1	1/7	1/7	1/7	1/7	1/7	1/7	1/7	1/7	1/7	1/7	1	1	1/7	1/7	1/7	1/7	1/7
C_{2a}	3	1	3	1/3	3	7	1	3	3	3	3	3	1/3	1/3	1/3	1/3	1/7	1/7	1/7	1/7	1/7	1/7	1/7
C_{2b}	3	1/3	3	1/3	3	7	1/3	1	1/3	1/3	1/3	1/3	1/7	1/7	1/7	1/7	1/5	1/5	1/5	1/5	1/5	1/5	1/5
C_{2c}	3	1/3	3	1/3	3	7	1/3	3	1	3	3	3	1/5	1/5	1/5	1/5	1/7	1/7	1/7	1/7	1/7	1/7	1/7
C_{2d}	3	1/3	3	1/3	3	7	1/3	3	1/3	1	1/3	1/3	1/7	1/7	1/7	1/7	1/5	1/5	1/9	1/9	1/9	1/9	1/9
C_{2e}	3	1/3	3	1/3	3	7	1/3	3	1/3	3	1	1/7	1/5	1/5	1/5	1/5	1/3	1/3	1/5	1/5	1/5	1/5	1/5
C_{2f}	3	1/3	3	1/3	3	7	1/3	3	1/3	3	7	1	3	3	3	3	1/7	1/7	1/7	1/7	1/7	1/7	1/7
C_{3a}	3	1/3	3	3	5	7	3	7	5	7	5	1/3	1	7	7	7	1/3	1/3	1/3	1/3	1/3	1/3	1/3
C_{3b}	3	1/3	3	3	5	7	3	7	5	7	5	1/3	1/7	1	7	7	1/3	1/3	1/5	1/5	1/5	1/5	1/5
C_{3c}	3	1/3	3	3	5	7	3	7	5	7	5	1/3	1/7	1/7	1	5	1/5	1/5	1/3	1/3	1/3	1/3	1/3
C_{3d}	3	1/3	3	3	5	7	3	7	5	7	5	1/3	1/7	1/7	1/5	1	1/5	1/5	1/7	1/7	1/7	1/7	1/7
C_{4a}	3	3	5	5	1	1	7	5	7	5	3	7	3	3	5	5	1	7	3	3	3	3	3
C_{4b}	3	3	5	5	1	1	7	5	7	5	3	7	3	3	5	5	1/7	1	5	5	5	5	5
C_{5a}	3	1/3	3	7	5	7	7	5	7	9	5	7	3	5	3	7	1/3	1/5	1	1/7	1/7	1/7	1/7
C_{5b}	3	1/3	3	3	5	7	7	5	7	9	5	7	3	5	3	7	1/3	1/5	7	1	3	3	3
C_{5c}	3	1/3	3	3	5	7	7	5	7	9	5	7	3	5	3	7	1/3	1/5	7	1/3	1	3	3
C_{5d}	3	1/3	3	3	5	7	7	5	7	9	5	7	3	5	3	7	1/3	1/5	7	1/3	1/3	1	1/3
C_{5e}	3	1/3	7	5	5	7	7	5	7	9	5	7	3	5	3	7	1/3	1/5	7	1/3	1/3	3	1

Table 17: Relative importance of each item within CE criteria for DM 17.

DM 17	C_{1a}	C_{1b}	C_{1c}	C_{1d}	C_{1e}	C_{1f}	C_{2a}	C_{2b}	C_{2c}	C_{2d}	C_{2e}	C_{2f}	C_{3a}	C_{3b}	C_{3c}	C_{3d}	C_{4a}	C_{4b}	C_{5a}	C_{5b}	C_{5c}	C_{5d}	C_{5e}
C_{1a}	1	1/3	1/5	1	9	1/9	1/3	5	1/3	1/9	1/9	1/7	1/5	1/7	1/7	1/5	1/3	1/7	1/7	1/5	1/9	1/9	1
C_{1b}	3	1	7	5	9	1/3	3	7	5	1/7	1/7	1/7	1/3	1/5	5	1	7	7	1/3	7	1/3	1/3	7
C_{1c}	5	1/7	1	1/3	7	1/5	1	3	1	1/9	1/5	1/5	1	1/5	5	1	1	1/3	1/5	1/5	3	3	9
C_{1d}	1	1/5	3	1	9	3	3	7	7	1/9	1/7	1/7	1/5	1/7	9	3	5	5	3	5	1/5	1/5	3
C_{1e}	1/9	1/9	1/7	1/9	1	1/7	1/3	1	1/3	1/9	1/9	1/9	1/5	1/5	1	1/5	1/3	1/5	1/9	1/7	1/9	1/7	5
C_{1f}	9	3	5	1/3	7	1	3	5	7	1/5	1/5	1/5	5	1/7	9	3	9	7	5	7	9	9	7
C_{2a}	3	1/3	1	1/3	3	1/3	1	5	1/5	1/9	1/9	1/9	1/5	1/9	1/3	1/7	1/7	1/7	1/9	1/9	1/9	1/9	1/3
C_{2b}	1/5	1/7	1/3	1/7	1	1/5	1/5	1	1/7	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/7	1/7	1/9	1/9	1/9	1/9	1/9
C_{2c}	3	1/5	1	1/7	3	1/7	5	7	1	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9
C_{2d}	9	7	9	9	9	5	9	9	9	1	7	9	7	7	9	5	9	9	1	1/5	1/7	1/3	1
C_{2e}	9	7	5	7	9	5	9	9	9	1/7	1	9	3	1/3	7	1	1	1	1	1/5	1/5	1/3	1
C_{2f}	7	7	5	7	9	5	9	9	9	1/9	1/9	1	1/3	1/3	3	1/3	3	5	1/5	1/5	1/5	1/3	1
C_{3a}	5	3	1	5	5	1/5	5	9	9	1/7	1/3	3	1	1/9	5	1/7	7	7	5	5	1/3	5	9
C_{3b}	7	5	5	7	5	7	9	9	9	1/7	3	3	9	1	9	7	9	9	7	3	7	9	9
C_{3c}	7	1/5	1/5	1/9	1	1/9	3	9	9	1/9	1/7	1/3	1/5	1/9	1	1/5	9	1	1/5	1/7	1/9	1/9	7
C_{3d}	5	1	1	1/3	5	1/3	7	9	9	1/5	1	3	7	1/7	5	1	5	3	1	3	1	5	9
C_{4a}	3	1/7	1	1/5	3	1/9	7	7	9	1/9	1	1/3	1/7	1/9	1/9	1/5	1	1/5	1/7	1/7	1/9	1/7	1
C_{4b}	7	1/7	3	1/5	5	1/7	7	7	9	1/9	1	1/5	1/7	1/9	1	1/3	5	1	1/5	1/7	1/9	1/5	9
C_{5a}	7	3	5	1/3	9	1/5	9	9	9	1	1	5	1/5	1/7	5	1	7	5	1	1/5	7	5	7
C_{5b}	5	1/7	5	1/5	7	1/7	9	9	9	5	5	5	1/5	1/3	7	1/3	7	7	5	1	1/5	7	9
C_{5c}	9	3	1/3	5	9	1/9	9	9	9	7	5	5	3	1/7	9	1	9	9	1/7	5	1	1/5	9
C_{5d}	9	3	1/3	5	7	1/9	9	9	9	3	3	3	1/5	1/9	9	1/5	7	5	1/5	1/7	5	1	9
C_{5e}	1	1/7	1/9	1/3	1/5	1/7	3	9	9	1	1	1	1/9	1/9	1/7	1/9	1	1/9	1/7	1/9	1/9	1/9	1

Table 18: Relative importance of each item within CE criteria for DM 18.

DM 18	C_{1a}	C_{1b}	C_{1c}	C_{1d}	C_{1e}	C_{1f}	C_{2a}	C_{2b}	C_{2c}	C_{2d}	C_{2e}	C_{2f}	C_{3a}	C_{3b}	C_{3c}	C_{3d}	C_{4a}	C_{4b}	C_{5a}	C_{5b}	C_{5c}	C_{5d}	C_{5e}
C_{1a}	1	7	7	7	7	7	5	1	5	1/3	1/5	1	5	1	1	3	5	1	3	1/3	3	1	1
C_{1b}	1/7	1	5	5	5	5	3	5	3	1	1/3	1	1/3	1	1	3	3	1	3	5	1/3	1	5
C_{1c}	1/7	1/5	1	7	7	7	5	1	1	1	1/3	1	1/5	5	1/3	1	1	1/3	1/3	7	1/3	3	5
C_{1d}	1/7	1/5	1/7	1	7	7	1	1/3	3	1/3	5	1	3	5	7	3	1/3	3	1	7	3	3	7
C_{1e}	1/7	1/5	1/7	1/7	1	5	3	1/3	5	1	1	1/3	1/3	7	3	5	1	3	5	1	3	5	5
C_{1f}	1/7	1/5	1/7	1/7	1/5	1	1	1	3	1	5	3	3	5	7	3	5	1	1	5	1	5	3
C_{2a}	1/5	1/3	1/5	1	1/3	1	1	1/7	1/5	1/5	5	1/5	7	1	1/3	3	1/5	1	3	1/3	3	1	3
C_{2b}	1	1/5	1	3	3	1	7	1	1/3	1/5	1/5	1/3	3	1/3	5	1/3	1/3	3	1	1/3	1	3	1/5
C_{2c}	1/5	1/3	1	1/3	1/5	1/3	5	3	1	1/3	1/3	1/5	3	5	1	3	1	3	5	1	1/3	5	1
C_{2d}	3	1	1	3	1	1	5	5	3	1	1/5	1/3	1	3	1/3	3	7	1	1/3	3	1	1/3	3
C_{2e}	5	3	3	1/5	1	1/5	1/5	5	3	5	1	1	3	5	3	3	3	5	1/3	3	1	1/3	1
C_{2f}	1	1	1	1	3	1/3	5	3	5	3	1	1	5	7	3	7	1/3	5	3	1/3	1/3	1	3
C_{3a}	1/5	3	5	1/3	3	1/3	1/7	1/3	1/3	1	1/3	1/5	1	3	1/3	5	3	5	5	3	1/3	1/3	1
C_{3b}	1	1	1/5	1/5	1/7	1/5	1	3	1/5	1/3	1/5	1/7	1/3	1	3	1/5	5	1	3	1/3	3	1	1
C_{3c}	1	1	3	1/7	1/3	1/7	3	1/5	1	3	1/3	1/3	3	1/3	1	7	3	1/3	1/5	1/3	1/3	3	1
C_{3d}	1/3	1/3	1	1/3	1/5	1/3	1/3	3	1/3	1/3	1/3	1/7	1/5	5	1/7	1	1	1	3	3	1/3	1/5	1/3
C_{4a}	1/5	1/3	1	3	1	1/5	5	3	1	1/7	1/3	3	1/3	1/5	1/3	1	1	5	3	3	1	1	3
C_{4b}	1	1	3	1/3	1/3	1	1	1/3	1/3	1	1/5	1/5	1/5	1	3	1	1/5	1	5	1	1/3	1	3
C_{5a}	1/3	1/3	3	1	1/5	1	1/3	1	1/5	3	3	1/3	1/5	1/3	5	1/3	1/3	1/5	1	1/3	1	3	1
C_{5b}	3	1/5	1/7	1/7	1	1/5	3	3	1	1/3	1/3	3	1/3	3	3	1/3	1/3	1	3	1	1/3	1	1
C_{5c}	1/3	3	3	1/3	1/3	1	1/3	1	3	1	1	3	3	1/3	3	3	1	3	1	3	1	5	1/3
C_{5d}	1	1	1/3	1/3	1/5	1/5	1	1/3	1/5	3	3	1	3	1	1/3	5	1	1	1/3	1	1/5	1	3
C_{5e}	1	1/5	1/5	1/7	1/5	1/3	1/3	5	1	1/3	1	1/3	1	1	1	3	1/3	1/3	1	1	3	1/3	1

Appendix H (Questionnaire result from phase 1 pertaining to sustainability dimension)

Table 1: Relative importance of each dimension within sustainability criteria for DM 1.

DM 1	S_1	S_2	S_3
S_1	1	3	5
S_2	1/3	1	3
S_3	1/5	1/3	1

Table 2: Relative importance of each dimension within sustainability criteria for DM 2.

DM 2	S_1	S_2	S_3
S_1	1	1/7	1/7
S_2	7	1	7
S_3	7	1/7	1

Table 3: Relative importance of each dimension within sustainability criteria for DM 3.

DM 3	S_1	S_2	S_3
S_1	1	3	3
S_2	1/3	1	1
S_3	1/3	1	1

Table 4: Relative importance of each dimension within sustainability criteria for DM 4.

DM 4	S_1	S_2	S_3
S_1	1	1/9	1/9
S_2	9	1	9
S_3	9	1/9	1

Table 5: Relative importance of each dimension within sustainability criteria for DM 5.

DM 5	S_1	S_2	S_3
S_1	1	7	7
S_2	1/7	1	5
S_3	1/7	1/5	1

Table 6: Relative importance of each dimension within sustainability criteria for DM 6.

DM 6	S_1	S_2	S_3
S_1	1	1/7	5
S_2	7	1	3
S_3	1/5	1/3	1

Table 7: Relative importance of each dimension within sustainability criteria for DM 7.

DM 7	S_1	S_2	S_3
S_1	1	1/9	1/9
S_2	9	1	1/9
S_3	9	9	1

Table 8: Relative importance of each dimension within sustainability criteria for DM 8.

DM 8	S_1	S_2	S_3
S_1	1	1/3	1/3
S_2	3	1	3
S_3	3	1/3	1

Table 9: Relative importance of each dimension within sustainability criteria for DM 9.

DM 9	S_1	S_2	S_3
S_1	1	1/9	1/9
S_2	9	1	1/9
S_3	9	9	1

Table 10: Relative importance of each dimension within sustainability criteria for DM 10.

DM 10	S_1	S_2	S_3
S_1	1	5	7
S_2	1/5	1	5
S_3	1/7	1/5	1

Table 11: Relative importance of each dimension within sustainability criteria for DM 11.

DM 11	S_1	S_2	S_3
S_1	1	1/9	1/3
S_2	9	1	9
S_3	3	1/9	1

Table 12: Relative importance of each dimension within sustainability criteria for DM 12.

DM 12	S_1	S_2	S_3
S_1	1	1/9	1/9
S_2	9	1	1/9
S_3	9	9	1

Table 13: Relative importance of each dimension within sustainability criteria for DM 13.

DM 13	S_1	S_2	S_3
S_1	1	5	5
S_2	1/5	1	1/3
S_3	1/5	3	1

Table 14: Relative importance of each dimension within sustainability criteria for DM 14.

DM 14	S_1	S_2	S_3
S_1	1	1/5	1/9
S_2	5	1	5
S_3	9	1/5	1

Table 15: Relative importance of each dimension within sustainability criteria for DM 15.

DM 15	S_1	S_2	S_3
S_1	1	1	1
S_2	1	1	1
S_3	1	1	1

Table 16: Relative importance of each dimension within sustainability criteria for DM 16.

DM 16	S_1	S_2	S_3
S_1	1	1	7
S_2	1	1	7
S_3	1/7	1/7	1

Table 17: Relative importance of each dimension within sustainability criteria for DM 17.

DM 17	S_1	S_2	S_3
S_1	1	1/3	3
S_2	3	1	3
S_3	1/3	1/3	1

Table 18: Relative importance of each dimension within sustainability criteria for DM 18.

DM 18	S_1	S_2	S_3
S_1	1	5	3
S_2	1/5	1	1/3
S_3	1/3	3	1

Appendix I (Questionnaire result from phase 1 pertaining to sustainability item)

Table 1: Relative importance of each item within sustainability criteria for DM 1.

DM 1	S_{1a}	S_{1b}	S_{1c}	S_{2a}	S_{2b}	S_{2c}	S_{2d}	S_{3a}	S_{3b}	S_{3c}	S_{3d}	S_{3e}
S_{1a}	1	1	3	1/5	1/5	1/5	1/5	1/3	1/5	1/5	1/5	1/3
S_{1b}	1	1	3	1/5	1/5	1/5	1/5	1/3	1/5	1/5	1/3	1
S_{1c}	1/3	1/3	1	1/5	1/5	1/5	1/5	1/3	1/5	1/5	1/3	1/3
S_{2a}	5	5	5	1	1	3	3	5	3	3	5	7
S_{2b}	5	5	5	1	1	3	3	5	1	1	3	7
S_{2c}	5	5	5	1/3	1/3	1	1/3	5	1	1	3	7
S_{2d}	5	5	5	1/3	1/3	3	1	7	5	5	7	7
S_{3a}	3	3	3	1/5	1/5	1/5	1/7	1	1/5	1/5	1/3	1
S_{3b}	5	5	5	1/3	1	1	1/5	5	1	1	5	5
S_{3c}	5	5	5	1/3	1	1	1/5	5	1	1	5	5
S_{3d}	5	3	3	1/5	1/3	1/3	1/7	3	1/5	1/5	1	1
S_{3e}	3	1	3	1/7	1/7	1/7	1/7	1	1/5	1/5	1	1

Table 2: Relative importance of each item within sustainability criteria for DM 2.

DM 2	S_{1a}	S_{1b}	S_{1c}	S_{2a}	S_{2b}	S_{2c}	S_{2d}	S_{3a}	S_{3b}	S_{3c}	S_{3d}	S_{3e}
S_{1a}	1	7	1/7	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9
S_{1b}	1/7	1	1/7	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9
S_{1c}	7	7	1	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9
S_{2a}	9	9	9	1	1	1	1/7	9	9	1/9	1/9	9
S_{2b}	9	9	9	1	1	1	1/7	9	1	1	1/9	9
S_{2c}	9	9	9	1	1	1	1/7	9	1	1	1	9
S_{2d}	9	9	9	7	7	7	1	9	9	9	1/9	9
S_{3a}	9	9	9	1/9	1/9	1/9	1/9	1	1/7	1/7	1/9	1/7
S_{3b}	9	9	9	1/9	1	1	1/9	7	1	1/7	1/9	1
S_{3c}	9	9	9	9	1	1	1/9	7	7	1	1/9	9
S_{3d}	9	9	9	9	9	1	9	9	9	9	1	9
S_{3e}	9	9	9	1/9	1/9	1/9	1/9	7	1	1/9	1/9	1

Table 3: Relative importance of each item within sustainability criteria for DM 3.

DM 3	S_{1a}	S_{1b}	S_{1c}	S_{2a}	S_{2b}	S_{2c}	S_{2d}	S_{3a}	S_{3b}	S_{3c}	S_{3d}	S_{3e}
S_{1a}	1	7	1/9	1/5	1/5	1/5	1/5	3	3	1	1	3
S_{1b}	1/7	1	1/7	1/5	1/5	1/5	1/5	3	3	1	1	3
S_{1c}	9	7	1	1/3	1/3	1/3	1/3	1	1	1	1	3
S_{2a}	5	5	3	1	1	1	1	5	5	1	1	3
S_{2b}	5	5	3	1	1	1	3	3	3	1	1	5
S_{2c}	5	5	3	1	1	1	3	3	3	3	1	5
S_{2d}	5	5	3	1	1/3	1/3	1	3	3	3	1	5
S_{3a}	1/3	1/3	1	1/5	1/3	1/3	1/3	1	1	3	1	5
S_{3b}	1/3	1/3	1	1/5	1/3	1/3	1/3	1	1	1	1	5
S_{3c}	1	1	1	1	1	1/3	1/3	1/3	1	1	1	5
S_{3d}	1	1	1	1	1	1	1	1	1	1	1	5
S_{3e}	1/3	1/3	1/3	1/3	1/5	1/5	1/5	1/5	1/5	1/5	1/5	1

Table 4: Relative importance of each item within sustainability criteria for DM 4.

DM 4	S_{1a}	S_{1b}	S_{1c}	S_{2a}	S_{2b}	S_{2c}	S_{2d}	S_{3a}	S_{3b}	S_{3c}	S_{3d}	S_{3e}
S_{1a}	1	9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9
S_{1b}	1/9	1	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9
S_{1c}	9	9	1	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9	1/9
S_{2a}	9	9	9	1	1	1	1	9	9	1/9	1/9	9
S_{2b}	9	9	9	1	1	1	1	9	9	9	1/9	9
S_{2c}	9	9	9	1	1	1	1	9	9	9	1/9	9
S_{2d}	9	9	9	1	1	1	1	9	9	9	1/9	9
S_{3a}	9	9	9	1/9	1/9	1/9	1/9	1	1/9	1/9	1/9	1
S_{3b}	9	9	9	1/9	1/9	1/9	1/9	9	1	1/9	1/9	1
S_{3c}	9	9	9	9	1/9	1/9	1/9	9	9	1	1/9	9
S_{3d}	9	9	9	9	9	9	9	9	9	9	1	9
S_{3e}	9	9	9	1/9	1/9	1/9	1/9	1	1	1/9	1/9	1

Table 5: Relative importance of each item within sustainability criteria for DM 5.

DM 5	S_{1a}	S_{1b}	S_{1c}	S_{2a}	S_{2b}	S_{2c}	S_{2d}	S_{3a}	S_{3b}	S_{3c}	S_{3d}	S_{3e}
S_{1a}	1	5	1/3	5	3	7	3	5	5	5	7	7
S_{1b}	1/5	1	1/3	3	1/3	7	3	1/3	1/3	3	5	7
S_{1c}	3	3	1	1/3	1/3	5	1/3	1/5	1/3	1/5	1/3	3
S_{2a}	1/5	1/3	3	1	1	5	1	1/3	5	1/3	5	5
S_{2b}	1/3	3	3	1	1	5	1	3	3	5	3	5
S_{2c}	1/7	1/7	1/5	1/5	1/5	1	1/5	1/7	1/7	1/7	1/5	1/5
S_{2d}	1/3	1/3	3	1	1	5	1	1/7	3	5	5	7
S_{3a}	1/5	3	5	3	1/3	7	7	1	5	1/3	5	7
S_{3b}	1/5	3	3	1/5	1/3	7	1/3	1/5	1	1	5	3
S_{3c}	1/5	1/3	5	3	1/5	7	1/5	3	1	1	3	3
S_{3d}	1/7	1/5	3	1/5	1/3	5	1/5	1/5	1/5	1/3	1	1/3
S_{3e}	1/7	1/7	1/3	1/5	1/5	5	1/7	1/7	1/3	1/3	3	1

Table 6: Relative importance of each item within sustainability criteria for DM 6.

DM 6	S_{1a}	S_{1b}	S_{1c}	S_{2a}	S_{2b}	S_{2c}	S_{2d}	S_{3a}	S_{3b}	S_{3c}	S_{3d}	S_{3e}
S_{1a}	1	1	5	1/9	1/5	5	1/5	1	3	1/9	7	5
S_{1b}	1	1	3	1/9	1/7	1/3	1/5	3	1/7	1/9	5	1/5
S_{1c}	1/5	1/3	1	1/9	1/5	1/7	1/7	5	1/5	1/9	7	5
S_{2a}	9	9	9	1	7	5	7	9	9	1/5	9	9
S_{2b}	5	7	5	1/7	1	1	1/5	5	1/7	1/9	7	5
S_{2c}	1/5	3	7	1/5	1	1	1/5	5	1/3	1/9	5	5
S_{2d}	5	5	7	1/7	5	5	1	7	5	1/7	7	7
S_{3a}	1	1/3	1/5	1/9	1/5	1/5	1/7	1	1/5	1/5	9	1/5
S_{3b}	1/3	7	5	1/9	7	3	1/5	5	1	1/7	9	1/5
S_{3c}	9	9	9	5	9	9	7	5	7	1	9	7
S_{3d}	1/7	1/5	1/7	1/9	1/7	1/5	1/7	1/9	1/9	1/9	1	1/5
S_{3e}	1/5	5	1/5	1/9	1/5	1/5	1/7	5	5	1/7	5	1

Table 7: Relative importance of each item within sustainability criteria for DM 7.

DM 7	S_{1a}	S_{1b}	S_{1c}	S_{2a}	S_{2b}	S_{2c}	S_{2d}	S_{3a}	S_{3b}	S_{3c}	S_{3d}	S_{3e}
S_{1a}	1	5	1/9	3	3	1/5	3	7	7	5	7	7
S_{1b}	1/5	1	1/9	1/3	1/3	1/5	1/5	5	3	1	7	9
S_{1c}	9	9	1	3	3	3	3	9	7	9	9	9
S_{2a}	1/3	3	1/3	1	1/5	1/7	1/5	1	3	1/5	1/3	1
S_{2b}	1/3	3	1/3	5	1	1/7	5	9	9	9	7	5
S_{2c}	5	5	1/3	7	7	1	5	5	5	5	5	7
S_{2d}	1/3	5	1/3	5	1/5	1/5	1	9	9	7	5	7
S_{3a}	1/7	1/5	1/9	1	1/9	1/5	1/9	1	1/7	1/7	1/7	1/7
S_{3b}	1/7	1/3	1/7	1/3	1/9	1/5	1/9	7	1	1/3	3	3
S_{3c}	1/5	1	1/9	5	1/9	1/5	1/7	7	3	1	3	3
S_{3d}	1/7	1/7	1/9	3	1/7	1/5	1/5	7	1/3	1/3	1	7
S_{3e}	1/7	1/9	1/9	1	1/5	1/7	1/7	7	1/3	1/3	1/7	1

Table 8: Relative importance of each item within sustainability criteria for DM 8.

DM 8	S_{1a}	S_{1b}	S_{1c}	S_{2a}	S_{2b}	S_{2c}	S_{2d}	S_{3a}	S_{3b}	S_{3c}	S_{3d}	S_{3e}
S_{1a}	1	1	1	1/7	1/7	9	9	1/5	1/5	1/5	1/7	1
S_{1b}	1	1	1	1/7	1/7	7	1/5	1/7	1/7	1/7	1/9	1
S_{1c}	1	1	1	1/5	1/7	5	1/5	1/7	1/7	1/7	1/9	1
S_{2a}	7	7	5	1	1/5	9	1	1	1	1	1/3	7
S_{2b}	7	7	7	5	1	9	1	1	1	1	1	9
S_{2c}	1/9	1/7	1/5	1/9	1/9	1	1/9	1/9	1/9	1/9	1/9	1
S_{2d}	1/9	5	5	1	1	9	1	1	1/5	1/5	1/9	1
S_{3a}	5	7	7	1	1	9	1	1	1	1/9	1/9	9
S_{3b}	5	7	7	1	1	9	5	1	1	1	1	9
S_{3c}	5	7	7	1	1	9	5	9	1	1	1	9
S_{3d}	7	9	9	3	1	9	9	9	1	1	1	9
S_{3e}	1	1	1	1/7	1/9	1	1	1/9	1/9	1/9	1/9	1

Table 9: Relative importance of each item within sustainability criteria for DM 9.

DM 9	S_{1a}	S_{1b}	S_{1c}	S_{2a}	S_{2b}	S_{2c}	S_{2d}	S_{3a}	S_{3b}	S_{3c}	S_{3d}	S_{3e}
S_{1a}	1	3	1/9	5	1	1/3	1	5	3	5	1	1
S_{1b}	1/3	1	1/9	1/5	1/7	1/5	1/9	3	5	7	5	7
S_{1c}	9	9	1	5	7	5	5	7	9	9	9	7
S_{2a}	1/5	5	1/5	1	1/3	1/5	3	1/3	1/3	1/3	1	1/3
S_{2b}	1	7	1/7	3	1	1/5	9	1	7	9	7	7
S_{2c}	3	5	1/5	5	5	1	7	3	5	9	9	9
S_{2d}	1	9	1/5	1/3	1/9	1/7	1	5	7	9	9	9
S_{3a}	1/5	1/3	1/7	3	1	1/3	1/5	1	1/5	1/5	1/5	1/5
S_{3b}	1/3	1/5	1/9	3	1/7	1/5	1/7	5	1	1	1	7
S_{3c}	1/5	1/7	1/9	3	1/9	1/9	1/9	5	1	1	5	1
S_{3d}	1	1/5	1/9	1	1/7	1/9	1/9	5	1	1/5	1	5
S_{3e}	1	1/7	1/7	3	1/7	1/9	1/9	5	1/7	1	1/5	1

Table 10: Relative importance of each item within sustainability criteria for DM 10.

DM 10	S_{1a}	S_{1b}	S_{1c}	S_{2a}	S_{2b}	S_{2c}	S_{2d}	S_{3a}	S_{3b}	S_{3c}	S_{3d}	S_{3e}
S_{1a}	1	3	1/9	7	7	7	7	7	7	1	7	7
S_{1b}	1/3	1	1/7	3	3	5	5	5	5	5	5	5
S_{1c}	9	7	1	9	9	9	9	9	9	9	9	9
S_{2a}	1/7	1/3	1/9	1	1/5	3	7	3	1/3	1/3	3	5
S_{2b}	1/7	1/3	1/9	5	1	7	7	5	3	5	5	5
S_{2c}	1/7	1/5	1/9	1/3	1/7	1	1	1	1/3	1	1	1
S_{2d}	1/7	1/5	1/9	1/7	1/7	1	1	1/5	1/5	1/5	1	1
S_{3a}	1/7	1/5	1/9	1/3	1/5	1	5	1	1/5	1/3	1/5	1
S_{3b}	1/7	1/5	1/9	3	1/3	3	5	5	1	7	7	7
S_{3c}	1	1/5	1/9	3	1/5	1	5	3	1/7	1	5	5
S_{3d}	1/7	1/5	1/9	1/3	1/5	1	1	5	1/7	1/5	1	1
S_{3e}	1/7	1/5	1/9	1/5	1/5	1	1	1	1/7	1/5	1	1

Table 11: Relative importance of each item within sustainability criteria for DM 11.

DM 11	S_{1a}	S_{1b}	S_{1c}	S_{2a}	S_{2b}	S_{2c}	S_{2d}	S_{3a}	S_{3b}	S_{3c}	S_{3d}	S_{3e}
S_{1a}	1	7	1/3	1/5	1/5	1/5	1/5	1/3	1/5	1/5	1/9	1/3
S_{1b}	1/7	1	1/5	1/5	1/5	1/5	1/5	1/5	1/5	1/5	1/9	1/3
S_{1c}	3	5	1	1/5	1/5	1/5	1/5	1/5	1/5	1/5	1/9	1/3
S_{2a}	5	5	5	1	9	9	9	3	3	3	1/9	3
S_{2b}	5	5	5	1/9	1	1	1/7	1	1	1	1/9	1
S_{2c}	5	5	5	1/9	1	1	1/7	1	1	1	1/9	1
S_{2d}	5	5	5	1/9	7	7	1	1	1	1	1/9	1
S_{3a}	3	5	5	1/3	1	1	1	1	1/7	1/5	1/9	1
S_{3b}	5	5	5	1/3	1	1	1	7	1	1/7	1/9	5
S_{3c}	5	5	5	1/3	1	1	1	5	7	1	1/9	7
S_{3d}	9	9	9	9	9	9	9	9	9	9	1	9
S_{3e}	3	3	3	1/3	1	1	1	1	1/5	1/7	1/9	1

Table 12: Relative importance of each item within sustainability criteria for DM 12.

DM 12	S_{1a}	S_{1b}	S_{1c}	S_{2a}	S_{2b}	S_{2c}	S_{2d}	S_{3a}	S_{3b}	S_{3c}	S_{3d}	S_{3e}
S_{1a}	1	7	1/9	1	1/3	1/9	1/5	9	7	9	5	5
S_{1b}	1/7	1	1/9	1	1/5	1/9	1/7	9	7	3	3	9
S_{1c}	9	9	1	7	5	7	7	9	9	7	9	9
S_{2a}	1	1	1/7	1	1/7	1/9	5	3	1/5	1/7	1/5	0
S_{2b}	3	5	1/5	7	1	1/9	7	1	9	7	7	7
S_{2c}	9	9	1/7	9	9	1	9	1/3	3	7	7	7
S_{2d}	5	7	1/7	1/5	1/7	1/9	1	7	5	5	7	7
S_{3a}	1/9	1/9	1/9	1/3	1	3	1/7	1	1/9	1/3	1/5	1/3
S_{3b}	1/7	1/7	1/9	5	1/9	1/3	1/5	9	1	1/5	7	1
S_{3c}	1/9	1/3	1/7	7	1/7	1/7	1/5	3	5	1	5	1/3
S_{3d}	1/5	1/3	1/9	5	1/7	1/7	1/7	5	1/7	1/5	1	9
S_{3e}	1/5	1/9	1/9	27	1/7	1/7	1/7	3	1	3	1/9	1

Table 13: Relative importance of each item within sustainability criteria for DM 13.

DM 13	S_{1a}	S_{1b}	S_{1c}	S_{2a}	S_{2b}	S_{2c}	S_{2d}	S_{3a}	S_{3b}	S_{3c}	S_{3d}	S_{3e}
S_{1a}	1	5	1/7	3	3	1/5	3	7	7	1/3	1/3	7
S_{1b}	1/5	1	1/7	1/3	1/3	1/5	1/5	1/3	1/3	1/3	1/3	5
S_{1c}	7	7	1	3	3	3	3	7	7	5	3	7
S_{2a}	1/3	3	1/3	1	1/5	1/7	1/5	1/3	1/3	1/5	1/5	3
S_{2b}	1/3	3	1/3	5	1	1/7	5	5	5	5	5	5
S_{2c}	5	5	1/3	7	7	1	5	5	5	5	5	7
S_{2d}	1/3	5	1/3	5	1/5	1/5	1	5	5	5	5	7
S_{3a}	1/7	3	1/7	3	1/5	1/5	1/5	1	1/7	1/7	1/7	1/7
S_{3b}	1/7	3	1/7	3	1/5	1/5	1/5	7	1	1/3	3	3
S_{3c}	3	3	1/5	5	1/5	1/5	1/5	7	3	1	3	3
S_{3d}	3	3	1/3	5	1/5	1/5	1/5	7	1/3	1/3	1	7
S_{3e}	1/7	1/5	1/7	1/3	1/5	1/7	1/7	7	1/3	1/3	1/7	1

Table 14: Relative importance of each item within sustainability criteria for DM 14.

DM 14	S_{1a}	S_{1b}	S_{1c}	S_{2a}	S_{2b}	S_{2c}	S_{2d}	S_{3a}	S_{3b}	S_{3c}	S_{3d}	S_{3e}
S_{1a}	1	5	1/7	3	1/5	3	3	1/3	1	1/5	1/9	3
S_{1b}	1/5	1	1/5	3	1/3	1/5	1/5	1/5	1/3	1/3	1/9	1
S_{1c}	7	5	1	3	5	5	3	3	3	3	5	3
S_{2a}	1/3	1/3	1/3	1	1/5	5	3	3	5	3	3	5
S_{2b}	5	3	1/5	5	1	5	3	3	5	3	5	1/5
S_{2c}	1/3	5	1/5	1/5	1/5	1	1/5	3	1	5	3	5
S_{2d}	1/3	5	1/3	1/3	1/3	5	1	1/3	3	1	3	3
S_{3a}	3	5	1/3	1/3	1/3	1/3	3	1	1	1/9	1/9	5
S_{3b}	1	3	1/3	1/5	1/5	1	1/3	1	1	1/5	1/9	3
S_{3c}	5	3	1/3	1/3	1/3	1/5	1	9	5	1	1/9	5
S_{3d}	9	9	1/5	1/3	1/5	1/3	1/3	9	9	9	1	9
S_{3e}	1/3	1	1/3	1/5	5	1/5	1/3	1/5	1/3	1/5	1/9	1

Table 15: Relative importance of each item within sustainability criteria for DM 15.

DM 15	S_{1a}	S_{1b}	S_{1c}	S_{2a}	S_{2b}	S_{2c}	S_{2d}	S_{3a}	S_{3b}	S_{3c}	S_{3d}	S_{3e}
S_{1a}	1	1	1	7	1	7	9	3	5	5	1	5
S_{1b}	1	1	1	7	1	9	9	5	5	5	1	9
S_{1c}	1	1	1	9	1	9	1	5	5	5	1	9
S_{2a}	1/7	1/7	1/9	1	1/9	1	7	1/9	1/9	1/9	1	9
S_{2b}	1	1	1	9	1	9	9	1	1	1	1	9
S_{2c}	1/7	1/9	1/9	1	1/9	1	3	1/9	1/9	1/9	1	1
S_{2d}	1/9	1/9	1	1/7	1/9	1/3	1	1/9	1/9	1/9	1	1
S_{3a}	1/3	1/5	1/5	9	1	9	9	1	5	3	1/3	7
S_{3b}	1/5	1/5	1/5	9	1	9	9	1/5	1	1	1	5
S_{3c}	1/5	1/5	1/5	9	1	9	9	1/3	1	1	1	9
S_{3d}	1	1	1	1	1	1	1	3	1	1	1	1
S_{3e}	1/5	1/9	1/9	1/9	1/9	1	1	1/7	1/5	1/9	1	1

Table 16: Relative importance of each item within sustainability criteria for DM 16.

DM 16	S_{1a}	S_{1b}	S_{1c}	S_{2a}	S_{2b}	S_{2c}	S_{2d}	S_{3a}	S_{3b}	S_{3c}	S_{3d}	S_{3e}
S_{1a}	1	5	1	1	1/3	9	9	3	5	5	5	5
S_{1b}	1/5	1	1	3	1	9	9	1	5	5	5	5
S_{1c}	1	1	1	5	5	9	9	3	7	7	7	7
S_{2a}	1	1/3	1/5	1	5	9	9	5	7	7	7	7
S_{2b}	3	1	1/5	1/5	1	9	9	5	7	7	7	7
S_{2c}	1/9	1/9	1/9	1/9	1/9	1	1/7	1/9	1/3	1/5	1/7	1/7
S_{2d}	1/9	1/9	1/9	1/9	1/9	7	1	1/9	1	1	1	1
S_{3a}	1/3	1	1/3	1/5	1/5	9	9	1	7	7	9	9
S_{3b}	1/5	1/5	1/7	1/7	1/7	3	1	1/7	1	1	1	1
S_{3c}	1/5	1/5	1/7	1/7	1/7	5	1	1/7	1	1	3	1/7
S_{3d}	1/5	1/5	1/7	1/7	1/7	7	1	1/9	1	1/3	1	1/7
S_{3e}	1/5	1/5	1/7	1/7	1/7	7	1	1/9	1	7	7	1

Table 17: Relative importance of each item within sustainability criteria for DM 17.

DM 17	S_{1a}	S_{1b}	S_{1c}	S_{2a}	S_{2b}	S_{2c}	S_{2d}	S_{3a}	S_{3b}	S_{3c}	S_{3d}	S_{3e}
S_{1a}	1	7	7	1/3	1/3	1/3	1/3	1/7	1/7	1/7	1/7	1/7
S_{1b}	1/7	1	3	1/5	1/5	1/5	1/5	1/3	1/3	1/3	1/3	1/3
S_{1c}	1/7	1/3	1	1/7	1/7	1/7	1/7	1/9	1/9	1/9	1/9	1/9
S_{2a}	3	5	7	1	1/3	1/3	1/3	1/3	1/3	1/3	1/3	1/3
S_{2b}	3	5	7	3	1	3	3	1/5	1/5	1/5	1/5	1/5
S_{2c}	3	5	7	3	1/3	1	1/3	1/7	1/7	1/7	1/7	1/7
S_{2d}	3	5	7	3	1/3	3	1	1/3	1/3	1/3	1/3	1/3
S_{3a}	7	3	9	3	5	7	3	1	1/7	1/7	1/7	1/7
S_{3b}	7	3	9	3	5	7	3	7	1	1/9	1/9	1/9
S_{3c}	7	3	9	3	5	7	3	7	9	1	1	1
S_{3d}	7	3	9	3	5	7	3	7	9	1	1	1
S_{3e}	7	3	9	3	5	7	3	7	9	1	1	1

Table 18: Relative importance of each item within sustainability criteria for DM 18.

DM 18	S_{1a}	S_{1b}	S_{1c}	S_{2a}	S_{2b}	S_{2c}	S_{2d}	S_{3a}	S_{3b}	S_{3c}	S_{3d}	S_{3e}
S_{1a}	1	1/3	1/3	5	1	3	3	5	3	3	5	5
S_{1b}	3	1	1	5	5	5	5	5	5	5	5	5
S_{1c}	3	1	1	5	5	5	5	5	5	5	5	5
S_{2a}	1/5	1/5	1/5	1	1/5	1	1/3	1/3	1/3	1/3	1	1
S_{2b}	1	1/5	1/5	5	1	3	1	3	3	3	5	5
S_{2c}	1/3	1/5	1/5	1	1/3	1	1/3	1/3	1/5	1/3	1	1
S_{2d}	1/3	1/5	1/5	3	1	3	1	1/3	1/3	1/3	3	1
S_{3a}	1/5	1/5	1/5	3	1/3	3	3	1	1	1	3	3
S_{3b}	1/3	1/5	1/5	3	1/3	5	3	1	1	1	3	3
S_{3c}	1/3	1/5	1/5	3	1/3	3	3	1	1	1	3	3
S_{3d}	1/5	1/5	1/5	1	1/5	1	1/3	1/3	1/3	1/3	1	1/3
S_{3e}	1/5	1/5	1/5	1	1/5	1	1	1/3	1/3	1/3	3	1

Appendix J (Questionnaire result from phase 2)

Table 1: Rating of recycling alternatives by Decision Maker 1 under CE criteria

DM 1	Alternatives				
Items	A1	A2	A3	A4	A5
C_{1a}	M	M	ML	VL	L
C_{1b}	ML	ML	ML	M	M
C_{1c}	MH	MH	MH	L	M
C_{1d}	M	M	ML	L	ML
C_{1e}	M	M	MH	L	MH
C_{1f}	ML	ML	M	VL	L
C_{2a}	L	L	L	VH	H
C_{2b}	ML	ML	ML	L	L
C_{2c}	VL	VL	VL	VL	VL
C_{2d}	ML	ML	ML	ML	ML
C_{2e}	ML	ML	M	VL	VL
C_{2f}	VL	VL	VL	VL	VL
C_{3a}	VL	VL	VL	VL	VL
C_{3b}	VH	MH	MH	VH	VH
C_{3c}	MH	MH	M	H	MH
C_{3d}	L	L	L	VL	VL
C_{4a}	H	H	MH	VL	VL
C_{4b}	M	M	M	M	M
C_{5a}	M	MH	MH	MH	H
C_{5b}	M	ML	L	M	M
C_{5c}	H	MH	M	M	M
C_{5d}	MH	MH	MH	M	M
C_{5e} **	Y	Y	Y	N	N

Table 2: Rating of recycling alternatives by Decision Maker 2 under CE criteria

DM 2	Alternatives				
Items	A1	A2	A3	A4	A5
C_{1a}	ML	MH	L	VL	VL
C_{1b}	L	M	L	ML	MH
C_{1c}	M	H	M	VL	ML
C_{1d}	ML	MH	L	VL	L
C_{1e}	ML	MH	M	VL	M
C_{1f}	L	M	ML	VL	VL
C_{2a}	VL	ML	VL	H	MH
C_{2b}	L	M	L	VL	VL
C_{2c}	VL	L	VL	L	VL
C_{2d}	L	M	L	M	L
C_{2e}	L	L	ML	VL	VL
C_{2f}	VL	L	VL	L	VL
C_{3a}	VL	L	VL	L	VL
C_{3b}	H	M	H	H	VH
C_{3c}	M	H	ML	MH	M
C_{3d}	VL	ML	VL	VL	L
C_{4a}	VH	MH	M	VL	L
C_{4b}	ML	MH	ML	MH	ML
C_{5a}	ML	M	H	M	MH
C_{5b}	ML	L	VL	ML	MH
C_{5c}	MH	M	ML	ML	MH
C_{5d}	M	H	M	ML	MH
C_{5e} **	N	Y	N	Y	N

Table 3: Rating of recycling alternatives by Decision Maker 3 under CE criteria

DM 3	Alternatives				
Items	A1	A2	A3	A4	A5
C_{1a}	MH	ML	M	L	ML
C_{1b}	M	L	M	MH	ML
C_{1c}	H	M	H	ML	ML
C_{1d}	MH	ML	M	ML	M
C_{1e}	MH	ML	H	ML	H
C_{1f}	M	L	MH	L	ML
C_{2a}	ML	VL	ML	VH	VH
C_{2b}	M	L	M	ML	ML
C_{2c}	L	VL	L	VL	L
C_{2d}	M	L	M	L	M
C_{2e}	M	M	MH	L	L
C_{2f}	L	VL	L	VL	L
C_{3a}	L	VL	L	VL	L
C_{3b}	VH	H	M	VH	H
C_{3c}	H	M	MH	VH	H
C_{3d}	ML	VL	ML	L	VL
C_{4a}	MH	VH	H	L	VL
C_{4b}	MH	ML	MH	ML	MH
C_{5a}	MH	H	M	H	VH
C_{5b}	MH	M	ML	MH	ML
C_{5c}	VH	H	MH	MH	ML
C_{5d}	H	M	H	MH	ML
C_{5e} **	Y	N	Y	N	Y

Table 4: Rating of recycling alternatives by Decision Maker 1 under Sustainability criteria

DM1	Alternatives				
Item	A1	A2	A3	A4	A5
S_{1a}	M	MH	H	VL	ML
S_{1b}	M	M	MH	L	L
S_{1c}	L	ML	ML	L	L
S_{2a}	L	L	L	VL	L
S_{2b}	ML	ML	M	VL	VL
S_{2c}	L	L	VL	ML	M
S_{2d}	MH	M	M	VH	VH
S_{3a}	ML	ML	M	L	L
S_{3b}	M	M	M	L	L
S_{3c}	L	L	L	M	M
S_{3d}	VL	VL	VL	VL	VL
S_{3e} **	N	N	N	N	N

Table 5: Rating of recycling alternatives by Decision Maker 2 under Sustainability criteria

DM2	Alternatives				
Item	A1	A2	A3	A4	A5
S_{1a}	ML	M	MH	VL	L
S_{1b}	ML	MH	M	VL	ML
S_{1c}	VL	L	M	VL	ML
S_{2a}	VL	VL	VL	VL	VL
S_{2b}	L	L	ML	VL	VL
S_{2c}	VL	VL	VL	L	ML
S_{2d}	M	ML	ML	H	VH
S_{3a}	L	L	ML	VL	VL
S_{3b}	ML	ML	ML	VL	VL
S_{3c}	VL	ML	VL	ML	MH
S_{3d}	VL	L	VL	L	VL
S_{3e} **	N	N	N	N	N

Table 6: Rating of recycling alternatives by Decision Maker 3 under Sustainability criteria

DM3	Alternatives				
Item	A1	A2	A3	A4	A5
S_{1a}	MH	H	VH	L	M
S_{1b}	MH	ML	H	ML	VL
S_{1c}	ML	M	L	ML	VL
S_{2a}	ML	ML	ML	L	ML
S_{2b}	M	M	MH	L	L
S_{2c}	ML	ML	L	M	MH
S_{2d}	H	MH	MH	VH	H
S_{3a}	M	M	MH	ML	ML
S_{3b}	MH	MH	MH	ML	ML
S_{3c}	ML	VL	ML	MH	ML
S_{3d}	L	VL	L	VL	L
S_{3e} **	Y	Y	Y	Y	Y

Table 7: The weighted normalised decision matrix, FPIS and FNIS for circularity.

		A1	A2	A3	A4	A5	FPIS, A^*	FNIS, A^-
C_1	C_{1a}	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)
	C_{1b}	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)
	C_{1c}	(0.01,0.03,0.06)	(0.01,0.03,0.06)	(0.01,0.03,0.06)	(0.00,0.01,0.03)	(0.00,0.02,0.04)	(0.01,0.03,0.06)	(0.00,0.01,0.03)
	C_{1d}	(0.00,0.03,0.07)	(0.00,0.03,0.07)	(0.00,0.02,0.06)	(0.00,0.01,0.04)	(0.00,0.02,0.06)	(0.00,0.03,0.07)	(0.00,0.01,0.04)
	C_{1e}	(0.00,0.01,0.05)	(0.00,0.01,0.05)	(0.00,0.00,0.02)	(0.00,0.01,0.01)	(0.00,0.00,0.02)	(0.00,0.01,0.05)	(0.00,0.00,0.01)
	C_{1f}	(0.00,0.02,0.08)	(0.00,0.02,0.08)	(0.01,0.04,0.10)	(0.00,0.00,0.03)	(0.00,0.01,0.05)	(0.01,0.04,0.10)	(0.00,0.00,0.03)
C_2	C_{2a}	(0.00,0.00,0.02)	(0.00,0.00,0.02)	(0.00,0.00,0.02)	(0.02,0.03,0.04)	(0.01,0.03,0.04)	(0.02,0.03,0.04)	(0.00,0.00,0.02)
	C_{2b}	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)
	C_{2c}	(0.00,0.00,0.05)	(0.00,0.00,0.05)	(0.00,0.00,0.05)	(0.00,0.00,0.05)	(0.00,0.00,0.05)	(0.00,0.00,0.05)	(0.00,0.00,0.05)
	C_{2d}	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)
	C_{2e}	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)
	C_{2f}	(0.00,0.00,0.05)	(0.00,0.00,0.05)	(0.00,0.00,0.05)	(0.00,0.00,0.05)	(0.00,0.00,0.05)	(0.00,0.00,0.05)	(0.00,0.00,0.05)
C_3	C_{3a}	(0.00,0.00,0.05)	(0.00,0.00,0.05)	(0.00,0.00,0.05)	(0.00,0.00,0.05)	(0.00,0.00,0.05)	(0.00,0.00,0.05)	(0.00,0.00,0.05)
	C_{3b}	(0.03,0.06,0.08)	(0.01,0.04,0.08)	(0.01,0.04,0.08)	(0.03,0.06,0.08)	(0.03,0.06,0.08)	(0.03,0.06,0.08)	(0.01,0.04,0.08)
	C_{3c}	(0.01,0.03,0.05)	(0.01,0.03,0.05)	(0.00,0.02,0.05)	(0.01,0.03,0.05)	(0.01,0.03,0.05)	(0.01,0.03,0.05)	(0.00,0.02,0.05)
	C_{3d}	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)
C_4	C_{4a}	(0.02,0.05,0.08)	(0.02,0.05,0.08)	(0.01,0.04,0.08)	(0.00,0.00,0.02)	(0.00,0.00,0.02)	(0.02,0.05,0.08)	(0.00,0.00,0.02)
	C_{4b}	(0.00,0.00,0.03)	(0.00,0.00,0.03)	(0.00,0.00,0.03)	(0.00,0.00,0.03)	(0.00,0.00,0.03)	(0.00,0.00,0.03)	(0.00,0.00,0.03)
C_5	C_{5a}	(0.00,0.02,0.05)	(0.01,0.03,0.05)	(0.01,0.03,0.05)	(0.01,0.03,0.05)	(0.01,0.03,0.05)	(0.01,0.03,0.05)	(0.00,0.02,0.05)
	C_{5b}	(0.00,0.02,0.06)	(0.00,0.01,0.05)	(0.00,0.01,0.03)	(0.00,0.02,0.06)	(0.00,0.02,0.06)	(0.00,0.02,0.06)	(0.00,0.01,0.03)
	C_{5c}	(0.03,0.06,0.10)	(0.02,0.05,0.10)	(0.01,0.04,0.09)	(0.01,0.04,0.09)	(0.01,0.04,0.09)	(0.03,0.06,0.10)	(0.01,0.04,0.09)
	C_{5d}	(0.01,0.04,0.07)	(0.01,0.04,0.07)	(0.01,0.04,0.07)	(0.00,0.03,0.07)	(0.00,0.03,0.07)	(0.01,0.04,0.07)	(0.00,0.03,0.07)
	C_{5e}	(0.00,0.02,0.04)	(0.00,0.02,0.04)	(0.00,0.02,0.04)	(0.00,0.01,0.04)	(0.00,0.01,0.04)	(0.00,0.02,0.04)	(0.00,0.01,0.04)

Table 8: Distance between alternatives and FPIS, FNIS with respect to each item for circularity.

		Distance from FPIS, D (A_i, A*)					Distance from FNIS, D (A_i, A^-)				
		A1	A2	A3	A4	A5	A1	A2	A3	A4	A5
C_1	C_{1a}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	C_{1b}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	C_{1c}	0.0000	0.0000	0.0000	0.0238	0.0143	0.0238	0.0238	0.0238	0.0000	0.0095
	C_{1d}	0.0000	0.0000	0.0120	0.0231	0.0120	0.0231	0.0231	0.0112	0.0000	0.0112
	C_{1e}	0.0004	0.0004	0.0174	0.0209	0.0174	0.0209	0.0209	0.0035	0.0007	0.0035
	C_{1f}	0.0158	0.0158	0.0000	0.0432	0.0302	0.0278	0.0278	0.0432	0.0000	0.0133
C_2	C_{2a}	0.0218	0.0218	0.0218	0.0000	0.0031	0.0000	0.0000	0.0000	0.0218	0.0196
	C_{2b}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	C_{2c}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	C_{2d}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	C_{2e}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	C_{2f}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_3	C_{3a}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	C_{3b}	0.0000	0.0128	0.0128	0.0000	0.0000	0.0128	0.0000	0.0000	0.0128	0.0128
	C_{3c}	0.0047	0.0047	0.0105	0.0000	0.0047	0.0061	0.0061	0.0000	0.0105	0.0061
	C_{3d}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_4	C_{4a}	0.0000	0.0000	0.0075	0.0452	0.0452	0.0452	0.0452	0.0407	0.0000	0.0000
	C_{4b}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
C_5	C_{5a}	0.0109	0.0049	0.0049	0.0049	0.0000	0.0000	0.0064	0.0064	0.0064	0.0109
	C_{5b}	0.0000	0.0095	0.0183	0.0000	0.0000	0.0183	0.0088	0.0000	0.0183	0.0183
	C_{5c}	0.0000	0.0093	0.0205	0.0205	0.0205	0.0205	0.0119	0.0000	0.0000	0.0000
	C_{5d}	0.0000	0.0000	0.0000	0.0086	0.0086	0.0086	0.0086	0.0086	0.0000	0.0000
	C_{5e}	0.0000	0.0000	0.0000	0.0061	0.0061	0.0061	0.0061	0.0061	0.0000	0.0000

Sum (D_i*, D_i^-)	0.0537	0.0793	0.1258	0.1961	0.1621	0.2131	0.1886	0.1433	0.0705	0.1052

Table 9: The weighted normalised decision matrix, FPIS and FNIS for sustainability.

		A1	A2	A3	A4	A5	FPIS, A^*	FNIS, A^-
S_1	S_{1a}	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)
	S_{1b}	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)
	S_{1c}	(0.00,0.02,0.10)	(0.00,0.04,0.13)	(0.00,0.04,0.13)	(0.00,0.02,0.10)	(0.00,0.02,0.10)	(0.00,0.04,0.13)	(0.00,0.02,0.10)
S_2	S_{2a}	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)
	S_{2b}	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)
	S_{2c}	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)
	S_{2d}	(0.02,0.07,0.13)	(0.01,0.05,0.12)	(0.01,0.05,0.12)	(0.05,0.10,0.13)	(0.05,0.10,0.13)	(0.05,0.10,0.13)	(0.01,0.05,0.12)
S_3	S_{3a}	(0.00,0.02,0.05)	(0.00,0.02,0.05)	(0.00,0.03,0.07)	(0.00,0.01,0.04)	(0.00,0.01,0.04)	(0.00,0.03,0.07)	(0.00,0.01,0.04)
	S_{3b}	(0.01,0.04,0.10)	(0.01,0.04,0.10)	(0.01,0.04,0.10)	(0.00,0.01,0.05)	(0.00,0.01,0.05)	(0.01,0.04,0.10)	(0.00,0.01,0.05)
	S_{3c}	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)
	S_{3d}	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)	(0.00,0.00,0.00)
	S_{3e}	(0.00,0.01,0.05)	(0.00,0.01,0.05)	(0.00,0.01,0.05)	(0.00,0.01,0.05)	(0.00,0.01,0.05)	(0.00,0.01,0.05)	(0.00,0.01,0.05)

Table 10: Distance between alternatives and FPIS, FNIS with respect to each item for sustainability.

		Distance from FPIS, D (A_i, A*)					Distance from FNIS, D (A_i, A^-)				
		A1	A2	A3	A4	A5	A1	A2	A3	A4	A5
S_1	S_{1a}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	S_{1b}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	S_{1c}	0.0260	0.0000	0.0000	0.0260	0.0260	0.0000	0.0260	0.0260	0.0000	0.0000
S_2	S_{2a}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	S_{2b}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	S_{2c}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	S_{2d}	0.0230	0.0380	0.0380	0.0000	0.0000	0.0160	0.0000	0.0000	0.0380	0.0380
S_3	S_{3a}	0.0110	0.0110	0.0000	0.0210	0.0210	0.0100	0.0100	0.0210	0.0000	0.0000
	S_{3b}	0.0000	0.0000	0.0000	0.0300	0.0300	0.0300	0.0300	0.0300	0.0000	0.0000
	S_{3c}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	S_{3d}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	S_{3e}	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Sum (D_i*, D_i^-)		0.0605	0.0491	0.0379	0.0778	0.0778	0.0567	0.0668	0.0778	0.0379	0.0379

Appendix K (Interview transcript for phase 4)

Interviewer:
Thank you for meeting with me today! The purpose of this interview is to explore the discrepancies between the modelling results and the actual business. This includes identifying the barriers that obstruct the company from the attempt towards achieving the optimum result shown in the modelling and the enablers that would improve this situation. As a participant in this study, I consider you to be an expert on this topic and would like to understand your thoughts in regard to the questions I am going to ask. I will be recording this interview with this device (shows the recorder). After our interview is over, I will make a transcript of what you said, but I will replace your name, as well as those of anyone you mention and any places you mention, so that nothing can be traced. I will be the only one who has access to this data and will keep it locked away and safe until it is time to erase the data entirely.
If you want to stop participating in this interview or not respond to any specific questions for any reason, you may do so any time. Before we begin, do you have any questions?

Manager A:
No questions from me, others?

Manager B:
No for me too, I think everything is fine.

Manager C:
I think everything is alright as long as it is kept anonymous? Ha!

Interviewer:
Alright! For your information, this interview is expected to take about 60 minutes. Are you willing to start the interview and be recorded right now? Can you affirm, for the recording, that you understand and assent to having your words to be recorded in this interview?

Manager A:
Yup.

Manager B:
Yea.

Manager C:
Sure!

Interviewer:
Okay, I've started the recording. Thank you! Let's begin with the first question. Can you please share your organisation background with me?

Manager A:
Well, we XXX is one of the largest ELT collectors in Europe. The company has been operating for 17 years since err…

Manager B:
Since 2003.

Manager A:
Yes 2003. Our average annual gross sale is USD 69 million.

Manager C:
Yes, the company has been operated for quite a while, but we don’t have a lot of employees working on site though, as we don’t really need a lot of employees anyway.

Interviewer:
Thank you! For the next question. Can you please share with me the contextual situation in ELT recycling industry? What are the main drivers behind the recycling alternative selection?

Manager B:
Money of course! Profit!

Manager A:
Yes, that is right. Profit. Ideally, it will be legislation that is advising and guiding the outlet selection. But now, it is driven mainly by profit and cost. We are worried about the viability and growth of the company. We can go out of business if we do not make sure that our company continue to make enough profit. Even today, we are considered lucky if we can cover the cost of collecting and processing the ELT. That’s the reason for what we are doing right now, as long as they can give us high profit with the lowest cost required.

Manager B:
You know, the market is very competitive. We are considered lucky if we get $50/ tonne max by selling the ELT just to cover the cost. Our profit margin is very low currently and we don’t have the luxury to pay extra attention on other dimension or items within circularity or sustainability, as in your research. Well, don’t get me wrong, I don’t mean that they are impractical, I just saying that our hands are tighten. We are of course aware of what circularity or sustainability is, but we can’t really focus too much on it sadly.

Manager C:
That’s right. We can’t really compete by offering a luxurious product with superior brand, since the ELT are going to be grinded to pieces or powder anyway. So, we can only compete by offering a product with low price, which makes our profit margin very low

and makes us focus primarily on the profit. I think that sum up our answers to your question, right? Haha!

Interviewer:
Yes, thanks for the sharing! Can you tell me what are the practical criteria and measurements used in guiding the recycling outlet selection, probably in the future? Or if profit is no longer an issue?

Manager A:
Currently, we are aiming to gain more profit by selling the ELT to the new emerging market, such as high-value technical product manufacturer who is willing to pay more, like tyre manufacturer. When their technology is mature, they will purchase many ELTs available in the market with higher price, since their product has bigger profit margin. By making more profits, we can then focus less on profit and shift to focus more on circularity or sustainability. That is definitely a future way to go.

Manager B:
Yes, you know, some companies in the industry which have financial supports from the government can select the outlet with the best-known technology to recycle the ELT and sell the products. The financial supports can lessen their worries on cost or profit, allowing them to look for outlet that is more circular or sustainable.

Manager A:
Yea, to elaborate, there are some partners in the supply chain that are aiming to be more sustainable and circular, such as 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. I definitely see this become more and more important.

Manager B:
Let me give you another example beside that. 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, circularity and sustainability have become more and more important nowadays and will be prominent aspects in the near future.

Manager C:
I definitely agree with what my colleague have said. The practical criteria and measurements used in guiding the recycling outlet selection, would be circularity and sustainability if we no longer need to worry about profit. Finger crossed!

Interviewer:

I noticed that the solution provided by the model is different than current business condition. Why A4- Tyre-to-cement is currently selected over other recycling outlets as a major outlet? Even when the model suggests that it is actually not circular nor sustainable? What could be the reasons that stop you from applying the solution provided by the model?

Manager C:

Cost. The shredded tyre can the 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. It is so easy to process it, or we don't really need to process it! This makes our life easy and also cutting down a lot of processing cost. If other alternative can use the ELT without complicated processing like cement, I think they can definitely be our primary customers, since we do not have to spend extra cost to process the ELT, which hurting our net profit. But this will depend on the advancement of the technology, which I think a lot of R&D effort is required to be put in it.

Manager B:

I agree to that.

Manager A:

Yes, Me too.

Interviewer:

I noticed that A1- Tyre-to-synthetic turf and A3- Tyre-to-moulded objects seem to be the best choice in terms of circularity and sustainability, why are they not being selected as major recycling outlets?

Manager A:

Blame the media and press I would say. You see, 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.

Manager B:

Yes, the negative customers' perception is sort of making them "boycotting" the products. Exactly, 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.

Interviewer:

What are the key challenges to take sustainability & circularity in recycling alternative selection?

Manager A:

Whether or not we make enough profit, so that we can start taking sustainability & circularity into consideration really.

Interviewer:

What do you think are the potential techniques to overcome the barriers?

Manager B:

Media and press ought to educate and guide the customers to understand the safety of using recycled materials, instead of tarnishing the image of products made by recycled tyre. Some consumers do not really check the credibility of sources and will be easily influenced and sway by the media and press. Only when customers are accepting the products made using recycled ELT, the market can be restored.

Interviewer:

That concludes our time. Thank you all for your participation in this interview! The results will help us to understand more about the barriers as well as enablers that would promote circular and sustainable practices in the ELT recycling industry. Do you have any questions for me before you go?

Manager A:

Not really. Do you have a question for me?

Interviewer:

I think I asked all the questions I wanted to ask.

Manager B:

No question from my side either.

Manager C:

Me too.

Interviewer:

Well! thank you very much! This research will not be possible without your participation.

Appendix L (Ethic documents)

Low Risk Research Ethics Approval

Project Title

A circular economy (CE) tool to maximise the value of manufacturing industry waste

Record of Approval

Principal Investigator

I **request an ethics peer review** and confirm that I have answered all relevant questions in this checklist honestly.	X
I confirm that I will carry out the project in the ways described in this checklist. I will immediately suspend research and request new ethical approval if the project subsequently changes the information I have given in this checklist.	X
I confirm that I, and all members of my research team (if any), have read and agreed to abide by the Code of Research Ethics issued by the relevant national learned society.	X
I confirm that I, and all members of my research team (if any), have read and agreed to abide by the University's Research Ethics, Governance and Integrity Framework.	X

Name: Sir Yee Lee ....

Date: 22/09/2018 ....

Student's Supervisor (if applicable)

I have read this checklist and confirm that it covers all the ethical issues raised by this project fully and frankly. I also confirm that these issues have been discussed with the student and will continue to be reviewed in the course of supervision.

Name: Ming Lim ....

Date: 23/09/2018 ....

Reviewer (if applicable)

Date of approval by anonymous reviewer: 24/09/2018

Low Risk Research Ethics Approval Checklist

Project Information

Project Ref	P76078
Full name	Sir Yee Lee
Faculty	Faculty of Business and Law
Department	Centre for Business in Society
Supervisor	Ming Lim
Module Code	FBL-PHD
EFAAF Number	
Project title	A circular economy (CE) tool to maximise the value of manufacturing industry waste
Date(s)	22/01/2018 - 31/07/2021
Created	22/09/2018 18:57

Project Summary

This phD project will focus in constructing a decision model in selecting a suitable reverse logistics strategy and a suitable waste processors based on sustainability indicators, the waste that returned back into the supply chain will be more sustainable and its value, view from different sustainability pillar, will be maximised.

Names of Co-Investigators and their organisational affiliation (place of study/employer)	
Is the project self-funded?	NO
Who is funding the project?	
Has the funding been confirmed?	NO
Are you required to use a Professional Code of Ethical Practice appropriate to your discipline?	NO
Have you read the Code?	YES

Project Details

What is the purpose of the project?	construct a decision model to select suitable waste processors from different competing supply chain, based on sustainability indicators.	
What are the planned or desired outcomes?	Working decision model to select suitable waste processors from different competing supply chain, based on sustainability indicators.	
Explain your research design	desk based secondary data research for first year literature review	
Outline the principal methods you will use	desk based secondary data research for first year literature review	
Are you proposing to use an external research instrument, validated scale or follow a published research method?		NO
If yes, please give details of what you are using		
Will your research involve consulting individuals who support, or literature, websites or similar material which advocates, any of the following: terrorism, armed struggles, or political, religious or other forms of activism considered illegal under UK law?		NO
Are you dealing with Secondary Data? (e.g. sourcing info from websites, historical documents)		YES
Are you dealing with Primary Data involving people? (e.g. interviews, questionnaires, observations)		NO
Are you dealing with personal or sensitive data?		NO
Will the Personal or Sensitive data be shared with a third party?		
Will the Personal or Sensitive data be shared outside of the European Economic Area ("EEA")?		
Is the project solely desk based? (e.g. involving no laboratory, workshop or off-campus work or other activities which pose significant risks to researchers or participants)		YES
Are there any other ethical issues or risks of harm raised by the study that have not been covered by previous questions?		NO
If yes, please give further details		

External Ethical Review

Question			Yes	No
1	Will this study be submitted for ethical review to an external organisation? (e.g. Another University, Social Care, National Health Service, Ministry of Defence, Police Service and Probation Office)			X
	If YES, name of external organisation			
2	Will this study be reviewed using the IRAS system?			X
3	Has this study previously been reviewed by an external organisation?			X

Risk of harm, potential harm and disclosure of harm

Question			Yes	No
1	Is there any significant risk that the study may lead to physical harm to participants or researchers?			X
	If YES, please explain how you will take steps to reduce or address those risks			
2	Is there any significant risk that the study may lead to psychological or emotional distress to participants?			X
	If YES, please explain how you will take steps to reduce or address those risks			
3	Is there any risk that the study may lead to psychological or emotional distress to researchers?			X
	If YES, please explain how you will take steps to reduce or address those risks			
4	Is there any risk that your study may lead or result in harm to the reputation of participants, researchers, or their employees, or any associated persons or organisations?			X
	If YES, please explain how you will take steps to reduce or address those risks			
5	Is there a risk that the study will lead to participants to disclose evidence of previous criminal offences, or their intention to commit criminal offences?			X
	If YES, please explain how you will take steps to reduce or address those risks			
6	Is there a risk that the study will lead participants to disclose evidence that children or vulnerable adults are being harmed, or at risk or harm?			X
	If YES, please explain how you will take steps to reduce or address those risks			
7	Is there a risk that the study will lead participants to disclose evidence of serious risk of other types of harm?			X
	If YES, please explain how you will take steps to reduce or address those risks			
8	Are you aware of the CU Disclosure protocol?		X	

Online and Internet Research

<table>
<tr><th colspan="4">Question</th><th>Yes</th><th>No</th></tr>
<tr><td rowspan="2">1</td><td colspan="3">Will any part of your study involve collecting data by means of electronic media (e.g. the Internet, e-mail, Facebook, Twitter, online forums, etc)?</td><td></td><td>X</td></tr>
<tr><td colspan="2">If YES, please explain how you will obtain permission to collect data by this means</td><td colspan="3"></td></tr>
<tr><td rowspan="2">2</td><td colspan="3">Is there a possibility that the study will encourage children under 18 to access inappropriate websites, or correspond with people who pose risk of harm?</td><td></td><td>X</td></tr>
<tr><td colspan="2">If YES, please explain further</td><td colspan="3"></td></tr>
<tr><td rowspan="2">3</td><td colspan="3">Will the study incur any other risks that arise specifically from the use of electronic media?</td><td></td><td>X</td></tr>
<tr><td colspan="2">If YES, please explain further</td><td colspan="3"></td></tr>
<tr><td rowspan="2">4</td><td colspan="3">Will you be using survey collection software (e.g. BoS, Filemaker)?</td><td></td><td>X</td></tr>
<tr><td colspan="2">If YES, please explain which software</td><td colspan="3"></td></tr>
<tr><td rowspan="6">5</td><td colspan="3">Have you taken necessary precautions for secure data management, in accordance with data protection and CU Policy?</td><td>X</td><td></td></tr>
<tr><td>If NO</td><td>please explain why not</td><td colspan="3"></td></tr>
<tr><td rowspan="4">If YES</td><td>Specify location where data will be stored</td><td colspan="3">University’s One Drive</td></tr>
<tr><td>Planned disposal date</td><td colspan="3">31/07/2021</td></tr>
<tr><td colspan="2">If the research is funded by an external organisation, are there any requirements for storage and disposal?</td><td></td><td>X</td></tr>
<tr><td>If YES, please specify details</td><td colspan="3"></td></tr>
</table>

Medium to High Risk Research Ethics Approval

Project Title

Second application for project [P76078]: An analysis of the impact on sustainability while achieving circular economy agenda: Assessing open and closed supply chain

Record of Approval

Principal Investigator

I **request an ethics peer review** and confirm that I have answered all relevant questions in this checklist honestly.	X
I confirm that I will carry out the project in the ways described in this checklist. I will immediately suspend research and request new ethical approval if the project subsequently changes the information I have given in this checklist.	X
I confirm that I, and all members of my research team (if any), have read and agreed to abide by the Code of Research Ethics issued by the relevant national learned society.	X
I confirm that I, and all members of my research team (if any), have read and agreed to abide by the University's Research Ethics, Governance and Integrity Framework.	X

Name: Sir Yee Lee...

Date: 30/04/2019...

Student's Supervisor (if applicable)

I have read this checklist and confirm that it covers all the ethical issues raised by this project fully and frankly. I also confirm that these issues have been discussed with the student and will continue to be reviewed in the course of supervision.

Name: Jiayao Hu...

Date: 02/05/2019...

Reviewer (if applicable)

Date of approval by anonymous reviewer: 10/05/2019

Medium to High Risk Research Ethics Approval Checklist

Project Information

Project Ref	P90303
Full name	Sir Yee Lee
Faculty	Faculty of Business and Law
Department	Centre for Business in Society
Supervisor	Jiayao Hu
Module Code	FBL-PHD
EFAAF Number	
Project title	Second application for project [P76078]: An analysis of the impact on sustainability while achieving circular economy agenda: Assessing open and closed supply chain
Date(s)	22/01/2018 - 31/07/2021
Created	30/04/2019 16:15

Project Summary

This phD project will focus on investigating how to measure performance of open-looped supply chain (OLSC) over closed-loop supply chain (CLSC) (i.e.: what is the important circular economy (CE) and sustainability metrics require to measure their performance?).Subsequently investigate what is the effect on sustainability when fulfilling CE. A decision model in selecting a suitable supply chain will be constructed based on the selected circular economy and sustainability indicators, ensuring that the waste that returned back into the supply chain will be more circular and sustainable.

Names of Co-Investigators and their organisational affiliation (place of study/employer)	
Is the project self-funded?	NO
Who is funding the project?	
Has the funding been confirmed?	NO
Are you required to use a Professional Code of Ethical Practice appropriate to your discipline?	NO
Have you read the Code?	NO

Project Details

What is the purpose of the project?	second application for project [P76078]: Use questionnaire to collect expert's opinion on how to measure performance of open-looped supply chain (OLSC) over closed-loop supply chain (CLSC) (i.e.: what is the important circular economy (CE) and sustainability metrics require to measure their performance?).Subsequently use the obtained metrics to investigate what is the effect on sustainability when fulfilling CE.	
What are the planned or desired outcomes?	A relative importance of one indicator over another is obtained, which can be input into analytic hierarchy process (AHP) to obtain weight of each indicator to be used to measure performance of open-looped supply chain (OLSC) over closed-loop supply chain (CLSC).	
Explain your research design	Survey using online questionnaire targeting experts in the circular economy field. The experts comprise of experienced academic such as lecturers or professors, as well as non-academic such as CEO of lobby organisation or NGO.	
Outline the principal methods you will use	Online questionnaire using Bristol Online Survey (BOS)	
Are you proposing to use an external research instrument, validated scale or follow a published research method?		NO
If yes, please give details of what you are using		
Will your research involve consulting individuals who support, or literature, websites or similar material which advocates, any of the following: terrorism, armed struggles, or political, religious or other forms of activism considered illegal under UK law?		NO
Are you dealing with Secondary Data? (e.g. sourcing info from websites, historical documents)		NO
Are you dealing with Primary Data involving people? (e.g. interviews, questionnaires, observations)		YES
Are you dealing with personal or sensitive data?		NO
Will the Personal or Sensitive data be shared with a third party?		
Will the Personal or Sensitive data be shared outside of the European Economic Area ("EEA")?		
Is the project solely desk based? (e.g. involving no laboratory, workshop or off-campus work or other activities which pose significant risks to researchers or participants)		NO

Are there any other ethical issues or risks of harm raised by the study that have not been covered by previous questions?		NO
If yes, please give further details		

DBS (Disclosure & Barring Service) formerly CRB (Criminal Records Bureau)

Question			Yes	No
1	Does the study require DBS (Disclosure & Barring Service) checks?			X
	If YES, please give details of the serial number, date obtained and expiry date			
2	If NO, does the study involve direct contact by any member of the research team:			
	a)	with children or young people under 18 years of age?		X
	b)	with adults who have learning difficulties, brain injury, dementia, degenerative neurological disorders?		X
	c)	with adults who are frail or physically disabled?		X
	d)	with adults who are living in residential care, social care, nursing homes, re-ablement centres, hospitals or hospices?		X
	e)	with adults who are in prison, remanded on bail or in custody?		X
		If you have answered YES to any of the questions above please explain the nature of that contact and what you will be doing		

External Ethical Review

Question			Yes	No
1	Will this study be submitted for ethical review to an external organisation? (e.g. Another University, Social Care, National Health Service, Ministry of Defence, Police Service and Probation Office)			X
	If YES, name of external organisation			
2	Will this study be reviewed using the IRAS system?			X
3	Has this study previously been reviewed by an external organisation?			X

Confidentiality, security and retention of research data

Question			**Yes**	**No**
1	Are there any reasons why you cannot guarantee the full security and confidentiality of any personal or confidential data collected for the study?			X
	If YES, please give an explanation			
2	Is there a significant possibility that any of your participants, and associated persons, could be directly or indirectly identified in the outputs or findings from this study?			X
	If YES, please explain further why this is the case			
3	Is there a significant possibility that a specific organisation or agency or participants could have confidential information identified, as a result of the way you write up the results of the study?			X
	If YES, please explain further why this is the case			
4	Will any members of the research team retain any personal of confidential data at the end of the project, other than in fully anonymised form?			X
	If YES, please explain further why this is the case			
5	Will you or any member of the team intend to make use of any confidential information, knowledge, trade secrets obtained for any other purpose than the research project?			X
	If YES, please explain further why this is the case			
6	Will you be responsible for destroying the data after study completion?		X	
	If NO, please explain how data will be destroyed, when it will be destroyed and by whom			

Participant Information and Informed Consent

Question			Yes	No
1	Will all the participants be fully informed BEFORE the project begins why the study is being conducted and what their participation will involve?		X	
	If NO, please explain why			
2	Will every participant be asked to give written consent to participating in the study, before it begins?			X
	If NO, please explain how you will get consent from your participants. If not written consent, explain how you will record consent	Not needed in this application for informal discussions at the start of the project		
3	Will all participants be fully informed about what data will be collected, and what will be done with this data during and after the study?		X	
	If NO, please specify			
4	Will there be audio, video or photographic recording of participants?			X
	Will explicit consent be sought for recording of participants?			
	If NO to explicit consent, please explain how you will gain consent for recording participants			
5	Will every participant understand that they have the right not to take part at any time, and/or withdraw themselves and their data from the study if they wish?		X	
	If NO, please explain why			
6	Will every participant understand that there will be no reasons required or repercussions if they withdraw or remove their data from the study?		X	
	If NO, please explain why			
7	Does the study involve deceiving, or covert observation of, participants?			X
	Will you debrief them at the earliest possible opportunity?			
	If NO to debrief them, please explain why this is necessary			

Risk of harm, potential harm and disclosure of harm

Question			Yes	No
1	Is there any significant risk that the study may lead to physical harm to participants or researchers?			X
	If YES, please explain how you will take steps to reduce or address those risks			
2	Is there any significant risk that the study may lead to psychological or emotional distress to participants?			X
	If YES, please explain how you will take steps to reduce or address those risks			
3	Is there any risk that the study may lead to psychological or emotional distress to researchers?			X
	If YES, please explain how you will take steps to reduce or address those risks			
4	Is there any risk that your study may lead or result in harm to the reputation of participants, researchers, or their employees, or any associated persons or organisations?			X
	If YES, please explain how you will take steps to reduce or address those risks			
5	Is there a risk that the study will lead to participants to disclose evidence of previous criminal offences, or their intention to commit criminal offences?			X
	If YES, please explain how you will take steps to reduce or address those risks			
6	Is there a risk that the study will lead participants to disclose evidence that children or vulnerable adults are being harmed, or at risk or harm?			X
	If YES, please explain how you will take steps to reduce or address those risks			
7	Is there a risk that the study will lead participants to disclose evidence of serious risk of other types of harm?			X
	If YES, please explain how you will take steps to reduce or address those risks			
8	Are you aware of the CU Disclosure protocol?		X	

Payments to participants

Question			Yes	No
1	Do you intend to offer participants cash payments or any kind of inducements, or reward for taking part in your study?			X
	If YES, please explain what kind of payment you will be offering (e.g. prize draw or store vouchers)			
2	Is there any possibility that such payments or inducements will cause participants to consent to risks that they might not otherwise find acceptable?			
3	Is there any possibility that the prospect of payment or inducements will influence the data provided by participants in any way?			
4	Will you inform participants that accepting payments or inducements does not affect their right to withdraw from the study at any time?			

Capacity to give valid consent

Question			Yes	No
1	Do you propose to recruit any participants who are:			
	a)	children or young people under 18 years of age?		X
	b)	adults who have learning difficulties, mental health condition, brain injury, advanced dementia, degenerative neurological disorders?		X
	c)	adults who are physically disabled?		X
	d)	adults who are living in residential care, social care, nursing homes, re-ablement centres, hospitals or hospices?		X
	e)	adults who are in prison, remanded on bail or in custody?		X
		If you answer YES to any of the questions please explain how you will overcome any challenges to gaining valid consent		
2	Do you propose to recruit any participants with possible communication difficulties, including difficulties arising from limited use of knowledge of the English language?			X
	If YES, please explain how you will overcome any challenges to gaining valid consent			
3	Do you propose to recruit any participants who may not be able to understand fully the nature of the study, research and the implications for them of participating in it or cannot provide consent themselves?			X
	If YES, please explain how you will overcome any challenges to gaining valid consent			

Recruiting Participants

Question				**Yes**	**No**
1	Do you propose to recruit any participants who are:				
	a)	students or employees of Coventry University or partnering organisation(s)?		X	
		If YES, please explain if there is any conflict of interest and how this will be addressed	No conflict of interest		
	b)	employees/staff recruited through other businesses, voluntary or public sector organisations?			X
		If YES, please explain how permission will be gained			
	c)	pupils or students recruited through educational institutions (e.g. primary schools, secondary schools, colleges)?			X
		If YES, please explain how permission will be gained			
	d)	clients/volunteers/service users recruited through voluntary public services?			X
		If YES, please explain how permission will be gained			
	e)	participants living in residential care, social care, nursing homes, re-ablement centres hospitals or hospices?			X
		If YES, please explain how permission will be gained			
	f)	recruited by virtue of their employment in the police or armed forces?			X
		If YES, please explain how permission will be gained			
	g)	adults who are in prison, remanded on bail or in custody?			X
		If YES, please explain how permission will be gained			
	h)	who may not be able to refuse to participate in the research?			X
		If YES, please explain how permission will be gained			

Online and Internet Research

<table>
<tr><th colspan="4">Question</th><th>Yes</th><th>No</th></tr>
<tr><td rowspan="2">1</td><td colspan="3">Will any part of your study involve collecting data by means of electronic media (e.g. the Internet, e-mail, Facebook, Twitter, online forums, etc)?</td><td>X</td><td></td></tr>
<tr><td colspan="2">If YES, please explain how you will obtain permission to collect data by this means</td><td colspan="3">Participant information sheet</td></tr>
<tr><td rowspan="2">2</td><td colspan="3">Is there a possibility that the study will encourage children under 18 to access inappropriate websites, or correspond with people who pose risk of harm?</td><td></td><td>X</td></tr>
<tr><td colspan="2">If YES, please explain further</td><td colspan="3"></td></tr>
<tr><td rowspan="2">3</td><td colspan="3">Will the study incur any other risks that arise specifically from the use of electronic media?</td><td></td><td>X</td></tr>
<tr><td colspan="2">If YES, please explain further</td><td colspan="3"></td></tr>
<tr><td rowspan="2">4</td><td colspan="3">Will you be using survey collection software (e.g. BoS, Filemaker)?</td><td>X</td><td></td></tr>
<tr><td colspan="2">If YES, please explain which software</td><td colspan="3">BOS</td></tr>
<tr><td rowspan="6">5</td><td colspan="3">Have you taken necessary precautions for secure data management, in accordance with data protection and CU Policy?</td><td>X</td><td></td></tr>
<tr><td>If NO</td><td>please explain why not</td><td colspan="3"></td></tr>
<tr><td rowspan="4">If YES</td><td>Specify location where data will be stored</td><td colspan="3">University’s One Drive</td></tr>
<tr><td>Planned disposal date</td><td colspan="3">31/07/2021</td></tr>
<tr><td colspan="2">If the research is funded by an external organisation, are there any requirements for storage and disposal?</td><td></td><td>X</td></tr>
<tr><td>If YES, please specify details</td><td colspan="3"></td></tr>
</table>

Languages

<table>
<tr><th colspan="3">Question</th><th>Yes</th><th>No</th></tr>
<tr><td rowspan="2">1</td><td colspan="2">Are all or some of the consent forms, information leaflets and research instruments associated with this project likely to be used in languages other than English?</td><td></td><td>X</td></tr>
<tr><td>If YES, please specify the language[s] to be used</td><td colspan="3"></td></tr>
<tr><td rowspan="3">2</td><td colspan="2">Have some or all of the translations been undertaken by you or a member of the research team?</td><td></td><td></td></tr>
<tr><td colspan="2">Are these translations in lay language and likely to be clearly understood by the research participants?</td><td></td><td></td></tr>
<tr><td>Please describe the procedures used when undertaking research instrument translation (e.g. forward and back translation), clarifying strategies for ensuring the validity and reliability or trustworthiness of the translation</td><td colspan="3"></td></tr>
<tr><td rowspan="3">3</td><td colspan="2">Have some or all of the translations been undertaken by a third party?</td><td></td><td></td></tr>
<tr><td>If YES, please specify the name[s] of the persons or agencies performing the translations</td><td colspan="3"></td></tr>
<tr><td>Please describe the procedures used when undertaking research instrument translation (e.g. forward and back translation), clarifying strategies for ensuring the validity and reliability of the translation</td><td colspan="3"></td></tr>
</table>

Laboratory/Workshops

<table>
<tr><th colspan="3">Question</th><th>Yes</th><th>No</th></tr>
<tr><td rowspan="2">1</td><td colspan="2">Does any part of the project involve work in a laboratory or workshop which could pose risks to you, researchers or others?</td><td></td><td>X</td></tr>
<tr><td>If YES:

If you have risk assessments for laboratory or workshop activities you can refer to them here & upload them at the end, or explain in the text box how you will manage those risks</td><td colspan="3"></td></tr>
</table>

Research with non-human vertebrates

Question		Yes	No
1	Will any part of the project involve animal habitats or tissues or non-human vertebrates?		X
	If YES, please give details		
2	Does the project involve any procedure to the protected animal whilst it is still alive?		
3	Will any part of your project involve the study of animals in their natural habitat?		
	If YES, please give details		
4	Will the project involve the recording of behaviour of animals in a non-natural setting that is outside the control of the researcher?		
	If YES, please give details		
5	Will your field work involve any direct intervention other than recording the behaviour of the animals available for observation?		
	If YES, please give details		
6	Is the species you plan to research endangered, locally rare or part of a sensitive ecosystem protected by legislation?		
	If YES, please give details		
7	Is there any significant possibility that the welfare of the target species of those sharing the local environment/habitat will be detrimentally affected?		
	If YES, please give details		
8	Is there any significant possibility that the habitat of the animals will be damaged by the project, such that their health and survival will be endangered?		
	If YES, please give details		
9	Will project work involve intervention work in a non-natural setting in relation to invertebrate species other than Octopus vulgaris?		
	If YES, please give details		

Blood Sampling / Human Tissue Analysis

<table>
<tr><th colspan="3">Question</th><th>Yes</th><th>No</th></tr>
<tr><td rowspan="2">1</td><td colspan="2">Does your study involve collecting or use of human tissues or fluids?
(e.g. collecting urine, saliva, blood or use of cell lines, 'dead' blood)</td><td></td><td>X</td></tr>
<tr><td>If YES, please give details</td><td colspan="3"></td></tr>
<tr><td rowspan="2">2</td><td colspan="2">If your study involves blood samples or body fluids (e.g. urine, saliva) have you clearly stated in your application that appropriate guidelines are to be followed (e.g. The British Association of Sport and Exercise Science Physiological Testing Guidelines (2007) or equivalent) and that they are in line with the level of risk?</td><td></td><td></td></tr>
<tr><td>If NO, please explain why not</td><td colspan="3"></td></tr>
<tr><td rowspan="2">3</td><td colspan="2">If your study involves human tissue other than blood and saliva, have you clearly stated in your application that appropriate guidelines are to be followed (e.g. The Human Tissues Act, or equivalent) and that they are in line with level of risk?</td><td></td><td></td></tr>
<tr><td>If NO, please explain why not</td><td colspan="3"></td></tr>
</table>

Travel

Question			Yes	No
1	Does any part of the project require data collection off campus? (e.g. work in the field or community)			X
	If YES: You must consider the potential hazards from off campus activities (e.g. working alone, time of data collection, unfamiliar or hazardous locations, using equipment, the terrain, violence or aggression from others). Outline the precautions that will be taken to manage these risks, AS A MINIMUM this must detail how researchers would summon assistance in an emergency when working off campus. For complex or high risk projects you may wish to complete and upload a separate risk assessment			
2	Does any part of the project involve the researcher travelling outside the UK (or to very remote UK locations)?			
	If YES: Please give details of where, when and how you will be travelling. For travel to high risk places you may wish to complete and upload a separate risk assessment			
3	Are all travellers aware of contact numbers for emergency assitance when away (e.g. local emergency assistance, ambulance/local hospital/police, insurance helpline [+44 (0) 2071 737797] and CU's 24/7 emergency line [+44 (0) 2476 888555])?			
4	Are there any travel warnings in place advising against all, or essential only travel to the destination? NOTE: Before travel to countries with 'against all travel', or 'essential only' travel warnings, staff must check with Finance to ensure insurance coverage is not affected. Undergraduate projects in high risk destinations will not be approved			
5	Are there increased risks to health and safety related to the destination? e.g. cultural differences, civil unrest, climate, crime, health outbreaks/concerns, and travel arrangements?			
	If YES, please specify			
6	Do all travelling members of the research team have adequate travel insurance?			
7	Please confirm all travelling researchers have been advised to seek medical advice regarding vaccinations, medical conditions etc, from their GP			

Medium to High Risk Research Ethics Approval

Project Title

Third application for project [P76078]: An analysis of the impact on sustainability while achieving circular economy agenda: Assessing open and closed supply chain

Record of Approval

Principal Investigator

I **request an ethics peer review** and confirm that I have answered all relevant questions in this checklist honestly.	X
I confirm that I will carry out the project in the ways described in this checklist. I will immediately suspend research and request new ethical approval if the project subsequently changes the information I have given in this checklist.	X
I confirm that I, and all members of my research team (if any), have read and agreed to abide by the Code of Research Ethics issued by the relevant national learned society.	X
I confirm that I, and all members of my research team (if any), have read and agreed to abide by the University's Research Ethics, Governance and Integrity Framework.	X

Name: Sir Yee Lee ....

Date: 18/12/2019 ....

Student's Supervisor (if applicable)

I have read this checklist and confirm that it covers all the ethical issues raised by this project fully and frankly. I also confirm that these issues have been discussed with the student and will continue to be reviewed in the course of supervision.

Name: Jiayao Hu...

Date: 18/12/2019 ....

Reviewer (if applicable)

Date of approval by anonymous reviewer: 24/02/2020

Medium to High Risk Research Ethics Approval Checklist

Project Information

Project Ref	P99875
Full name	Sir Yee Lee
Faculty	Faculty of Business and Law
Department	Centre for Business in Society
Supervisor	Jiayao Hu
Module Code	CBIS-PHD
EFAAF Number	
Project title	Third application for project [P76078]: An analysis of the impact on sustainability while achieving circular economy agenda: Assessing open and closed supply chain
Date(s)	22/01/2018 - 31/07/2021
Created	18/12/2019 09:35

Project Summary

This PhD project will focus on investigating how to allocate EOL tire to various EOL recycling strategy alternatives (i.e.: open-looped supply chain (OLSC) and closed-loop supply chain (CLSC)) under the influence of circular economy (CE) and sustainability. The optimisation model will be constructed based on the circular economy and sustainability criteria, to ensure that the EOL waste that returned back into the supply chain will be more circular and sustainable.

The inclusion of criteria that are necessary to measure the performance of EOL recycling strategy and their relative importance will be determined. The various alternatives will be evaluated and ranked using the selected criteria. Further, the effect on sustainability when fulfilling CE will also be explored.

Names of Co-Investigators and their organisational affiliation (place of study/employer)	
Is the project self-funded?	NO
Who is funding the project?	
Has the funding been confirmed?	NO
Are you required to use a Professional Code of Ethical Practice appropriate to your discipline?	NO
Have you read the Code?	NO

Project Details

What is the purpose of the project?	Third application for project [P76078]: Use questionnaire to collect industry decision makers' opinion on various alternative EOL strategy.	
What are the planned or desired outcomes?	Rating of alternatives using 7-point Likert scale, which can be input into TOPSIS to rank the alternatives.	
Explain your research design	Survey using online questionnaire targeting EOL tire collection company that have minimum of five years of operating experience; supply its collected tyre waste to CLSC to manufacture new tyre as well as at least 3 OLSC to manufacture new product, such as synthetic turf, rubber tiles or moulded objects decentralised company (not owned by the manufacturer, so that it possess free will to distribute the product to any interested party).	
Outline the principal methods you will use	Online questionnaire using Qualtrics	
Are you proposing to use an external research instrument, validated scale or follow a published research method?		NO
If yes, please give details of what you are using		
Will your research involve consulting individuals who support, or literature, websites or similar material which advocates, any of the following: terrorism, armed struggles, or political, religious or other forms of activism considered illegal under UK law?		NO
Are you dealing with Secondary Data? (e.g. sourcing info from websites, historical documents)		NO
Are you dealing with Primary Data involving people? (e.g. interviews, questionnaires, observations)		YES
Are you dealing with personal or sensitive data?		NO
Will the Personal or Sensitive data be shared with a third party?		
Will the Personal or Sensitive data be shared outside of the European Economic Area ("EEA")?		
Is the project solely desk based? (e.g. involving no laboratory, workshop or off-campus work or other activities which pose significant risks to researchers or participants)		NO
Are there any other ethical issues or risks of harm raised by the study that have not been covered by previous questions?		NO

If yes, please give further details	

DBS (Disclosure & Barring Service) formerly CRB (Criminal Records Bureau)

Question		Yes	No
1	Does the study require DBS (Disclosure & Barring Service) checks?		X
	If YES, please give details of the serial number, date obtained and expiry date		
2	If NO, does the study involve direct contact by any member of the research team:		
	a) with children or young people under 18 years of age?		X
	b) with adults who have learning difficulties, brain injury, dementia, degenerative neurological disorders?		X
	c) with adults who are frail or physically disabled?		X
	d) with adults who are living in residential care, social care, nursing homes, re-ablement centres, hospitals or hospices?		X
	e) with adults who are in prison, remanded on bail or in custody?		X
	If you have answered YES to any of the questions above please explain the nature of that contact and what you will be doing		

External Ethical Review

Question			Yes	No
1	Will this study be submitted for ethical review to an external organisation? (e.g. Another University, Social Care, National Health Service, Ministry of Defence, Police Service and Probation Office)			X
	If YES, name of external organisation			
2	Will this study be reviewed using the IRAS system?			X
3	Has this study previously been reviewed by an external organisation?			X

Confidentiality, security and retention of research data

Question			Yes	No
1	Are there any reasons why you cannot guarantee the full security and confidentiality of any personal or confidential data collected for the study?			X
	If YES, please give an explanation			
2	Is there a significant possibility that any of your participants, and associated persons, could be directly or indirectly identified in the outputs or findings from this study?			X
	If YES, please explain further why this is the case			
3	Is there a significant possibility that a specific organisation or agency or participants could have confidential information identified, as a result of the way you write up the results of the study?			X
	If YES, please explain further why this is the case			
4	Will any members of the research team retain any personal of confidential data at the end of the project, other than in fully anonymised form?			X
	If YES, please explain further why this is the case			
5	Will you or any member of the team intend to make use of any confidential information, knowledge, trade secrets obtained for any other purpose than the research project?			X
	If YES, please explain further why this is the case			
6	Will you be responsible for destroying the data after study completion?		X	
	If NO, please explain how data will be destroyed, when it will be destroyed and by whom			

Participant Information and Informed Consent

Question			Yes	No
1	Will all the participants be fully informed BEFORE the project begins why the study is being conducted and what their participation will involve?		X	
	If NO, please explain why			
2	Will every participant be asked to give written consent to participating in the study, before it begins?		X	
	If NO, please explain how you will get consent from your participants. If not written consent, explain how you will record consent			
3	Will all participants be fully informed about what data will be collected, and what will be done with this data during and after the study?		X	
	If NO, please specify			
4	Will there be audio, video or photographic recording of participants?			X
	Will explicit consent be sought for recording of participants?			
	If NO to explicit consent, please explain how you will gain consent for recording participants			
5	Will every participant understand that they have the right not to take part at any time, and/or withdraw themselves and their data from the study if they wish?		X	
	If NO, please explain why			
6	Will every participant understand that there will be no reasons required or repercussions if they withdraw or remove their data from the study?		X	
	If NO, please explain why			
7	Does the study involve deceiving, or covert observation of, participants?			X
	Will you debrief them at the earliest possible opportunity?			
	If NO to debrief them, please explain why this is necessary			

Risk of harm, potential harm and disclosure of harm

Question			**Yes**	**No**
1	Is there any significant risk that the study may lead to physical harm to participants or researchers?			X
	If YES, please explain how you will take steps to reduce or address those risks			
2	Is there any significant risk that the study may lead to psychological or emotional distress to participants?			X
	If YES, please explain how you will take steps to reduce or address those risks			
3	Is there any risk that the study may lead to psychological or emotional distress to researchers?			X
	If YES, please explain how you will take steps to reduce or address those risks			
4	Is there any risk that your study may lead or result in harm to the reputation of participants, researchers, or their employees, or any associated persons or organisations?			X
	If YES, please explain how you will take steps to reduce or address those risks			
5	Is there a risk that the study will lead to participants to disclose evidence of previous criminal offences, or their intention to commit criminal offences?			X
	If YES, please explain how you will take steps to reduce or address those risks			
6	Is there a risk that the study will lead participants to disclose evidence that children or vulnerable adults are being harmed, or at risk or harm?			X
	If YES, please explain how you will take steps to reduce or address those risks			
7	Is there a risk that the study will lead participants to disclose evidence of serious risk of other types of harm?			X
	If YES, please explain how you will take steps to reduce or address those risks			
8	Are you aware of the CU Disclosure protocol?		X	

Payments to participants

Question			Yes	No
1	Do you intend to offer participants cash payments or any kind of inducements, or reward for taking part in your study?			X
	If YES, please explain what kind of payment you will be offering (e.g. prize draw or store vouchers)			
2	Is there any possibility that such payments or inducements will cause participants to consent to risks that they might not otherwise find acceptable?			
3	Is there any possibility that the prospect of payment or inducements will influence the data provided by participants in any way?			
4	Will you inform participants that accepting payments or inducements does not affect their right to withdraw from the study at any time?			

Capacity to give valid consent

Question			Yes	No
1	Do you propose to recruit any participants who are:			
	a) children or young people under 18 years of age?			X
	b) adults who have learning difficulties, mental health condition, brain injury, advanced dementia, degenerative neurological disorders?			X
	c) adults who are physically disabled?			X
	d) adults who are living in residential care, social care, nursing homes, re-ablement centres, hospitals or hospices?			X
	e) adults who are in prison, remanded on bail or in custody?			X
	If you answer YES to any of the questions please explain how you will overcome any challenges to gaining valid consent			
2	Do you propose to recruit any participants with possible communication difficulties, including difficulties arising from limited use of knowledge of the English language?			X
	If YES, please explain how you will overcome any challenges to gaining valid consent			
3	Do you propose to recruit any participants who may not be able to understand fully the nature of the study, research and the implications for them of participating in it or cannot provide consent themselves?			X
	If YES, please explain how you will overcome any challenges to gaining valid consent			

Recruiting Participants

Question				Yes	No
1	Do you propose to recruit any participants who are:				
	a)	students or employees of Coventry University or partnering organisation(s)?			X
		If YES, please explain if there is any conflict of interest and how this will be addressed			
	b)	employees/staff recruited through other businesses, voluntary or public sector organisations?		X	
		If YES, please explain how permission will be gained	the survey information and consent statement makes it clear that doing the questionnaire is voluntary		
	c)	pupils or students recruited through educational institutions (e.g. primary schools, secondary schools, colleges)?			X
		If YES, please explain how permission will be gained			
	d)	clients/volunteers/service users recruited through voluntary public services?			X
		If YES, please explain how permission will be gained			
	e)	participants living in residential care, social care, nursing homes, re-ablement centres hospitals or hospices?			X
		If YES, please explain how permission will be gained			
	f)	recruited by virtue of their employment in the police or armed forces?			X
		If YES, please explain how permission will be gained			
	g)	adults who are in prison, remanded on bail or in custody?			X
		If YES, please explain how permission will be gained			
	h)	who may not be able to refuse to participate in the research?			X
		If YES, please explain how permission will be gained			

Online and Internet Research

Question				Yes	No
1	Will any part of your study involve collecting data by means of electronic media (e.g. the Internet, e-mail, Facebook, Twitter, online forums, etc)?			X	
	If YES, please explain how you will obtain permission to collect data by this means		The appropriate information and consent statement (and tick box) is provided at the start of the survey questionnaire		
2	Is there a possibility that the study will encourage children under 18 to access inappropriate websites, or correspond with people who pose risk of harm?				X
	If YES, please explain further				
3	Will the study incur any other risks that arise specifically from the use of electronic media?				X
	If YES, please explain further				
4	Will you be using survey collection software (e.g. BoS, Filemaker)?			X	
	If YES, please explain which software		Qualtrics		
5	Have you taken necessary precautions for secure data management, in accordance with data protection and CU Policy?			X	
	If NO	please explain why not			
	If YES	Specify location where data will be stored	CU OneDrive		
		Planned disposal date	31/01/2021		
		If the research is funded by an external organisation, are there any requirements for storage and disposal?			X
		If YES, please specify details			

Languages

Question			Yes	No
1	Are all or some of the consent forms, information leaflets and research instruments associated with this project likely to be used in languages other than English?			X
	If YES, please specify the language[s] to be used			
2	Have some or all of the translations been undertaken by you or a member of the research team?			
	Are these translations in lay language and likely to be clearly understood by the research participants?			
	Please describe the procedures used when undertaking research instrument translation (e.g. forward and back translation), clarifying strategies for ensuring the validity and reliability or trustworthiness of the translation			
3	Have some or all of the translations been undertaken by a third party?			
	If YES, please specify the name[s] of the persons or agencies performing the translations			
	Please describe the procedures used when undertaking research instrument translation (e.g. forward and back translation), clarifying strategies for ensuring the validity and reliability of the translation			

Laboratory/Workshops

<table>
<tr><th colspan="3">Question</th><th>Yes</th><th>No</th></tr>
<tr><td rowspan="2">1</td><td colspan="2">Does any part of the project involve work in a laboratory or workshop which could pose risks to you, researchers or others?</td><td></td><td>X</td></tr>
<tr><td>If YES:
If you have risk assessments for laboratory or workshop activities you can refer to them here & upload them at the end, or explain in the text box how you will manage those risks</td><td colspan="3"></td></tr>
</table>

Research with non-human vertebrates

<table>
<tr><th colspan="3">Question</th><th>Yes</th><th>No</th></tr>
<tr><td rowspan="2">1</td><td colspan="2">Will any part of the project involve animal habitats or tissues or non-human vertebrates?</td><td></td><td>X</td></tr>
<tr><td>If YES, please give details</td><td colspan="3"></td></tr>
<tr><td>2</td><td colspan="2">Does the project involve any procedure to the protected animal whilst it is still alive?</td><td></td><td></td></tr>
<tr><td rowspan="2">3</td><td colspan="2">Will any part of your project involve the study of animals in their natural habitat?</td><td></td><td></td></tr>
<tr><td>If YES, please give details</td><td colspan="3"></td></tr>
<tr><td rowspan="2">4</td><td colspan="2">Will the project involve the recording of behaviour of animals in a non-natural setting that is outside the control of the researcher?</td><td></td><td></td></tr>
<tr><td>If YES, please give details</td><td colspan="3"></td></tr>
<tr><td rowspan="2">5</td><td colspan="2">Will your field work involve any direct intervention other than recording the behaviour of the animals available for observation?</td><td></td><td></td></tr>
<tr><td>If YES, please give details</td><td colspan="3"></td></tr>
<tr><td rowspan="2">6</td><td colspan="2">Is the species you plan to research endangered, locally rare or part of a sensitive ecosystem protected by legislation?</td><td></td><td></td></tr>
<tr><td>If YES, please give details</td><td colspan="3"></td></tr>
<tr><td rowspan="2">7</td><td colspan="2">Is there any significant possibility that the welfare of the target species of those sharing the local environment/habitat will be detrimentally affected?</td><td></td><td></td></tr>
<tr><td>If YES, please give details</td><td colspan="3"></td></tr>
<tr><td rowspan="2">8</td><td colspan="2">Is there any significant possibility that the habitat of the animals will be damaged by the project, such that their health and survival will be endangered?</td><td></td><td></td></tr>
<tr><td>If YES, please give details</td><td colspan="3"></td></tr>
<tr><td rowspan="2">9</td><td colspan="2">Will project work involve intervention work in a non-natural setting in relation to invertebrate species other than Octopus vulgaris?</td><td></td><td></td></tr>
<tr><td>If YES, please give details</td><td colspan="3"></td></tr>
</table>

Blood Sampling / Human Tissue Analysis

<table>
<tr><th colspan="3">Question</th><th>Yes</th><th>No</th></tr>
<tr><td rowspan="2">1</td><td colspan="2">Does your study involve collecting or use of human tissues or fluids?
(e.g. collecting urine, saliva, blood or use of cell lines, 'dead' blood)</td><td></td><td>X</td></tr>
<tr><td>If YES, please give details</td><td colspan="3"></td></tr>
<tr><td rowspan="2">2</td><td colspan="2">If your study involves blood samples or body fluids (e.g. urine, saliva) have you clearly stated in your application that appropriate guidelines are to be followed (e.g. The British Association of Sport and Exercise Science Physiological Testing Guidelines (2007) or equivalent) and that they are in line with the level of risk?</td><td></td><td></td></tr>
<tr><td>If NO, please explain why not</td><td colspan="3"></td></tr>
<tr><td rowspan="2">3</td><td colspan="2">If your study involves human tissue other than blood and saliva, have you clearly stated in your application that appropriate guidelines are to be followed (e.g. The Human Tissues Act, or equivalent) and that they are in line with level of risk?</td><td></td><td></td></tr>
<tr><td>If NO, please explain why not</td><td colspan="3"></td></tr>
</table>

Travel

Question			Yes	No
1	Does any part of the project require data collection off campus? (e.g. work in the field or community)			X
	If YES: You must consider the potential hazards from off campus activities (e.g. working alone, time of data collection, unfamiliar or hazardous locations, using equipment, the terrain, violence or aggression from others). Outline the precautions that will be taken to manage these risks, AS A MINIMUM this must detail how researchers would summon assistance in an emergency when working off campus. For complex or high risk projects you may wish to complete and upload a separate risk assessment			
2	Does any part of the project involve the researcher travelling outside the UK (or to very remote UK locations)?			
	If YES: Please give details of where, when and how you will be travelling. For travel to high risk places you may wish to complete and upload a separate risk assessment			
3	Are all travellers aware of contact numbers for emergency assitance when away (e.g. local emergency assistance, ambulance/local hospital/police, insurance helpline [+44 (0) 2071 737797] and CU's 24/7 emergency line [+44 (0) 2476 888555])?			
4	Are there any travel warnings in place advising against all, or essential only travel to the destination? NOTE: Before travel to countries with 'against all travel', or 'essential only' travel warnings, staff must check with Finance to ensure insurance coverage is not affected. Undergraduate projects in high risk destinations will not be approved			
5	Are there increased risks to health and safety related to the destination? e.g. cultural differences, civil unrest, climate, crime, health outbreaks/concerns, and travel arrangements?			
	If YES, please specify			
6	Do all travelling members of the research team have adequate travel insurance?			
7	Please confirm all travelling researchers have been advised to seek medical advice regarding vaccinations, medical conditions etc, from their GP			