The Carbon Footprint of WEEE (Waste Electronic and Electrical Equipment) in the UK – a case study based on the UK's largest WEEE producer compliance scheme

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In collaboration with REPIC Ltd.

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“I declare that this dissertation is my own work and has not been submitted in substantially the same form towards the award of a degree or other qualification. Acknowledgement is made in the text of assistance received and all major sources of information have been appropriately referenced. I confirm that I have read and understood the publication Guidance on Writing Technical Reports published by the Department.”

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Abstract

500,000 tonnes of waste electrical and electronic equipment (WEEE) is collected and treated in the authorised WEEE system in the UK annually. Greenhouse gas emissions result from the transportation and treatment processes, but emissions reductions occur elsewhere in the economy when secondary materials, reused EEE and recovered electricity substitute virgin materials.

Here we investigate the carbon footprint of the authorised WEEE system in the UK, utilising a combined material flow analysis (MFA) and life cycle assessment (LCA). The potential for improvements in the carbon footprint are investigated through optimisation of logistics by solving a Vehicle Routing Problem with the objective of minimising carbon footprint. Detailed primary data was obtained from a producer compliance scheme and the collection and pre-treatment operators, yielding highly specific emissions and material flow data across these stages. Data covering the recycling, incineration and landfill stages was sourced from the Ecoinvent 3.7 database.

The LCA results show a net carbon footprint benefit for the collection and treatment across all WEEE streams. The average carbon footprint per tonne of WEEE was -2.01t$CO_{2eq.}$, consisting of 0.903t$CO_{2eq.}$ of gross emissions and -2.92t$CO_{2eq.}$ of avoided emissions. The gross emissions are mainly from recycling and energy-from-waste, and the avoided emissions from the substitution of 0.748t of virgin material with recycled material. Furthermore, optimisation of AATF allocation achieved a further improvement of 0.22t$CO_{2eq.}$ per tonne of WEEE by increasing use of AATFs with higher recovery rates.

Specific findings include the large range in total emissions when WEEE is sent to different pre-treatment plants, and the finding that energy-from-waste is less beneficial than landfill from a carbon footprint perspective.

Implications include informing decision making at the industry and policy level to improve the carbon footprint of the WEEE system and increasing public awareness of the benefit of correct WEEE disposal.

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Acronyms:

AATF	Approved Authorised Treatment Facility
(H)CFC	(Hydro)Chlorofluorocarbons – high GWP refrigerant gases.
$CO_{2eq.}$	Carbon Dioxide Equivalent – unit of GWP of different greenhouse gases scaled to the impact of carbon dioxide.
DCF	Designated Collection Facility
DEFRA	UK Government Department for Energy, Food and Rural Affairs
EEE	Electrical and Electronic Equipment
EFW	Energy-from-Waste Incineration
EoL	End-of-life
GDL	Gas Discharge Lamp
GWP	Global Warming Potential
HTI	High-temperature-incineration
LCA	Life Cycle Assessment
LHA	Large Household Appliances
SMW	Small Mixed WEEE
VRP	Vehicle Routing Problem
WEEE	Waste Electrical and Electronic Equipment

1. Introduction

1.1 Background and Rationale

1.1.1 Waste Electrical and Electronic Equipment (WEEE)

Electronic waste, also known as WEEE (Waste Electrical and Electronic Equipment), is a waste stream that encompasses any item "which is dependent on electric currents or electromagnetic fields in order to work properly" that has been disposed of by the owner (*The WEEE Regulations*, 2013). As a waste stream it has dramatically escalated in importance through the 21st century as the amount of discarded EEE has increased, along with the knowledge of the environmental and health risks posed by WEEE. In 2019 54 million tonnes of e-waste was generated worldwide, over double that in 2000 (Parajuly et al., 2019). Over this same period, multilateral treaties have highlighted the environmental and health risk of materials in WEEE, including: Refrigerant gases, some of which are highly potent greenhouse gases and deplete the ozone layer, phased out by the Montreal Protocol (*Amendment to the Montreal Protocol*, 2016; Calm, 2008); Mercury contained in lamps, phased out by the Minamata Convention (Budnik and Casteleyn, 2019; *Minamata Convention on Mercury*, 2013); And persistent organic pollutants contained in some WEEE plastics targeted by the Stockholm Convention (Keeley et al., 2020; *Stockholm Convention on Persistent Organic Pollutants*, 2001), all while climate change climbed in priority on the worldwide agenda.

In recent years focus on climate change has increased; it is now recognised to be a significant threat to environment and health in the 21st century (Field et al., 2014). The UK government has set legally binding targets to reduce emissions (Department for Business, Energy & Industrial Strategy, 2021), and it is becoming widespread for businesses to target emissions reductions (UNFCCC, 2020). These targets will require reductions in carbon emissions from across the economy. WEEE is relevant to carbon footprint because of the emissions produced when disposing of it, and the reduction in emissions elsewhere in the economy when the useful outputs of the treatment process substitute raw materials.

In the UK, extended producer responsibility requires the producers of EEE to finance the cost of the collection and treatment of a set amount of WEEE using the best available treatment recovery and recycling techniques (BATRRT) (*The WEEE Regulations*, 2013). 23.9kg of WEEE is estimated to be generated annually per capita in the UK, the 2nd highest rate in the world (Forti et al., 2020). Of this, 31% is 'Household WEEE' collected through the authorised WEEE collection network under BATRRT regulations. The remainder of the WEEE is split between reuse outside of the WEEE system, non-WEEE specific recycling, residual waste disposal, and illegal export or theft (Sayers et al., 2020).

The process of the authorised collection and treatment of WEEE has a carbon footprint from fossil fuel combustion and electricity usage, and directly from incineration of material. And its carbon benefit comes when materials are recycled, energy produced or WEEE reused, which all substitute the use of raw materials and their emissions. There is a consensus view in the literature that a net emissions reduction results from these avoided emissions exceeding the actual emissions from the treatment process (Baxter et al., 2016; Biganzoli et al., 2015; Wäger et al., 2011). Within the UK, little research has been conducted specific to the carbon footprint of authorised WEEE disposal. Turner, Williams and Kemp (2015) produced a value for the UK's WEEE recycling, but in a paper assessing the whole UK solid waste stream, and Clarke, Williams and Turner (2019) specifically investigated the carbon footprint of WEEE in the UK, but with a wide scope looking at all of the formal and informal disposal routes. Other countries have undertaken more detailed studies of the authorised WEEE disposal system using life cycle assessment; in Switzerland (Wäger et al., 2011), Italy (Biganzoli et al., 2015), Norway (Baxter et al., 2016) and the USA (Jaunich et al., 2020). These detailed studies use primary data collected from companies in the WEEE disposal supply chain to assess the environmental impact with more accuracy than the current UK studies, whose wide scope precluded that level of detail.

The UK WEEE industry would benefit from a better understanding of their impact and how it can be reduced, and consumer uptake of official WEEE disposal pathways could improve with their knowledge of the benefit. An improved understanding of the carbon footprint of the UK's authorised WEEE sector would also benefit government as legislation and policy is updated to achieve its aims of emissions reductions.

1.2 Industry Context

The authorised WEEE collection and treatment system is regulated by The UK WEEE Regulations (*The WEEE Regulations*, 2013), based on the extended producer responsibility strategy in the EU WEEE Directive. They require producers of >5 tonnes of EEE to become paying members of a Producer Compliance Scheme. The producer compliance scheme funds the compliant collection, treatment, recovery and recycling of WEEE at end-of-life, and recovers the cost from the producers. Post-Brexit, while the UK has initially continued using regulations based on the EU Directive, there is now the option to make regulatory changes domestically. In November 2020 the House of Commons Environmental Audit Committee produced 27 recommendations for alterations to the WEEE regulations (House of Commons Environmental Audit Committee, 2020). The current government position of gathering views on amendments to the WEEE system (Figure 1) makes for an excellent time to assess potential improvements that could be made to the system to improve the carbon footprint.

> "Now that we are no longer members of the European Union we have an opportunity to develop better regulations in relation to the management of e-waste in order to achieve the desired environmental outcomes more effectively... This is why we committed in the Resources and Waste Strategy 2018 to consult on reviewing the WEEE Regulations to tackle these areas and look at ways that reforms can better support the drive towards the circular economy and improve resource efficiency... We are also working closely with key stakeholders, ranging from producers, through to local authorities, treatment facilities and re-use organisations, in order to gather their views on how the system could be best amended to maximise opportunities for recycling and reuse..."

Figure 1: An excerpt from the government response to the House of Commons Environmental Audit Committee recommendations for altering the WEEE legislation. (The UK Government, 2021)

REPIC Ltd., for whom this work was commissioned, and whose data the research is based on, are a Producer Compliance Scheme that operates not-for-profit collection and treatment schemes for WEEE, batteries and packaging. REPIC finances the collection, treatment and recovery of around half of all UK household WEEE, allowing its producer members to meet their collection obligations.

1.2.1 REPIC's Supply Chain

REPIC's WEEE collection and downstream processing is a complex supply chain that collects WEEE from council areas across the UK. Some WEEE is diverted for reuse, and the remainder undergoes treatment and separation into material fractions at facilities in the UK, after which the materials are transported to an end-of-life process either in the UK or abroad. The end-of-life of WEEE materials encompasses recycling, landfill or incineration (Figure 2).

REPIC becomes responsible for WEEE when it has been deposited by consumers at a Designated Collection Facility (DCF), which can be Household Waste Recycling Centres or retailer deposit points. WEEE is collected in 6 different WEEE streams at each DCF, and REPIC has arrangements to collect 5 of these (Table 1), only excluding Photovoltaic Panels, which in 2019 only represented 0.013% of collected household WEEE (Environment Agency, 2021a). Each WEEE stream is collected separately either when the DCF is nearing capacity, or on a regular schedule, and transported by road to an Approved Authorised Treatment Facility (AATF) that can process that WEEE stream. Collections of WEEE are either by single out-and-back collections from a single DCF, sometimes using roll-on-roll-off skips, or by "milkround" collections where multiple DCFs are collected from in a single journey. Additionally, some collections transport WEEE to a consolidation point where it is bulked for more efficient transport to the AATF in larger vehicles. REPIC works with over 500 DCFs and over 50 AATFs so this is a complex logistics network.

*Table 1: The 6 WEEE Strems collected in the UK, and the shorthand that they are referred to as. * indicates that REPIC does not collect the Photovoltaic Panel WEEE Stream.*

WEEE Stream Letter	WEEE Stream Name	Shorthand
A	Large Domestic Appliances	LHA (Large Household Appliances)
B	Cooling Equipment	Cooling
C	Display Equipment	Displays
D	Lamps	GDL (Gas Discharge Lamps)
E	Small Mixed WEEE	SMW (Small Mixed WEEE)
F*	Photovoltaic Panels*	PV*

Each AATF undertakes treatment and pre-processing of WEEE and separates it into constituent materials. Before treatment, whole equipment may be separated from the waste stream and reconditioned to be sold for reuse. The remainder of the WEEE undergoes treatment in accordance with the WEEE regulation best available treatment recovery and recycling techniques (BATRRT), examples of which include removing refrigerant gases, separating out circuit boards >10cm^2, and shredding cooling WEEE in a nitrogen gas atmosphere to suppress flammability (Environment Agency, 2021b). The remaining WEEE material is then shredded or disassembled and separated into different material fractions – REPIC's AATFs reported 27 different material fractions in 2019.

Each WEEE fraction is then transported to its different end-of-life processes (EoL). Depending on the material, the quality, and the AATF's arrangements, the end-of-life process can be recycling, energy-from-waste (EfW), landfill, or high-temperature-incineration (HTI). The WEEE regulations specify a required minimum recycling and recovery rate for each WEEE category that must be achieved for AATFs to keep their permit (Environment Agency, 2020a). The legislation also dictates specifics, such as that hazardous materials, such as plastics containing persistent organic pollutants (POPs), must be destroyed, usually by incineration. The processes of recycling and recovery have benefits beyond just treating the waste. The recycling process produces secondary raw materials that enter the global market for use in new products, reducing the need for virgin material production. Additionally, recovery, analogous to EfW, recovers energy from the WEEE, either through heat and electricity-generating incineration, or conversion to solid recovered fuel (SRF) to power cement kilns, which both substitute other energy sources.

REPIC's direct contracts, and the influence that these infer, are with the Local Authority areas where the WEEE is collected, the collection hauliers, and the AATFs. The supply chain downstream of the AATFs is coordinated by the AATFs and the downstream companies themselves. The destinations of the recyclable materials vary based on market conditions and government legislation in receiving countries, for example the ban of plastic waste imports into China (World Trade Organisation, 2017).

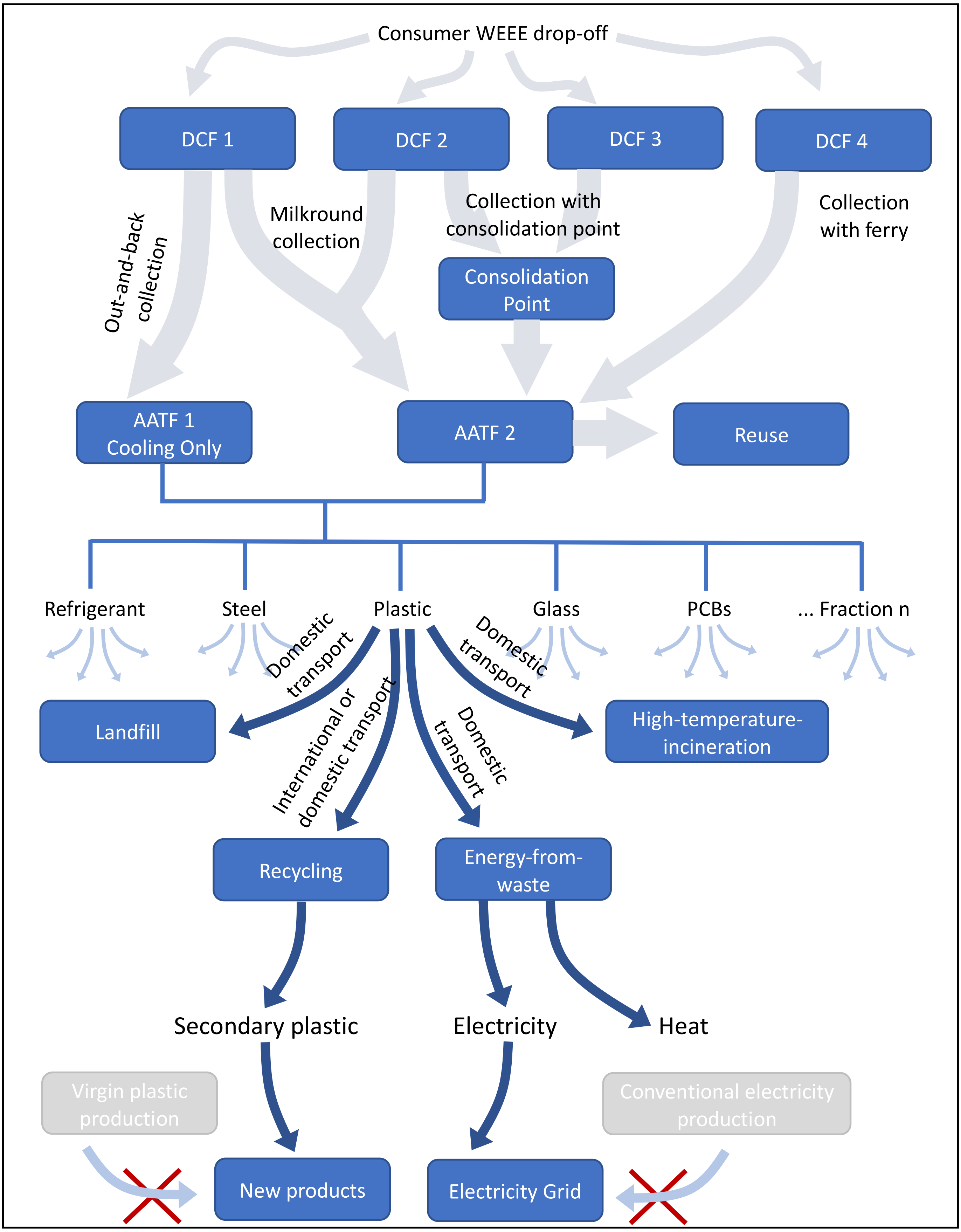


Figure 2 – Simplified flow chart showing the Household WEEE supply chain in the UK from consumer drop off to disposal/substitution of other materials. 4 DCFs and 2 AATFs are shown, and 6 material fractions, with the full supply chain only displayed for plastic.

1.2.2 The Materials in WEEE

E-waste is composed of a wide variety of materials, many of them in very small quantities (Goosey, 2012). The composition of WEEE is also constantly changing due to the high pace of technological development, changes include: the transition from cathode-ray displays to flat panel displays, reducing glass and lead content of WEEE; and transition of cooling devices away from ozone-depleting refrigerants (Wager et al., 2017). The range of EEE lifetime before consumers dispose of items results in the waste stream containing devices with a range of ages, with a lag for when transitions in new technology reach the waste stream.

Studies on the material composition of WEEE show that steel and plastic make up the majority of the WEEE by weight (WRAP, 2012). As such we can expect the end-of-life processes for these materials to contribute a large proportion of the emissions from that stage of the supply chain. Materials going to energy-from-waste or high-temperature-incineration are also likely to contribute significantly to the emissions due to the direct burning of the material releasing CO_2. The benefit of substituted virgin material is again likely to be dominated by the recycled fractions of steel and plastic due to their high proportion of the composition, but some of the smaller material fractions are known to have extremely high virgin production emissions, so they are likely to also contribute significantly to the carbon benefit. Namely aluminium, copper and precious metals from circuit boards fit into this category. Detail of the technologies used in each material's end-of-life processes are given in Appendix A.

In the context of carbon footprint, refrigerant gases are a material deserving special discussion. While the other materials in WEEE only result in direct carbon emissions when burnt or decomposed, the refrigerants are themselves greenhouse gases and cause direct global warming impact if released into the atmosphere. R12, a legacy refrigerant, that has been phased out in new products but is still present in the waste stream, has a GWP of 12,000, and even a modern refrigerant, R134a, has a GWP of 1,430. A full discussion of the refrigerant timeline and presence in the waste stream is presented in Appendix B.

1.2.3 Industry Interest in Carbon Footprint

Up until this point, REPIC's knowledge of its carbon footprint has come from ISO14001 monitoring of Scope 1 and 2 emissions for their own office, and data published from other PCSs elsewhere in the EU on the WEEE supply chain emissions and benefits, but they have had no data to verify the emissions from their own WEEE supply chain. Their intuitions to improve carbon footprint have included reducing collection distances using multiple collections per journey and securing contracts with adjacent local authorities to allow vehicles to have more local household waste recycling centres to fill up at. REPIC's interest in quantifying its carbon footprint includes gathering data in order to set benchmarks, monitor and report, and evaluate future changes to logistics and planning. Further anticipated benefits include:

- Being able to measure and quantify where the impacts lie across its business activities, to help reduce carbon emissions.
- Added value to REPIC's service for its members; in the form of transparency and reporting on the carbon benefits and impacts of the WEEE which producers finance.
- Preparation for any future government requirements for emissions reporting or reductions.
- Evidence to inform government policy suggestions from REPIC in the consulting phase of the UK WEEE Legislation Reform.
- Emissions and cost savings where logistics can be optimised to reduce fuel/electricity usage.
- Use of emissions data in contract bidding to demonstrate the benefit of REPIC's service.
- Use of emissions data to communicate to consumers the benefit of disposing of WEEE correctly, which may increase uptake of the WEEE system and help REPIC meet the obligations of its producers.

To achieve these outcomes REPIC's main deliverable requested from the research is a carbon footprint calculator for quantifying the emissions related to the treatment of WEEE within their operations. Initially for a reference year, with functionality to update annually for carbon reporting and to assess the impact of different future scenarios. A supplementary deliverable is logistics optimisation suggestions for where carbon emissions savings could be made.

1.2.4 Industry Interest in Optimisation

REPIC is interested in using the results of the carbon footprint calculator to investigate ways of reducing their carbon footprint. REPIC has direct contracts with the local authorities, collection hauliers and pre-processing facilities (AATFs) and so has scope to improve the carbon footprint by making changes to these stages of the supply chain. Changes to vehicle routing and collection schedules have potential to reduce the collection emissions (Gamberini et al., 2010), and this was one of REPIC's intuitions for reducing carbon footprint. Additionally, if there are differences in recovery rate between different AATFs, changes to the choice of AATFs used for treating the WEEE would have potential to reduce the emissions of the whole downstream disposal process due to more or less material being recycled (Unger et al., 2017).

Currently, REPIC allocates each collection facility (DCF) to a specific pre-treatment site (AATF) based on long-standing contracts that aim to reduce the cost of the service for REPIC's members who fund it. A haulier company is assigned to collect WEEE from multiple DCFs, often an entire local authority area, and transport it to the assigned AATF. Arrangements for when to pick up the WEEE vary, either running on a regular schedule, or on a 'pick-up when full' arrangement. Route choice, and whether to collect from multiple DCFs in a single journey, is left to the haulier to decide.

Logistics optimisation methods can be used to assess the current collection efficiency and investigate improvements. Whereas typical logistical optimisation focuses on reducing financial cost, with carbon footprint data for the WEEE supply chain there will be an opportunity for allocation and routing to be optimised to reduce net carbon footprint. Changes could decrease gross carbon emissions and/or increase the avoided emissions from the substitution of virgin materials. Future decisions by REPIC on AATF allocation and haulier coordination could add this carbon footprint evaluation as a factor alongside cost.

1.3 Aims and Objectives

There is a general consensus that the formal collection and treatment of WEEE is beneficial from a carbon footprint perspective (Ismail and Hanafiah, 2019), but the accuracy of studies evaluating this in the UK have lagged behind the state-of-the-art. It is also noted that there has been minimal research investigating ways in which the logistics of the WEEE system can be improved to reduce the carbon footprint (Gamberini et al., 2010), leaving uncertainty for stakeholders in the supply chain in how to reduce the carbon footprint.

This research contributes to the scholarly field of WEEE carbon footprint through the production of a methodology that utilises UK data from a WEEE producer compliance scheme and companies in the WEEE supply chain to produce a more granular and up-to-date carbon footprint of the UK's authorised WEEE system than has been produced to date. This provides better knowledge for the UK WEEE supply chain on the baseline of its emissions, and where the largest impacts are found. The study also contributes to the field of WEEE logistics optimisation - the high granularity of data in the carbon footprint model allowed development and testing of a logistics optimisation model that minimises the supply chain carbon footprint, expanding beyond simple vehicle routing to encompass how logistical decisions affect the entire downstream supply chain footprint, a novel approach. The output has provided suggestions to producer compliance schemes on ways they may be able to reduce the carbon footprint of the supply chain. The data collected also represents the most up-to-date and specific dataset in the UK for: WEEE collection vehicle emissions, Approved Authorised Treatment Facility (AATF) emissions, and post-AATF WEEE material composition.

The aims and objectives of the research were designed to fulfil REPIC's desired deliverables, while contributing to the above areas of the UK WEEE research literature and producing findings that can inform policy decisions.

Aims:

- Aim 1: Develop a model which calculates the carbon emissions associated with the collection and treatment of REPIC's WEEE.
- Aim 2: Evaluate the carbon footprint/benefit across the whole WEEE supply chain.
- Aim 3: Evaluate ways in which the carbon footprint of REPIC's WEEE supply chain could be improved through optimisation of collection journeys and AATF allocation.

To fulfil these aims, the following objectives were addressed:

- Collect data from REPIC on the annual collections of WEEE, and the locations and companies involved.
- Gather primary data from operators in the supply chain to get specific details of the emissions from transportation and pre-processing, the material composition and the destination post pre-processing.
- Collect carbon footprint data for the end-of-life treatment options for each material from a life cycle inventory database.
- Construct a material flow analysis to track the materials resulting from WEEE pre-treatment and what end-of-life process they go through.
- Collate the emissions and material flow data in an Excel carbon footprint calculator that shows the magnitude of emissions, both gross and net, and where in the supply chain they are emitted, with the option to update data for future years.
- Conduct sensitivity analysis on the data inputs and assumptions.
- Use the output from the carbon footprint calculator as the input for an optimisation model that minimises the carbon footprint of the logistics of WEEE collection and treatment.

2 Literature Review

2.1 Introduction

The disposal of e-waste has been the subject of research and policy since the 1976 Resource Conservation and Recovery Act which required controls on the disposal of hazardous waste, including electronics (Congress, 1976). E-waste was further implicated in the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal in 1989. The introduction of legislation on e-waste disposal around the world was initially focused on reducing the environmental pollution and danger to human health from hazardous substances in electronics, but has since expanded to also promote the resource benefit of recycling electronics (Khetriwal et al., 2011). Since the EU WEEE Directive was publicly announced in the 1990s there have been numerous studies assessing the environmental benefit and cost of WEEE recycling in Europe, with carbon footprint becoming more of a focus in the last decade (Baxter et al., 2016; Clarke et al., 2019; Hischier et al., 2005; Huisman, 2003; Snowdon et al., 2000).

This review starts by investigating the literature relevant to Aims 1 and 2 of the research – outlining the overall concept of carbon footprint calculation before focusing on carbon footprint research specifically involving WEEE. It discusses the methods utilised and conclusions reached in the WEEE literature and some of the debates that merit further investigation. The methods that apply to the optimisation scenario are then discussed, before finally the knowledge gap that this research seeks to address is summarised.

2.2 Carbon Footprint Measurement

For the purposes of this study, carbon footprint is defined as in ISO 14067, as the: “sum of greenhouse gas emissions and removals in a product system, expressed as CO_2 equivalents and based on a life cycle assessment using the single impact category of climate change” (ISO, 2018).

A further breakdown of carbon footprint, as defined by the Greenhouse Gas Protocol, is into 'Scopes' that categorise different sources of emissions with respect to a company or household (WRI, 2004). Scope 1 includes only direct emissions of greenhouse gases from company owned or controlled sources, mostly from burning of hydrocarbons. Scope 2 covers indirect emissions from purchased energy in the form of electricity, steam, heating or cooling. Scope 3 encompasses the remainder of indirect emissions and can be broken down into Upstream Scope 3, from the upstream supply chain of suppliers, and Downstream Scope 3, covering emissions from the downstream supply chain, including use and end-of-life disposal of goods.

The complexity of the WEEE supply chain, with a range of emissions sources and avoided emissions, makes the carbon footprint complex to assess and not readily apparent. Life cycle assessment (LCA) is a bottom-up approach to assessing environmental impact, well suited to complex problems. It aims to compile all the material and energy inputs and outputs of a system and work out their combined impact against different environmental indicators. The objective assessment that LCA offers, covering the whole supply chain of a process, reduces the risk of incorrect conclusions being drawn where an improvement in one area may be offset by worsening in another area.

The concept of life cycle assessment was first used in the late 1960s as a tool for assessing single products' raw material and energy requirements, initially implemented by The Coca Cola Company to assess their packaging products (Frankl and Rubik, 2000). The concept later

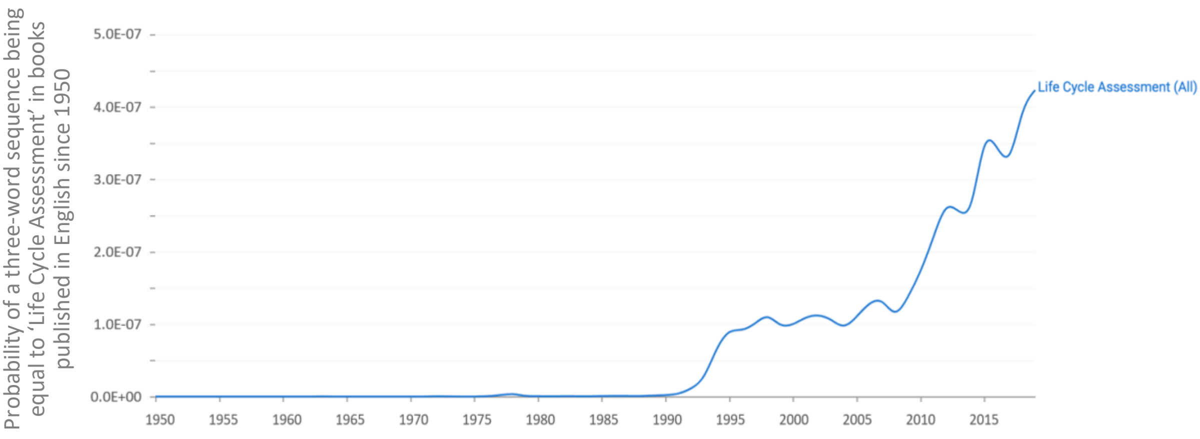


Figure 3: Usage of the term 'Life Cycle Assessment' (case insensitive) in books published in English since 1950 (Michel et al., 2011). There has been a massive growth since 1990 when reducing environmental impact started coming to the foreground.

expanded to be used for assessing entire supply chains, and to compare different waste management systems in the late 1980s (Hunt et al., 1996). Since 1990 the usage of LCA has increased enormously (Figure 3) and it is now a widely used tool that is applied to a variety of industries. It is now commonly confined to looking at global warming potential as the only impact indicator, to find the carbon footprint of a system (Guinee et al., 2011).

LCA requires decisions to be made relating to where the boundary is drawn for stopping assessing impact, how impact is allocated between multiple beneficiaries of a process, and what units of impact to use. The International Organization for Standardization (ISO) introduced standards, starting in 1997, to reduce the subjectiveness of the process and improve comparability between studies. In order of increasing specificity to e-waste recycling exists ISO 14040 and 14044 for LCA, ISO 14067 for Carbon Footprint of a Product, and the European Committee for Electrotechnical Standardization product category rules (CENELEC PCR) for LCA of electronic and electrical products and systems (ISO, 2006a, 2006b, 2018; CENELEC, 2019). These LCA standards do not contradict one another, instead, each becomes more specific and detailed in the guidelines given. They all share the same basic LCA framework, consisting of 4 stages: setting the goal and scope of the study, producing an inventory of life cycle processes, undertaking an impact assessment, and finally an interpretation stage. The details of each stage are briefly detailed below.

- <u>Goal and scope definition:</u>

  This first stage sets the goal, assumptions and boundaries of the study. The goals of the study then guide choices of functional unit, system boundary and impact categories.

  A functional unit of reference is set that the inputs and outputs are scaled to, such as 1 tonne of output from a process.

  A system boundary is decided upon that sets a limit for where processes will stop being included in the analysis.

- <u>Life cycle inventory analysis:</u>

  The inventory analysis is the main stage of data collection and model creation of the LCA. Within the system boundary, inputs and outputs of raw material and energy are found, as well as the amount of functional unit that they relate to.

- Life cycle impact assessment:

  The impact assessment phase of LCA evaluates the data from the inventory against indicators that show environmental impact in one or more categories. The inventory data is converted into midpoint indicators that are physical environmental damage units e.g. Global Warming Potential in $kgCO_{2eq.}$. Following this, an optional stage combines multiple midpoint indicators into endpoint indicators that represent the actual damage e.g. damage to human health, damage to ecosystems.

- Life cycle Interpretation:

  The interpretation phase is where the results are assessed in the context of the goal of the study. The different stages of the process can be separately assessed to find where the greatest impacts are produced. Sensitivity analysis is used to assess the relative importance of each of the data inputs. Data inputs should also be evaluated for quality.

2.3 The Carbon Footprint of WEEE

The carbon footprint of the WEEE collection and treatment process can be categorised as part of the Scope 3 emissions of producer compliance schemes, such as REPIC for whom this work was commissioned. It also represents the downstream Scope 3 end-of-life emissions for EEE producers.

LCA is the carbon footprint methodology underlying all the WEEE treatment carbon footprint studies that were found. Studies have been undertaken in a range of different countries, and the studies vary in their methodological choices such as system boundary choice, and in the specificity of data sources.

Hischier et al.'s (2005) study on the environmental impact of the WEEE treatment system in Switzerland is the most cited early paper discussing the environmental impact of WEEE treatment, and sets a general methodology based on ISO 14040 which is shared by most subsequent papers on the subject. They complete a combined material flow analysis and life cycle assessment analysing the entire Swiss WEEE treatment system in 2004. It compares the Swiss recycling-based system to a baseline scenario where all WEEE is incinerated and equivalent materials to those produced from recycling in the Swiss system are produced from virgin sources. The system boundary for the LCA starts at the point that EEE becomes waste and ends when the WEEE material is either disposed of by landfill or incineration, or when a secondary raw material has been produced from recycling. The functional unit used was all WEEE collected in 2004 in Switzerland. The main conclusions reached are that WEEE recycling is environmentally advantageous compared to the baseline, and that the greatest environmental impact of the Swiss system lies in the final recycling processes. The study used multiple midpoint indicators including climate change, acidification, eutrophication, resource depletion and ecotoxicity, and they all show similar trends that the Swiss system has a lower impact than incineration. While this paper quantified for the first time the carbon footprint of recycling a mixed WEEE stream, and showed it is possible to calculate the material flow of WEEE through the supply chain, its validity suffers due to some non-specific inputs. While primary data specific to Switzerland in 2004 was collected for the material flow calculation, the inputs for the LCA were less specific secondary data. For example, the WEEE pre-processing electricity usage value, of 38.2kWh per tonne, is sourced from a 2001 paper in the Netherlands (Ansems and van Gijlswijk, 2001). Collection distances are estimates, of between 35 and 50km, and the remainder of the transport and material recovery data comes from data from the Swiss Ecoinvent life cycle inventory (LCI) database or published material. The database values used are also limited in their specificity, for example, all metals and metal-plastic mixtures are assumed to be steel. The use of mostly secondary data inputs highlights the ease of using secondary data rather than collecting primary data.

More recent studies have sometimes improved on these limitations, but other times not. Use of secondary data and LCI database values still saves time and avoids issues of accessing commercial sensitivity of data. Menikpura, Santo and Hotta (2014) make extensive use of database values for their LCA of WEEE recycling in Japan, relying on them for the recovery rates and proportion of materials in WEEE, the emissions from the recycling process, and the avoided emissions. This results in an LCA that is highly dependent on these average values and the research and assumptions that they are based on. LCI databases have expanded since

Hischier's original paper to allow most activities in the WEEE supply chain to be matched to a dataset. Despite this, LCAs aiming for high accuracy should minimise database use where possible because the values can vary greatly between different databases and often lack specificity to the technology and/or geography of the system being analysed (Brogaard et al., 2014).

Several European studies have overcome some of the limitations in Hischier's 2005 paper. Baxter *et al.*'s 2016 Norwegian LCA study looks at the carbon footprint of recycling refrigerators, flat panel screens and mobile phones, with the functional unit being the weight of 1 item for each. This made use of primary data from a Norwegian producer compliance scheme detailing the WEEE collection and transport at the single journey level. They combined GIS data and vehicle emissions data with the collection data to calculate accurate emissions of the collection transport stage. Database values are still used for the pre-processing and end-of-life processes, and material compositions are simplified down to 6 or 7 materials. While not undertaken in this study, the high level of data granularity and accuracy for the collections would be sufficient to allow evaluation and optimisation of the collection logistics.

Further improvements to accuracy are seen in a 2015 Italian WEEE LCA by Biganzoli *et al.* This WEEE LCA makes use of similar methods to those discussed above, but improves on them further with further use of primary data, and better consideration of the recycling rates achieved in the final recycling process. Collection and transport distances are based on single journey data and use Ecoinvent database values for transport emissions. The emissions from pre-processing and the material composition of the WEEE utilise primary data from the Approved Authorised Treatment Facilities (AATFs). The material composition is based on the material that leaves the pre-processing; Biganzoli notes this is less conventional than knowing the material composition of the EEE devices themselves, but that for a complex mixed waste stream like WEEE, the average output of the AATF is the best method of finding the average composition. The emissions from the end-of-life processes are a combination of primary data and Ecoinvent data. Other studies assume all secondary material directly substitutes the same mass of virgin material, but Biganzoli points out in reality there are quality losses in the process of recycling, due to contamination or the physical process itself – resulting in a substitution rate of less than 1:1. Most secondary metals, glass and concrete are still assumed to substitute 1:1, but plastics and wood are given lower substitution rates. Baxter et al. and Biganzoli et al.'s research using accurate and highly granular input data allows them to be used for identifying ways to reduce the carbon footprint, and aid in decision making within the supply chain.

Clarke, Williams and Turner (2019) is the most up-to-date and in-depth study of the UK's WEEE system carbon footprint. They conclude similarly to other studies that the recycling has a net carbon footprint benefit, but their methodology results in a less than ideal specificity to the UK's current WEEE system. The methodology follows the common structure of breaking the supply chain down into the collection, pre-processing, transport to end-of-life, end-of-life and avoided emissions stages, and presents gross and net emissions, but accuracy is hindered by out-of-date secondary data and heavy use of database data. This study's scope is wider than all others discussed, assessing the carbon footprint of all WEEE arising in the UK, including permanent hoarding and illegal flows. It also adds a forward-looking element with predictions of future flows and their environmental cost/benefit. It appears this wide scope precluded the time-consuming primary data collection and up-to-date database data collection which would have been required to increase accuracy to the level seen in other studies such as (Biganzoli et al., 2015). Data collection relies heavily on DEFRA, Environment Agency and WRAP studies dating between 2007 and 2012. Since the 2007 material composition data was published, the technology in lighting, displays, computers and consumer electronics have changed enormously, and their material composition with it – for example, the majority of displays in the waste stream have changed from cathode-ray to flat panel displays, with less glass and more metal and plastic (Wager et al., 2017). Hence out-of-date material compositions could lead to inaccurate results. Elsewhere in the study: distances of transport come from 2010 EA estimates; recycling rates for metals and plastics come from 2003 source data and assume no recycling of glass, cable or circuit boards; and the end-of-life emissions factors come from a Swiss publication in 2007. The overall impression is that most input data is over 10 years old and may not accurately reflect the 2019 situation. Further limitations in the model include reuse assuming 100% of the emissions of a new product are avoided, without considering the shorter lifespan and worse energy efficiency of a reused item, and for non-authorised WEEE treatment assuming no emissions from refrigerant gases which, when WEEE is disposed of outside of the authorised system, will all be emitted to the atmosphere with significant global warming potential.

The two other studies that assess the carbon footprint of WEEE treatment in the UK are from Turner, Williams and Kemp (2015, 2016) and analyse the whole solid waste management system in the UK. While they give useful insights into the UK's waste environment, the broad scope lacks specificity to WEEE, and so the data inputs and outputs are less detailed than WEEE specific studies.

2.4 Debates

A number of issues are not in consensus in the research literature on WEEE. The differences appear to be due to a combination of methodological choices and differences between countries. Each of the debates is discussed below, with reference to why the differences exist.

2.4.1 The Impact of Transport

The transportation of WEEE during its treatment is an area where research studies reach different conclusions on the contribution to the total carbon footprint. On one end of the spectrum there are studies that conclude that the carbon footprint of long, but not unfeasible, transport distances will outweigh the environmental benefits of recycling (Barba-Gutiérrez et al., 2008; Xiao et al., 2016). The 2016 Chinese paper shows a breakeven distance for global warming potential (where the environmental impact of transport totally offsets the benefits of the rest of the supply chain) at 590km of WEEE transport. Barba-Gutiérrez's paper doesn't use climate change as an LCA indicator, but for fossil fuel resources, the breakeven point is between 250 and 500km of road transport.

In contrast, Wäger, Hischier and Eugster (2011, p6) state "the contribution of collection [transport] and pre-processing is marginal" with respect to the overall environmental impact. This still holds if their assumption of 40km transport is scaled up by 10x to better match the distances quoted as breakeven in the other papers; this leads to transport contributing <15% of overall emissions and the recycling having a net avoidance of over 1tCO_2 per tonne of WEEE. Baxter *et al.* (2016) reinforce this view with transport contributing <10% of emissions, despite the modelled transport in Norway being over long distances of >500km.

2.4.2 The Impact of Pre-processing

Hischier et al. (2005, p2) states: "The results show that throughout the complete recycling chain the sorting and dismantling activities of companies are of minor interest; instead the main impact occurs during the treatment applied further downstream to turn the waste into secondary raw materials.", and further backs this in his 2011 LCA with Wäger and Eugster. This conclusion on the impact of pre-processing is debated by others who emphasise how the sorting and dismantling dictates the amount and quality of material going to downstream recycling. A comparison between WEEE pre-treatment in Austria with an 80.5% recovery rate and the legally required minimum of 62.5% showed an additional saving of >215kg$CO_{2eq.}$ per tonne of WEEE at the higher recovery rate (Unger et al., 2017). The lower recovery rate scenario has higher gross emissions from more material going to energy-from-waste, and reduced avoided emissions from recycled material substituting virgin material. Johansson and Björklund (2010) also conclude that changes to pre-processing can significantly reduce global warming potential: namely a manual pre-step to separate metals in dishwasher recycling, reducing contamination of the different scrap materials. Bigum et al. (2012) in Denmark state the importance of pre-processing in dictating the amount of precious metals recovery and the avoided emissions that their recycling constitutes.

2.4.3 The Benefit of Reuse

Reuse ranks above recycling in the waste hierarchy (DEFRA, 2011), but the improved efficiency of newer electronics complicates the matter for WEEE as continuing to use an old device could have a greater carbon footprint than producing and using a newer, more efficient device. Electronics with high embodied emissions and low use-phase emissions are most beneficial to reuse, as reuse avoids the production of another device and the associated embodied emissions, and the low use-phase emissions give little scope for improvement in newer devices. For example, O'Connell et al. (2013) show a clear case for reuse of ICT equipment due to its high embodied emissions, but for white goods the case is less clear due to 70-95% of their carbon footprint resulting from the use-phase. They also showed that the benefit of reuse depends on the rate of efficiency improvement in devices. High-efficiency gains made between 1990 and 2005 led to reuse in 2005 being less beneficial. Efficiency improvements are less clear between 2005 and 2020, improving the case for reusing electronics produced in that period. Additionally, in countries with lower electricity emissions intensity there is an improved case for reuse because the majority of use phase emissions are from electricity usage. Hischier and Böni (2021) further support that once EEE is beyond a certain age it is more beneficial to recycle it and produce a new item with higher efficiency. The benefit of reuse is also reliant on the reused item displacing the sale of a new item, which Cooper and Gutowski (2017) argue is not always the case, due to the lower price of reused EEE encouraging individuals to purchase items that they otherwise would not have.

Studies on WEEE carbon footprint vary in their approach to reuse. Some do not consider it at all (Baxter et al., 2016; Biganzoli et al., 2015; Ibanescu et al., 2018; Wäger et al., 2011). Others, such as Clarke (2019), include reuse and assume it avoids the emissions of producing a new EEE product, without attention paid to the above complications. This results in reuse being preferable over recycling for all types of WEEE. The most considered approach to reuse in the WEEE carbon footprint literature is assuming a substitution rate of <100% based on the expected lifespan of reused EEE vs new EEE (Jaunich et al., 2020; Turner et al., 2016). This results in EEE with a longer remaining lifespan constituting a larger carbon benefit from reuse, giving a similar conclusion to O'Connell and Hischier that reuse of older EEE is less beneficial.

2.4.4 The Impact of Refrigerant Emissions

Refrigerant gases, as mentioned in Section 1.2.2, can have such a high GWP that their emission can exceed all other areas of the process in terms of carbon footprint. In the WEEE literature several studies do not mention refrigerant gases (Clarke et al., 2019; Ibanescu et al., 2018; Menikpura et al., 2014; Wäger et al., 2011) and others discuss them with some confusion (Xiao et al., 2016).

Baxter *et al.* (2016) do include refrigerant gas emissions in their model, as it compares the official treatment scenario with a scenario where WEEE is landfilled, and the refrigerant is emitted. 410g of R134a refrigerant is assumed per cooling device and they conclude that emission to air of just 50g of refrigerant would negate the GWP benefit of recycling cooling devices. Per their model, if all the refrigerant gas in the annual WEEE stream were emitted, it would increase Norway's national carbon footprint by 0.4%. In the UK, the current WEEE collected contains a mixture of R12, R134a and R600a refrigerants, and R11 in insulation foam (Appendix B). These have a range of global warming potential (GWP) of over 3000x, so the carbon footprint calculated with the simplification to just R134a could be misrepresentative.

Xiao, Zhang and Yuan (2016) performed an LCA specifically on the cooling WEEE treatment process, but confusion is present around refrigerant emissions. Refrigerant emissions to air, and the ozone and climate impact, are included for recycling scenarios (the facility studied did not capture refrigerant during shredding) but excluded for the landfill baseline scenario, where the reality would be all refrigerant being emitted from the compressor circuit either due to removal and theft, crushing, or slow breakdown in landfill. A brief mention is made of this limitation, but it is only in the context of ozone depletion, not global warming potential.

Whether refrigerant emissions should be included in a WEEE LCA depends on if cooling devices are present and which WEEE disposal pathway is being analysed. Where cooling is considered and the disposal is by landfill, theft or non-authorised recycling, the refrigerant will be emitted to air and so its GWP should be included. For WEEE treated in the UK authorised system, the refrigerant should be captured at the AATF, as specified in the best available treatment recovery and recycling techniques guidance (Environment Agency, 2021c).

2.5 Consensus

While differences exist in the specific conclusions of the WEEE carbon footprint literature, there is consensus that formal WEEE collection and treatment is beneficial from a carbon footprint perspective, i.e. results in a world with less GHG emissions than if the collection and treatment did not occur. There is also consensus on some specific aspects of the footprint – namely that the final stage of actual material recycling, energy recovery and landfill produces greater emissions than the earlier stages of the supply chain; and that the avoided emissions which underly the net carbon benefit are predominantly from material outputs of the recycling process substituting production of virgin material.

The broad method of calculating the WEEE carbon footprint is also in consensus across the literature. The consensus method involves splitting the WEEE system into several supply chain stages, usually collection, pre-treatment, transport after pre-treatment, and final end-of-life process; tracking the mass of WEEE through each stage with a material flow analysis; and then undertaking a life cycle assessment by collecting data on the inputs and outputs at each stage of the supply chain and scaling these to the mass calculated by the material flow. Specific methodological choices are also shared, in particular the 'Zero Burden Approach' where emissions are excluded from the manufacture and use phase of the product, and from producing the capital goods in the supply chain, such as the vehicles and facilities.

2.6 State-of-the-art

The state-of-the-art in WEEE carbon footprint calculation is represented by studies which combine single-journey level collection data with primary data on energy usage and material output collected from pre-treatment facilities (AATFs in the UK). To the best of my knowledge, no studies have yet overcome the reliance on generic LCA databases for the final recycling, energy-from-waste and landfill disposal of WEEE material. Biganzoli's 2015 paper represents the state-of-the-art method for assessing the WEEE system's carbon footprint, achieving all of these criteria.

Within the UK there is only a limited research literature on the carbon footprint of WEEE, and the accuracy of the LCAs are not state-of-the-art. The reasons for a lack of UK research are not clear. We also note that the current state-of-the-art still leaves room for improvement. The WEEE carbon footprint from Biganzoli et al. does not attempt to quantify emissions from reuse. Furthermore, Biganzoli only produces a carbon baseline; despite having sufficient data granularity to assess different scenarios and investigate ways to reduce the footprint, no recommendations for improvements are made.

This study updates the UK literature on WEEE carbon footprint with single-journey level WEEE collection data from a producer compliance scheme, and primary data from haulage companies and AATFs, while also including a calculation for the carbon footprint of WEEE reuse. Furthermore, the granular carbon footprint data is used to assess the WEEE collection and pre-processing logistics of the producer compliance scheme, and optimisation modelling is used to find potential improvements.

2.7 Logistics Optimisation

The WEEE carbon footprint studies detailed above only offer broad suggestions on how the carbon footprint of the WEEE system can be improved, mainly focusing on the carbon footprint baseline numbers. While a carbon footprint baseline can aid decision making around the benefit of the WEEE system, producer compliance schemes such as REPIC are unsure how they can exert their influence on the supply chain to reduce the carbon footprint. Producer compliance schemes can most directly influence the supply chain through their logistics decision making for the collection of WEEE, and their choice of AATF pre-treatment operators.

Logistics optimisation is a broad and well-researched field. When applied to the WEEE collection and treatment system, the close relationship between collection vehicles' distance travelled and carbon footprint allows route optimisation to be a method for reducing carbon footprint. Route optimisation is wide-spread and has been applied to a WEEE collection network in Italy in research by Gamberini et al. (2010). Calculation of a granular carbon footprint of an entire WEEE supply chain, with emissions factors specific to different operators, allows a novel, wider-scope, form of carbon footprint optimisation that includes decision making on which AATF pre-treatment operator to use. The objective function of carbon footprint can then include not only the collection vehicle emissions, but also the entire downstream supply chain footprint specific to the utilised AATF pre-treatment operators. This allows evaluation of whether the lowest carbon option is to send WEEE to the closest AATF to minimise the transport emissions, or to a more distant AATF with better downstream supply chain emissions.

The optimisation model produced in this study aimed, as per Aim 3, to evaluate opportunities for reductions in the carbon footprint of REPIC's entire WEEE supply chain through optimisation of collection journeys and AATF allocation. A brief discussion follows of optimisation methods and how they apply to the REPIC supply chain.

Our problem can be classified as a vehicle routing problem (VRP). VRPs have been a frequent subject of research since their inception in 1959 (Dantzig and Ramser, 1959). A wide variety of different routing problems fall under the umbrella of a VRP, but all share the characteristic of aiming to minimise a cost, often distance, of visiting a number of waypoints from a depot. The solution is a tour, or series of tours of vehicles, that visit all the required waypoints. However, the specific properties of our problem make it difficult to classify under a single type of VRP. Solving of a VRP of WEEE collections has only been undertaken once before by Gamberini et al. (2010) in Italy.

The wide variety of problems covered by VRPs have led to multiple different versions being developed, with different objectives and constraints. Our problem combines several of these. Capacitated VRPs consider the limited capacity of the collection vehicles (Kumar and Panneerselvam, 2012). VRPs with Time Windows require the delivery to be made within a specified period of the day (Cordeau et al., 2002). Periodic VRPs extend the problem to cover multiple days and multiple trips to the customer at a set frequency (Coene et al., 2010). A different class of problem is the Inventory Routing Problem which, instead of just needing to deliver to a set of customers, accounts for the customers' rates of goods usage, and accounts for the customers' inventory size, or inventory cost, for storing goods (Bertazzi and Speranza, 2012). A further extension of routing problems, relevant to our problem, is the Green Routing

Problem, where the objective minimised is the environmental cost – often CO_2 emissions (Lin et al., 2014). Our problem reverses the VRP by being a case of collection from multiple customers (Designated Collection Facilities (DCFs)), and delivery to a single depot (AATF). In the light of the above information, we can classify our problem, which requires multiple collections over the year with the aim of reducing carbon footprint, as a capacitated periodic green vehicle routing problem with time windows and inventory restrictions.

Our VRP also has the peculiarity that the carbon footprint, which we aim to minimise, depends on which AATF the route ends at, due to the differences in recovery rate and emissions of pre-processing between different AATFs. The solution approach to address this consists of preceding the routing problem with an allocation problem that decides which AATF will be allocated to each DCF. This bears some similarities to the common Facility Location-Allocation Problem (Boyacı et al., 2021). In location-allocation there is consumer demand which must be fulfilled, and the location of warehouses and the allocation of which warehouse will fulfil each consumer's demand are decided upon, with various possible objectives such as minimising transport cost or minimising time-taken to deliver (Klose and Drexl, 2005). Our problem has the "consumer demand" being DCFs requiring vehicles to collect their WEEE before their capacity is exceeded, and in our case the locations of the DCFs and AATFs is already fixed, allowing the allocation to be solved using exact mathematical optimisation. The unique feature of our allocation problem will be the objective function, which will be aiming to minimise the entire supply chain's carbon footprint – both from the transportation and the downstream supply chain.

The NP-hard characteristics of VRPs and the computational challenge to solve them leads to widespread use of heuristic methods to achieve near-optimal solutions (Kumar and Panneerselvam, 2012; Laporte, 1992). Heuristics is a field that covers any method to solve a problem more quickly based on making approximations (Pearl, 1984). Meta-heuristics are generic algorithm guidelines that can be applied to a range of computational problems (Sörensen and Glover, 2013).

Local Search is one such meta-heuristic that is commonly used as an improvement algorithm that iteratively improves a solution by making small changes (Pérez Castaño, 2018).

Hillclimbing is a Local Search algorithm which, applied to a VRP, changes the tour by swapping two of the nodes, and compares the cost to the initial solution. The new solution is only accepted if the cost is improved, otherwise the initial solution is kept. This process is iterated until a goal state is reached, or for a set number of iterations. Hillclimbing implementation is more simple than other heuristics such as iterative local search and genetic algorithms, but it has the weakness of being unable to escape local optima (Altiparmak et al., 2003). Other heuristic methods use more complex methods – either looking beyond the neighbourhood of solutions for an improvement or accepting worse solutions temporarily – to escape local optima.

2.8 Summary and Research Gap

The majority of WEEE LCAs show a similar overall study design of analysing the material flow of WEEE through each stage of the supply chain and working out the emissions of each stage. Differences exist in each studies' results due to different specific methodology choices, such as whether to include refrigerant emissions in the LCA, and due to differences in the data collected, with some studies reaching greater levels of detail and accuracy using primary data sources. The 'state-of-the-art' WEEE LCA studies have improved in accuracy over time by increasing their usage of specific primary data.

Previous studies in the UK are limited in number and accuracy – focusing on a broader scope with less specific data. Studies outside the UK have achieved a higher level of accuracy, showing that there is a gap in the detailed understanding of the formal treatment of WEEE in the UK.

While there is agreement on the overall benefit of the net carbon footprint of WEEE treatment, several details of the carbon footprint are not in consensus and merit further investigation as to how the UK compares. The impact of the different stages on the overall carbon footprint is the main source of debate, along with the impact of reuse and refrigerants.

The optimisation of WEEE carbon footprint is a novel research topic in the UK, but existing algorithms can be applied to the problem using a combination of mathematical and heuristic methods. Collection routing optimisation has been applied to the WEEE system in Italy, but optimisation of AATF allocation based on carbon footprint is a novel approach.

Table 2 lists some of the differentiating factors between WEEE carbon footprint studies, and where the UK specific studies fit in. To address our research aims, an LCA study would fulfil all of the factors, and we can see that Biganzoli *et al.* (2015) are the closest study to achieving this, but with a study outside the UK. Applying optimisation modelling to the output of the LCA will be novel.

Table 2: A summary of the key methodological features of the discussed WEEE carbon footprint models. Green shaded cells represent that methodological feature being present in the study.

WEEE Carbon Footprint Studies	Methodological features								
	Primary data collected	All WEEE Streams included	CFCs accounted for	Sensitivity/Uncertainty Analysis	Precious metals included	Re-use included	Absolute carbon footprint values	For use in optimisation	UK Specific
Hischier et al. (2005)		■			■				
Wäger et al. (2011)		■			■		■		
Menikpura et al. (2014)	■						■		
Biganzoli et al. (2014)	■	■	■	■	■		■		
Turner et al. (2015)		■					■		■
Baxter et al. (2016)	■		■		■		■		
Latunussa et al. (2016)				■	■		■		
Xiao et al. (2016)			■						
Ibanescu et al. (2018)							■		
Clarke et al. (2019)		■				■	■		■
Jaunich et al. (2020)	■			■			■		
Objectives of this study	■	■	■	■	■	■	■	■	■

3 Methodology

The research combined a material flow analysis (MFA) and a life cycle assessment (LCA), following REPIC's WEEE treatment supply chain to quantify the carbon footprint associated with each stage. The results are then used in a 2-stage mathematical and heuristic optimisation model that investigates improvements to logistics. Primary data was obtained and used for the earlier stages of the supply chain, with secondary data from an LCI database used for the less accessible downstream supply chain. This chapter discusses the overall LCA structure used in the study, the data that was collected, the analysis that was performed and the design of the optimisation model. The step-by-step reproducible detail of the carbon footprint calculator method follows in Chapter 4.

3.1 Study Design

The design of this study focused on creating a carbon footprint calculator that addressed the aims of the research. The calculator needed to:

- Be specific to REPIC's UK WEEE supply chain, addressing Aim 1: "Develop a model which calculates the carbon emissions associated with the collection and treatment of the UK's WEEE, based on REPIC's 2019 data"
- Produce results broken down into the different stages of the supply chain, addressing Aim 2: "Evaluate the carbon footprint/benefit across the whole WEEE supply chain".
- Have sufficient data granularity to allow comparison between different collection and treatment operators, and different scenarios of collection and treatment, addressing Aim 3: "Evaluate ways in which the carbon footprint of REPIC's WEEE supply chain could be improved through optimisation of collection journeys and Approved Authorised Treatment Facility (AATF) allocation".

Addressing Aim 3 required a separate modelling tool that took the output of the carbon footprint calculator and applied optimisation methods to improve the carbon footprint through changes to the logistics of collection and treatment of WEEE.

The study was desk-based and interdisciplinary in design, using methods developed over the course of the project. An initial study design was outlined based on literature on WEEE and LCA, and industry context information from REPIC, after which a data collection phase took place. Ongoing methodological decisions were made as the data availability and quality became apparent. Due to the dependency of Aim 2 on the output of Aim 1, and Aim 3 on the output of Aim 2, three sequential phases of research were undertaken.

The first phase of research was designing and populating a carbon calculator specific to REPIC's UK supply chain. This started with gathering an overview of the supply chain of the UK's WEEE collection and treatment – to find out what stages exist, the route that WEEE takes through them, and the potential sources of greenhouse gas emissions at each stage. A preliminary assessment of what data could be collected from primary and secondary sources was then undertaken to deduce the possible inputs for the carbon calculator. It was found that REPIC could provide data on every collection made in 2019 detailing the tonnage collected, the location of collection, the transport provider, and the AATF destination. Further primary data could be collected from REPIC's transport providers and AATFs that allows calculation of the emissions from collection and pre-processing, and the breakdown of different materials that leave the AATF. For the later stages of transport and the final end-of-life process, secondary data for UK or worldwide averages was the best available data, sourced from industry reports, UK government data and LCA databases. Based on the overview of the supply chain and the preliminary data availability, a method of the calculator was drafted – a material flow analysis would track the WEEE tonnage through each stage of the supply chain, and a life cycle assessment would calculate the greenhouse gas emissions resulting from the material at each stage. A data collection phase followed, where primary and secondary material flow and carbon footprint data was collected to populate the calculator. The calculator was finalised with several iterative stages of further data collection and improvement of assumptions based on input from industry representatives and the WEEE literature. Details of the data collected and the method of how the calculator was adapted to the data is discussed in Section 3.2 and Chapter 4.

The second phase was the evaluation of the calculator output (Aim 2) – a data analysis and interpretation phase that used the output data of the completed carbon calculator to address the debates found in the literature and to address specific industry interests. The analysis aimed to ascertain the carbon footprint for every WEEE stream and every supply chain stage, so that the areas of greatest carbon emissions and carbon benefit could be found, and any inter-WEEE stream differences observed. The analysis was intended to make full use of the highly granular data by comparing carbon footprint between different scenarios within the 2019 data, such as WEEE collected by different methods, WEEE sent to different AATFs, and material sent to different countries for final recycling. The granular data on different materials recovered from WEEE allowed evaluation of the carbon footprint of the useful outputs of recycling and energy-from-waste and how they compare to virgin production. The final part of the analysis phase was to undertake a sensitivity analysis of the inputs to the model and how they affect the output. This is suggested in the ISO14044 standard to help assess the reliability of the output.

The third phase addressed the optimisation of collection and treatment (Aim 3). It was designed to use REPIC's 2019 carbon footprint data from the calculator as a baseline, and investigate how changes to the logistics could allow REPIC to improve the carbon footprint of its supply chain. As such, the stages of the supply chain that were investigated were those early in the supply chain where REPIC has control of the logistics. The design of the optimisation was also influenced by the results of phase 2, which indicated that differences in recovery rate between different AATFs could have a large impact on total carbon footprint, so a focus was made on investigating if changing AATF choice could improve REPIC's carbon footprint.

3.2 Life Cycle Assessment Structure

The LCA design was guided by the CENELEC PCR (European Committee for Electrotechnical Standardization product category rules for LCA of electronic and electrical products and systems) which contains LCA guidelines specific to the end-of-life of EEE (CENELEC, 2019) and by the research literature on WEEE LCA. As detailed in section 1.1.2, LCA consists of 4 stages, each considered below.

3.2.1 Goal and Scope

The goal of the LCA was to produce a carbon footprint calculator to assess the WEEE treatment and recycling supply chain in the UK. To capture both the cost and benefit from a carbon perspective, the LCA needed to incorporate the gross emissions of the process, as well as the avoided emissions that can be attributed to the recycled material and electricity produced by the supply chain. The goals of the carbon footprint were to inform decision making at the producer compliance scheme level, to inform government policy calls for contribution, and to allow communication from the producer compliance scheme on the benefit of WEEE recycling to the public and local councils.

A functional unit of 1 tonne of WEEE deposited at a collection facility was selected, specific to each of the 5 WEEE streams REPIC collects. REPIC's data lends itself to this unit because it follows WEEE through the supply chain based on tonnage and WEEE stream. Alternative functional units ruled out included a single unit of each type of WEEE, ruled out for the difficulty in comparing between streams.

The system boundary selected is shown in Figure 4. The carbon footprint calculation begins at the point that the WEEE is collected from a designated collection facility, which coincides with when REPIC becomes responsible for its treatment. The EEE production and use stages were out of scope as this study is only seeking to assess the end-of-life process. The first stage of the end-of-life where the consumer transports the WEEE to the Designated Collection Facility (DCF) was excluded from the system boundary due to lack of consumer behaviour data on these journeys, this method is shared by Baxter et al. (2016) and is permitted under the CENELEC rules. Within the system boundary there then follows 4 stages of the supply chain, and a system expansion for the substituted virgin materials:

- Stage 1: Collection and Transport from DCF to AATF (sometimes via a consolidation point).
- Stage 2: Pre-processing at the AATF and separation into different material fractions, or diversion of whole items for reuse.
- Stage 3: Transport to End-of-Life process.

- Stage 4: End-of-Life process; either recycling, landfill, energy-from-waste or high-temperature-incineration.
- System Expansion: The production of virgin raw materials and grid electricity that is substituted by the production of secondary raw materials and electricity from the end-of-life processes, and by reuse of WEEE.

The system boundary terminates at the point of disposal or the point of substitution where the raw materials/electricity substitute primary production (CENELEC, 2019).

The system expansion to include the avoided emissions was undertaken using the CENELEC Circular Formula with Benefits. This represents a system expansion of the LCA that considers the fate of the recovered materials and energy, and the substitution of virgin material and energy that would otherwise have been produced. The method assumes that the substituted material is virgin and that the market demand for the material or energy is unchanged (CENELEC, 2019). Avoided emissions from heat substituted by energy-from-waste heat recovery is excluded from the system boundary due to its low utilisation in the UK (see Section 4.6). The inclusion of avoided emissions allows the model to evaluate changes to the WEEE treatment process beyond just the gross emissions of the process. If, for example, an AATF could adopt a new technology that increases recovery rate, but uses more electricity to do so, the gross emissions would only show an increase in emissions, but when avoided emissions are also considered, the carbon benefit of the increased recovery rate is also captured, allowing a more useful evaluation of the change.

As stated in CENELEC (2019), capital goods and business administrative activities are excluded from the system boundary as they cannot be directly allocated to the reference product. Emissions from capital goods are included in secondary data where they could not be distinguished from the rest of the process (Biganzoli et al., 2015).

Temporally, the system boundary was set to 12 months from 1st January to 31st December 2019. The 12 month time period allows the seasonal variation in WEEE collected to be captured – typically collection amounts are lowest in the 4th quarter (Environment Agency, 2021a). 2019 was chosen as it represents the most recent year that did not have collections disrupted by the COVID-19 pandemic.

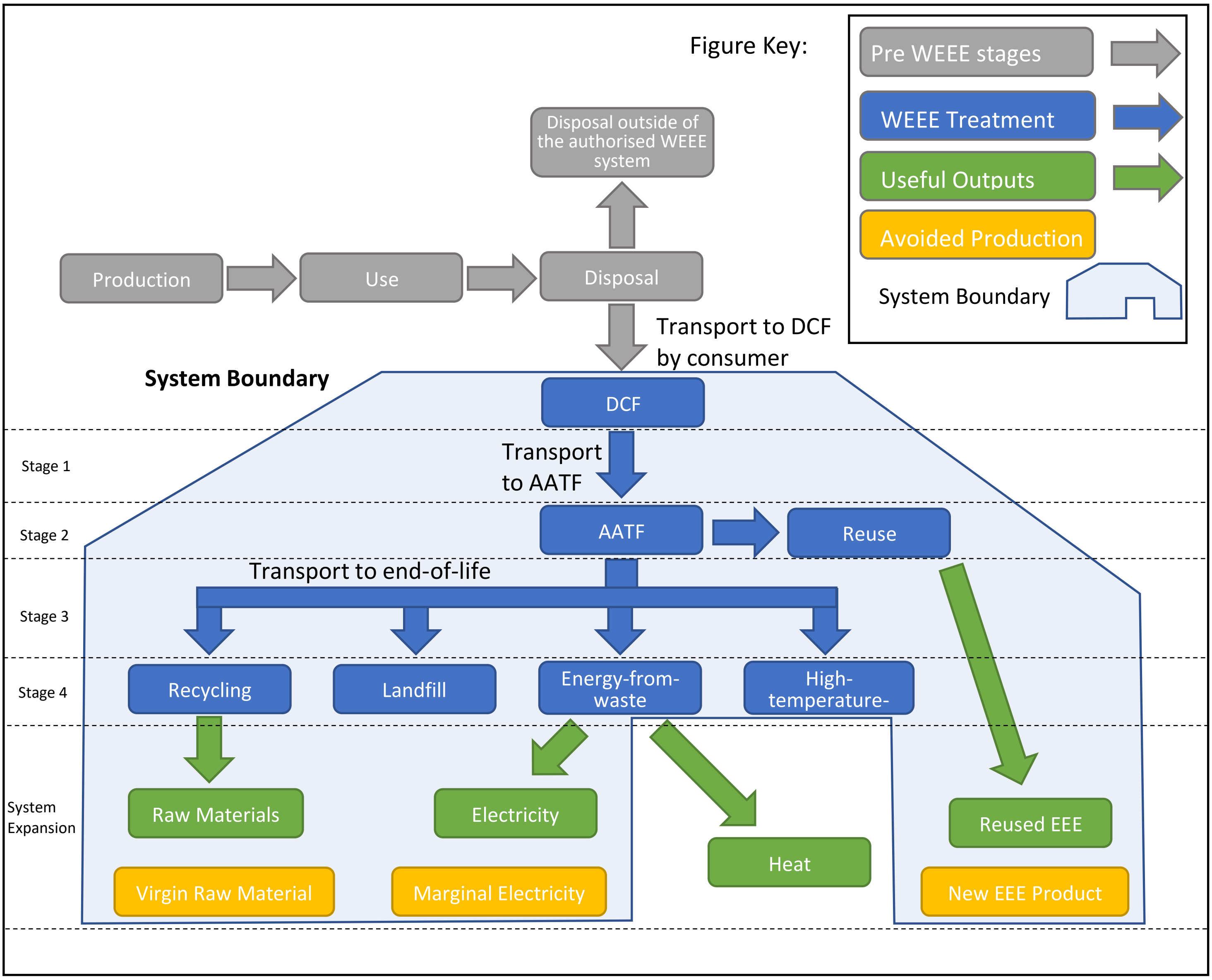


Figure 4: The System Boundary selected for this study.

3.2.2 Inventory Analysis

This section details the data that was collected for the inventory of the LCA, which then populates the carbon calculator. Data was collected for each of the 5 stages from a variety of sources – with the aim of collecting primary data specific to REPIC and the UK's supply chain where possible to increase the validity of the carbon footprint. Data was also collected for the material flow analysis to allow the carbon footprint of each process to be scaled correctly for the functional unit.

Table 5 details for each stage of the supply chain the data sources, the data that was collected and any processing of the data that was required. The early stages of the supply chain utilise primary data from REPIC and from questionnaires to REPIC's haulage operators and AATFs. Some primary data was provided by AATFs on the location where the materials undergo their end-of-life process, but the remainder of data on the post-AATF stages utilised secondary data collected from government databases, the Ecoinvent LCI database, academic literature and data provided by industry contacts.

The primary data collected from REPIC's haulage operators and AATFs was by means of questionnaires. 3 sets of data were collected through questionnaires distributed to operators in the supply chain, with data on: the emissions from the collection transport and how they should be allocated; the emissions from pre-processing and how they should be allocated; and details of the material outputs of the pre-processing. The design for each questionnaire was developed with input from several operators who indicated what data was available, and the easiest format to report it in. The questionnaires were designed to be simple templates to fill in as a Word/Excel document, or printed out and filled by hand as preferred by some of the companies. This was based on advice from REPIC that some of their operators preferred to handwrite documents. Follow up emails were sent to non-responders, but several companies did not provide responses. Issues of data confidentiality and the time required to collate the requested data were assumed to underly the non-responders. Questionnaires were sent to AATFs and Hauliers who REPIC still work with that handled >1000t of REPIC's WEEE in 2019, or >10% of any WEEE stream. The response rate is shown in Table 3. A large AATF and haulage company that operated in 2019 is no longer operating, so this is responsible for 8% of the tonnage not represented in the responses. Each questionnaire is briefly described below. Full questionnaires can be found in Appendix F.

- Haulier questionnaire: collected data on vehicle type, fuel consumption, weight of WEEE carried by vehicles, and whether vehicle backloading (where the return leg is used for another job) is used. Data was also collected about the location of vehicle depots and consolidation sites (if used).
- AATF Emissions questionnaire: collected data on treatment process (manual or mechanical), and the consumption of diesel, electricity and nitrogen per tonne of WEEE processed for each WEEE stream.

- AATF Residues questionnaire: collected data for each WEEE stream on the proportion of whole WEEE diverted to reuse, the material composition of the output of pre-processing, and what % of each material goes to recycling, landfill, energy-from-waste and high-temperature-incineration. It also requested details on the locations of the downstream facilities, such as the landfill site or recycling facility.

Table 3: The questionnaire contact and response rates.

Questionnaire	% of REPIC's 2019 WEEE tonnage	
	Contacted	**Responded**
Haulier	84%	54%
AATF Emissions	85%	53%
AATF Residues	85%	53%

The decision to use a life cycle inventory (LCI) database for the emissions factors of each end-of-life process is universal in the WEEE LCA literature and is suggested in the CENELEC guidance. LCI databases contain a large number of datasets which each represent a process that transforms an input to an output, and contain the exchanges of material and energy for that process. Several LCI databases were assessed for suitability (Table 4). The Swiss Ecoinvent 3.7 database was selected as its large number of datasets were most likely to fit the WEEE materials, and its widespread use in the literature improves the comparability of our study to others.

Table 4: Available LCI databases (ecoinvent, 2021; European Commission, 2018; GaBi, 2021)

Database:	Date of last update	Number datasets	Other Notes
Ecoinvent 3.7	2020	18,000	Most cited database in WEEE LCAs. Requires no additional software.
GaBi Professional	2021	3,892	Requires additional software to use data.
European Reference Life Cycle Database 2.0	2018	509	Discontinued and requires additional software to use data.

Table 5: Data collection sources and details

Treatment Stages	Data Source	Data Collected	Data Description	Data Processing
Stage 1: Transport from DCF to AATF	REPIC data reporting.	The tonnage and WEEE stream collected for every WEEE collection from DCFs in 2019; Postcodes of journey waypoints; unique journey identifier code; types of container at DCF.	The WEEE collection data supplied by REPIC had 2 sections: - Full data collections with data on every single collection journey, detailing which DCF, AATF and haulage company was used, tonnage collected of each WEEE stream and date of collection. - Limited data collections where multiple collections have been aggregated – only showing the DCF, the AATF and the total tonnage of each WEEE stream collected in 2019 from that DCF.	A custom Python program was written to extract latitude and longitude values for the postcodes using an opensource API from Ideal Postcodes (2021). Where this failed, manual checking of the postcode was performed, and corrections made.
	Questionnaires to hauliers.	Type of vehicle; fuel consumption of vehicle; vehicle capacity for WEEE; backloading rates of vehicles; % of load allocated to REPIC.	The questionnaire data combined to give an emissions per km travelled per vehicle, or per tonne of WEEE, as well as an allocation factor for how much of the emissions are allocatable to REPIC's WEEE.	Non-responders to the haulier questionnaire had the average value of the other hauliers applied.
	Google Maps API	Distances between waypoints.	Distance data in km for the best route chosen by Google Maps.	N/A
Stage 2: Pre-processing	REPIC data reporting.	Tonnage of WEEE processed at each AATF.	REPIC data indicated which AATF each WEEE collection was sent to.	N/A
	Questionnaires to AATFs.	Electricity, diesel, and nitrogen consumption per tonne of WEEE; breakdown of output materials per tonne WEEE; type of end-of-life process for each material, and location of end-of-life.	Questionnaire responses from major AATFs for each stream provided the energy usage of the pre-processing, and the material composition and end-of-life process.	Non-responders to the questionnaire had average data applied that is specific to the WEEE stream, and when known, the technology type.
Stage 3: Transport to End-of-Life	Questionnaires to AATFs.	Location of end-of-life; Distance of transport to end-of-life.	Indication of the most common location of end-of-life: either a country or a specific UK location.	N/A
	Recycling associations	Location of end-of-life; Type of transport to end-of-life.	Data on the locations that the UK's scrap steel, aluminium, copper and circuit boards were recycled in 2019, and the type of transport used.	N/A
	DEFRA Conversion Factors	Emissions factors for transport by road, rail and ship.	Emissions per tonne.km values, including well-to-tank emissions.	N/A

	Sea distance calculator	Distance of transport to end-of-life.	Real route distances between two ports.	N/A
Stage 4: End-of-Life Processing	Ecoinvent 3.7 LCI database.	$CO_{2eq.}$ emissions per tonne of waste material.	Datasets for the specific recycling, incineration and landfill processes. Carbon footprint calculated using "Allocation – cut off by classification" system model, and the IPCC (Intergovernmental Panel on Climate Change) 2013 values for GWP_{100}.	Adjusted to ensure the reference unit is 1 tonne of scrap input, not 1 tonne of output. Proxy to similar process or literature value where LCI data unavailable.
	Literature on end-of-life processes.	$CO_{2eq.}$ emissions per tonne of waste material.	Where Ecoinvent emissions factors not available for recycling, incineration or landfill, other literature values found for the emissions factors.	Adjusted to ensure the reference unit is 1 tonne of scrap input, not 1 tonne of output.
Stage 5: Avoided Emissions	Ecoinvent 3.7 LCI database.	Conversion efficiency of input to useful output; $CO_{2eq.}$ emissions per tonne of virgin material; electricity production from energy-from-waste processing of each material.	Datasets for the virgin production Carbon footprint calculated using "Allocation – cut off by classification" system model, and the IPCC (Intergovernmental Panel on Climate Change) 2013 values for GWP_{100}. kWh of electricity produced by energy-from-waste (EfW) of 1 tonne of each material.	Adjusted to ensure the reference unit is 1kg of scrap input. Proxy to similar process or literature value where LCI data unavailable.
	Literature on primary production processes.	$CO_{2eq.}$emissions per tonne of virgin material production.	Where Ecoinvent emissions factors not available, other literature values found for the emissions factors of virgin production.	Adjusted to ensure the reference unit is 1kg of scrap input.
	IPCC Fifth Assessment Report	$CO_{2eq.}$ emissions per kWh of electricity produced by combined cycle gas turbine (CCGT) power plant.	Median lifecycle emissions per kWh of electricity produced by a CCGT power plant.	N/A

3.2.3 Impact Assessment

The next stage of LCA structure is the aggregation of the inventory data to a common physical environmental damage unit, known as a midpoint indicator. To address the aim of calculating carbon footprint, only a single midpoint indicator was selected: Global Warming Potential over a 100-year timescale (GWP_{100}) using the Intergovernmental Panel on Climate Change (IPCC) 2013 values – this represents the amount of heat energy absorbed by a gas over a 100-year timescale relative to the absorption from the same mass of CO_2, measured in mass of CO_2 equivalent (CO_{2eq}). GWP_{100} is almost universally used (Turner et al., 2011) and is recommended in the CENELEC rules. Only focusing on a single midpoint indicator reduced the data collection requirements, while still achieving the goal of calculating carbon footprint. The LCA was terminated at this point rather than continuing to conversion into endpoint indicators because the GWP_{100} indicator fulfilled the goal of the study, and is suitable for addressing the single environmental concern (Kägi et al., 2016).

To aggregate the inventory data correctly scaled to the functional unit, a material flow analysis was needed to follow the material from 1 tonne of input to its end-of-life. The data collected in the inventory was designed to allow this, starting with REPIC's data that documents every tonne of WEEE collected in 2019 and which AATF it was sent to, then applying the material breakdown from the AATF residues questionnaires to find what material leaves the AATF, then applying the losses shown in each Ecoinvent 3.7 recycling processes to find the amount of useful output material produced.

3.2.4 Interpretation

The interpretation phase of the LCA addressed Aim 2: evaluating the carbon footprint. The gross, avoided and net (gross minus avoided) $CO_{2eq.}$ emissions were calculated for each WEEE stream, and for each of the supply chain stages, to allow assessment of where the main impacts and benefits are found per tonne of WEEE and overall in 2019. A range of further breakdowns of the data were undertaken for further insight, including comparison of the emissions of different types of collection, the emissions of different AATFs and the emissions from recycling different materials. The carbon footprint per item was also calculated based on product weights.

Sensitivity analysis was performed to assess the importance of each of the data inputs for the overall carbon footprint, and to assess how sensitive the output is to changes in the inputs. 17 different data inputs were varied ± 10% and the amount of change in the output assessed. The sensitivity of the output to changes in each of the 5 stages was also assessed by changing all the inputs in each stage by ±10% simultaneously.

3.3 Data Reliability and Validity

The data collected varies in its specificity to the WEEE supply chain in 2019, and the quality of the calculation method, and this impacts its reliability and validity for use in our scenario. The CENELEC guidance lists several aspects of data quality that should be assessed and reported. The data collected for each supply chain stage was rated against the data quality categories sourced from the CENELEC guidance, and a rating of their specificity to REPIC (Table 6). Time coverage assesses if the data is up-to-date and representative of the time-period studied, geographical coverage assesses if the data is specific to the country where each process is taking place, and technological coverage assesses whether the technology used in the data represents the technology of the system being studied. The completeness category is a quantitative report of the proportion of the system studied that is covered by the data collected. Together these assess how representative the data is of the system being studied. As stated in ISO 14044, qualitative assessments are required for consistency and reproducibility. Consistency rates how uniformly the methodology was applied, and reproducibility rates the extent that an external practitioner would be able to reproduce the results.

Our data collected is comparable in quality with the most detailed WEEE carbon footprint studies worldwide and exceeds the previous UK studies in terms of specificity. Strengths lie in the primary data from REPIC that supplies the starting point of the calculator, and the primary data collected from the hauliers. The REPIC data is audited and robustly calculated as it underlies their operations, and is highly granular, usually reporting data for every collection journey. The data from the hauliers is reliable because the vehicle data is closely related to cost and so is routinely measured, and often fuel consumption is automatically calculated by the vehicles. The consistency and reproducibility of the haulier data was rated moderate as while it is routinely measured data, we did not specify a method of calculating it, and there may be some inconsistency in methods used. The completeness of only 54% is the main limitation for the haulier data, with the other 46% of transport using average data from the 54%. While this reduces the specificity of the data to the real system, the use of average data, or generic database data, is commonly used in the literature (Baxter et al., 2016; Biganzoli et al., 2015; Clarke et al., 2019; Wäger et al., 2011), so our >50% operator specific data represents an improvement.

The data collected by questionnaire from the AATFs, on the consumables usage, and crucially on the material composition and proportion of each material going to each end-of-life process, is highly specific to REPIC's operations and the timeframe of calculation, but it was highlighted by the AATFs that the data was hard to calculate and required assumptions to be made. Within the timescale and funding limits of the study, third party verification of the data was not possible. This impacts the consistency and reproducibility of the data, as the methods of calculation and assumptions can vary between different AATFs. Despite these issues, the lack of up-to-date secondary data available for these inputs to the model makes our collected data more representative than alternatives in the literature. No published data specific to the UK's pre-processing emissions could be found, and the values from other EU countries are mostly based on old data such as from Ansems and van Gijlswijk (2001). Our collected AATF energy usage data fell within the range shown in the limited literature. Likewise, data on the material composition of the WEEE after pre-processing is not readily available. Some studies in the UK have published data on WEEE composition (WRAP, 2012) but they are out of date and calculated from product manual disassembly. Our AATF material composition data has the advantage that it records exactly what the AATF separates from the WEEE, so only contains the materials that are separated out, and not those that are unable to be separated or are in too small a quantity to be separated, a method shared with Biganzoli et al. (2015). While the AATF data has only 53% completeness, the data applied to the remainder of AATFs was specific to each WEEE stream, and where possible, data from an AATF with similar technology was applied. For the AATF emissions, other studies use average data without specificity to each WEEE stream (Clarke et al., 2019; Menikpura et al., 2014; Wäger et al., 2011), over which our data represents an advancement.

The data collected on end-of-life transport and location varies in its reliability and validity depending on material. For the materials where specific data for 2019 exports and domestic processing were able to be found, which covered over 50% of the WEEE, including steel, the most prevalent material, the data is highly consistent and reproducible government export data. The remainder of the data required more assumptions, and relied on indications from AATFs and research literature, which are less reliable data sources.

Finally, the LCI database data on the end-of-life processes quality is on par with other studies on WEEE environmental impact. Use of the Ecoinvent database is widespread and it is regarded as the most complete and comprehensive of available LCI databases (Martínez-Rocamora et al., 2016). Our use of the most recent version improves on some studies using older versions (Clarke et al., 2019). Within Ecoinvent, the method of calculation for each dataset is published, and where possible peer-reviewed, so consistency and reproducibility is good. The data is not specific to the materials extracted from WEEE, nor is it specific to the country where the end-of-life process is undertaken – assuming a UK or European average. This affects the validity of the data, as the technology coverage may not be representative of the actual technology used. This simplification is partly a choice in methodology to reduce the complexity of having multiple datasets per material to represent the different countries, and partly a response to Ecoinvent not having datasets for every country. The simplification is common in the literature (Biganzoli et al., 2015; Clarke et al., 2019; Wäger et al., 2011), with only Baxter et al. (2016) improving upon it by adapting processes to local electricity mix.

*Table 6 – The data quality evaluation for the data supporting each stage of the LCA. * indicates qualitative assessment*

	Specific to REPIC	Time Coverage	Geographical Coverage	Technology Coverage	Completeness	Consistency *	Reproducibility *	Possible to improve?
REPIC Data	Yes	Exact	Exact	Exact	100%	Consistent	High	No: data already at most precise level.
Collection and Routing questionnaire data	Yes	Exact	Exact	Exact	54%	Moderate: different operators' data collection methods can vary	Moderate: assumptions made by operators could change	No: hauliers do not record any more detail.
AATF questionnaire data	Yes	Exact	Exact	Exact	53%	Moderate: different operators' data collection methods can vary	Moderate: assumptions made by operators could change	Yes: audit of stated data would improve reliability.
End-of-life transport data	No	Exact	Only the top 4 destination countries included	Simplified to assume bulk ship transport and HGV road transport	Partial: some materials relied on estimates	Moderate: different data sources for different materials	High when government data used, moderate when AATF approximations used	Somewhat: by tracking flows of WEEE and material outputs around the world. But it often becomes mixed with other waste and so unable to be precisely attributed to a location.
End-of-life and avoided emissions data: Ecoinvent 3.7	No	LCA datasets covered 2019	Assumes location for Ecoinvent is the UK or Europe	Technology may be inaccurate due to geographical assumptions	77%	Consistent	High	Somewhat: geographical coverage could be improved by selecting datasets matched to the location of end-of-life and this would in turn improve technology coverage.

3.4 Optimisation Methodological Framework

To address Aim 3 of the study: optimising collection journeys and AATF allocation, existing methods were utilised to produce solutions that allocate DCFs to AATFs, and produce vehicle collection route suggestions, both with the objective of minimising the carbon footprint.

3.4.1 Problem Description

The problem to be solved can be summarised as follows. REPIC collects WEEE from hundreds of DCFs spread around the UK which each have a different capacity for storing WEEE and a different rate of WEEE generation. Each DCF must have WEEE collected by a haulier before the capacity is exceeded. There are a number of AATFs also spread around the UK which can treat one or several of the types of WEEE (the 5 WEEE streams) and each has an annual capacity for amount of WEEE they can process. An unlimited number of trucks, of varying size and capacity for carrying WEEE, can be hired to collect the WEEE, and are assumed to start and end their journey at the AATF. This is a slight simplification as only some hauliers operate out of the AATF, others have separate depots, but these are not considered in our problem. The trucks can collect from multiple DCFs in a single journey, as long as excess vehicle capacity still remains.

The latitude and longitude of each of the DCFs and AATFs is known, so the great-circle distance (i.e. the shortest arc on the surface of a sphere) between them can be presented in a matrix that represents every possible journey. The CO_2 emissions per km travelled by the vehicles is known from the haulier questionnaire, so once a conversion factor to convert from great-circle to road distance is applied, the carbon footprint of travelling between each DCF-AATF combination can be calculated.

The carbon footprint of the pre-processing and the downstream supply chain for each AATF is also known, and can be combined with this transport carbon footprint to give the total emissions of each DCF-AATF combination, assuming that single out-and-back collections are made.

The main objective of the problem is to reduce the net carbon footprint of the WEEE disposal over the whole year being modelled – which is the combination of the transportation carbon footprint, the AATF and downstream carbon footprint, and the downstream avoided emissions. Minimising distance travelled by collection vehicles is a further objective; for the collection phase the distance travelled is closely related to carbon emissions, and it is also of interest because REPIC's cost increases with the distance travelled due to additional fuel consumption and driver time when distance increases.

The solution is expected to assign each DCF to an AATF and then plan collection routes that visit each DCFs with a periodicity that keeps DCF capacity from being exceeded. The solution will be able to be evaluated based on the total carbon footprint and/or distance and how it compares to REPIC's 2019 situation.

The problem is difficult to solve due to the NP-hard characteristics of vehicle routing planning, and the allocation problem that must be solved simultaneously to routing adds further complexity (Lenstra and Kan, 1981). This makes finding optimal solutions difficult as the exact models cannot be solved in polynomial time, and so they are likely to fail to find feasible solutions in a reasonable time. The allocation problem on the other hand, is a problem that is easier to model and solve using exact methods. Given this, separating the problem into two separate problems to be solved sequentially reduces the complexity. Exact optimal solutions to the allocation problem can be produced by mathematical optimisation, and these solutions then provide an easier starting point for solving the NP-hard routing problem using heuristic methods. Separating NP-hard problems into exact and heuristic sub-problems is not uncommon (Boyacı et al., 2021).

3.4.2 Optimisation Design

The WEEE material flow and carbon footprint data from the carbon calculator was used as a data input for an optimisation problem that investigates the allocation of Designated Collection Facilities (DCFs) to Approved Authorised Treatment Facilities (AATFs) and the transport of WEEE between them. Division into two stages reduced the computational complexity of the problem, allowing a solution to the complex real-life problem to be calculated in a reasonable time. The first stage assigned each DCF to an AATF using an exact method, then the second stage planned truck collections that start at an AATF, collect from a number of DCFs and return to the AATF, with heuristics used to find a near-optimal routing solution. Figure 5 summarises the two-stage process.

Data from 2019 was used as this was the data collection year for the carbon calculator, and as it was the most recent year not disrupted by lockdowns. Using past data allows a comparison between the optimised scenario and what happened in reality, to assess the usefulness of application to future logistics. For future use in planning, a more advanced tool could also consider driver's hours, DCF and AATF openings hours and variation through the year. The AATFs considered were limited to those that provided data through the questionnaires, covering just over 50% of the WEEE tonnage, because the optimisation is based on this data, and the proxied data used for non-responding AATFs was not considered accurate enough to base comparisons on.

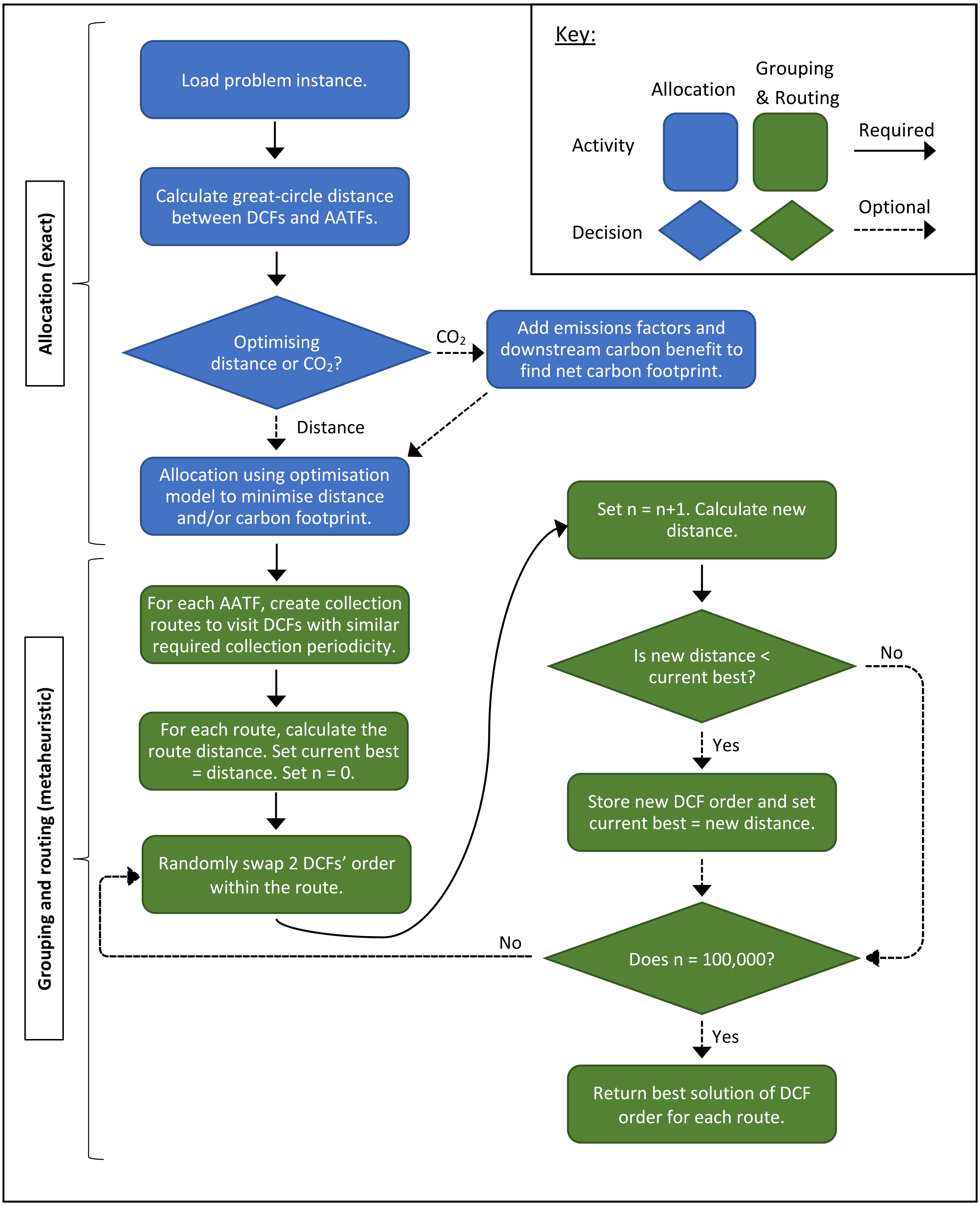


Figure 5: Coding flow chart for the allocation and routing 2 stage problem.

3.4.3 Problem Instance

In our problem we have a set of AATF pre-processing plants, and for each we have their latitude and longitude, an estimated capacity based on the tonnage of WEEE that REPIC sent to them in 2019, a carbon footprint of pre-processing per tonne of WEEE, and a downstream carbon footprint of the end-of-life transport, end-of-life emissions and avoided emissions that result from the material output of each AATF.

We also have a set of DCFs from where the WEEE is collected. For each we again have the latitude and longitude, their rate of waste generation in 2019, and an estimate of their capacity based on the largest collection that REPIC made from them in 2019.

Our final input taken from the carbon footprint model is vehicle data. For a >33T HGV vehicle we have the max loading capacity and the emissions factor for $kgCO_2$ per tonne.km.

5 different problem instances were created, one for each of the 5 WEEE streams (Table 7). Due to time constraints, the optimisation was only applied to the Cooling WEEE stream instance.

*Table 7: The problem instances used as inputs for the model. Only the Cooling WEEE Stream was modelled. * indicates REPIC confidential data. ** indicates low sample rate that would allow individual AATF's data to be ascertained, so it must be confidential..*

Instance	Number of AATFs	Number of DCFs	Vehicle Capacity (t)	Range of distance (km)	Range of carbon footprint (kg)
Cooling	*	*	7.5	0 to 1037	-1829 to -2440
Displays	*	*	13	0 to 1037	-1699 to -3710
GDL (Gas Discharge Lamps)	*	*	3	2 to 994	**
LHA (Large Household Appliances)	*	*	11	0 to 1112	-1656 to -2660
SMW (Small Mixed WEEE)	*	*	11	0 to 1041	-1639 to -3060

3.4.4 AATF Allocation

To address the allocation of AATFs, an optimisation problem was set up that produces exact solutions of optimised DCF to AATF allocation. Two different objective functions were tested, either minimising the distance between the DCFs and their allocated AATF or minimising the net carbon footprint of the entire supply chain. Each objective function was also tested both un-capacitated and with a capacity set for each AATF. The un-capacitated model represents a long-term view where REPIC is not restricted by contracts, and AATFs could increase their capacity if required. The capacitated model imposes a limited capacity for each AATF, based on the tonnage of REPIC WEEE they processed in 2019 increased by a multiplication factor to allow the model flexibility to improve over the 2019 allocation. Multiplication factors between 1 and 1.5 were tested, with a factor of 1.2 being selected based on discussion with REPIC (REPIC 2022, personal correspondence, 11th March). The capacitated model represents a short-term view of the supply chain, where REPIC has limited ability to change the tonnage sent to each AATF due to contracts in place, and limited total capacity of each AATF. The allocation method is detailed below and in Figure 6. The allocation optimisation was undertaken in Excel using the OpenSolver add-in (Mason, 2012).

A function for distance on a globe from latitude and longitude was defined and used to calculate great-circle distance between each AATF and each DCF. This allowed for an optimisation that minimised the distance between each DCF and its allocated AATF.
This distance minimising allocation is expected to be close to how the UK WEEE supply chain currently allocates AATFs, because of the transport costs of driver time, fuel, maintenance, tyres and depreciation that all increase with distance travelled.

A more complex allocation method considered the entire carbon footprint, rather than the distance. Additions to the model were: an emissions factor and great-circle to road distance multiplier to approximate the transport carbon footprint; the carbon footprint of each AATF's pre-processing; and the carbon footprint and benefit downstream of each AATF (differing between AATFs due to their different recovery rates) to work out an overall carbon footprint of each AATF allocation option. Again, a basic optimisation then selects the AATF for each DCF that minimises the carbon footprint, and this was tested both an un-capacitated and with AATF capacities of 1.2x the tonnage in 2019. It is worth noting that the data on AATF pre-processing and recovery rate which underly the carbon benefit was self-reported by AATFs, and as a result, the reliability is highly dependent on the accuracy of this self-reported data. While third party verification of the data was not possible in the given timescale and funding, AATF energy usage falls within the range shown in literature sources outside of the UK (Hischier, 2007; Wager, 2011; Bigum, 2012).

Sets:

$i \in I$	The set of AATFs
$j \in J$	The set of DCFs

Parameters:

$d(i,j)$	Distance (km) between AATF *i* and DCF *j*
or:	
$e(i,j)$	The net carbon footprint (tonnes $CO_{2eq.}$) of AATF *i* paired with DCF *j*
c_j	Tonnes of waste generated at DCF *j* per year
c_i	Tonnes of waste AATF I can process per year

Variables:

x_{ij}	1 if DCF *j* is assigned to AATF *i*; 0 otherwise

Objective:

$$Min \overbrace{\sum_{j \in J} \sum_{i \in I} x_{ij} c_j d(i,j)}^{\text{Total tonne.km}} \quad (1)$$

or

$$Min \underbrace{\sum_{j \in J} \sum_{i \in I} x_{ij} c_j e(i,j)}_{\text{Total carbon footprint}} \quad (2)$$

Subject to:

$$\sum_{i \in I} x_{ij} = 1 \qquad \forall j \in J \quad (3)$$

$$\sum_{j \in J} x_{ij}\, c_j \leq c_i \qquad \forall i \in I \quad (4)$$

$$x_{ij} \in \{0,1\} \qquad \forall i \in I;\ \forall j \in J \quad (5)$$

Figure 6: Mathematical formulation of the allocation optimisation.

- Objective Function (1) aims to reduce the total tonne.km of the transportation of WEEE from every DCF to its assigned AATF. The input for this is a matrix of distances between DCFs and AATFs.
- Objective Function (2) is an alternative objective function that aims to improve the total carbon footprint of the WEEE supply chain, including the emissions from transportation, the emissions from the AATF and the gross and avoided emissions that take place downstream of the AATF. The input for this is a matrix of the net carbon footprint of treating 1 tonne of WEEE for each combination of DCF and AATF.
- The only set of decision variables, x_{ij}, dictates whether an AATF is assigned to a DCF or not.
- Constraint set (3) dictates that each DCF can only be assigned to one and only one AATF.
- Constraint set (4) dictates that the annual capacity of any AATF should be enough to cover the sum of the waste generated from the DCFs allocated to that AATF.
- Constraints set (5) defines the domain of the decision variables – it dictates that DCFs either sent their entire waste to an AATF or they do not send anything to that AATF at all.

Initial results using Objective Function (2) (improving net carbon footprint) showed a preference for AATFs with a better carbon benefit, regardless of their distance from the DCF. This would have implications for REPIC's cost of operation, as cost increases with distance travelled due to greater fuel usage and driver hours. To investigate the trade-off, between net carbon footprint and cost, the model was adapted to have multiple objectives – minimising distance (assumed to = cost) and minimising net carbon footprint, with adjustable weighting for the two objectives. This approach is commonly used, with an adjustable weighting factor, and a factor to normalise the two objectives (Kheiri et al., 2015). Equation 1 shows this dual objective, with a weighting factor α, and normalisation by dividing by the mean value for both carbon footprint: $\overline{e(\imath,\jmath)}$ and distance: $\overline{d(\imath,\jmath)}$.

Equation 1: Objective function for the dual objective optimisation.

$$Min \sum_{i \in I} \sum_{j \in J} \alpha x_{ij} c_j \left(d(i,j)/\overline{d(\imath,\jmath)}\right) + (1-\alpha) x_{ij} c_j \left(e(i,j)/\overline{e(\imath,\jmath)}\right)$$

$$0 \leq \alpha \leq 1$$

3.4.5 Collection Planning and Routing

The routing of vehicles to their allocated AATF was addressed by minimising both the number of journeys and the distance travelled for each journey. Routes were created that collect from multiple DCFs in one journey, and then an improvement heuristic was applied to reduce the distance travelled on each journey. These objectives minimise the total distance travelled to collect the WEEE which, as in the carbon calculator, was assumed to be directly proportional to carbon footprint, based on a $kgCO_{2eq.}$ per distance travelled value. This approach was applied to the Cooling WEEE stream as an example, and could be replicated for the other WEEE streams.

The first step minimises the number of journeys. Starting with the output of the allocation problem – a list of DCFs assigned to each AATF, the list for each AATF was sorted by the periodicity that collections are required at. The periodicity was estimated by taking each DCF's annual waste generation tonnage from 2019, and dividing by the max capacity of the DCF, itself calculated by finding the largest tonnage collected in 2019 and applying an arbitrary multiplication factor (Equation 2). The multiplication factor is based on the assumption that DCF capacity is slightly greater than the largest collection made in 2019. Factors between 1 and 1.5 were tested, with a factor of 1.2 being selected that allowed some flexibility without far exceeding current capacity.

Equation 2: Collection periodicity calculation

$$Required\ Collection\ Periodicity\ (days) = \frac{365}{(DCF\ Annual\ Waste\ Generation\ (t) \div DCF\ Capacity\ (t))}$$

A vehicle type was then selected. We used a >33T HGV with a capacity for 7.5T of Cooling WEEE. Next, initial solutions of collection routes were created by iterating through the assigned DCF list, assigning each DCF to the 'route' and subtracting the collection tonnage from the vehicle capacity. When the next collection would exceed vehicle capacity, a new route is started with an empty vehicle. Iteration went from highest periodicity to lowest, with the aim of matching DCFs with similar periodicity to be collected together, to minimise the total number of collections. Periodicity was set to that of the first DCF in the route, which would have the highest periodicity due to the list sorting. Any DCFs with a lower required periodicity had the collected tonnage adjusted. E.g. DCF1 has a 9-day periodicity and 3-tonne capacity, DCF2 has a 12-day periodicity and 3-tonne capacity. The route periodicity is set to 9 days to match DCF1, so 3 tonnes is collected from DCF1, but only 9/12 * 3 tonnes is collected from DCF2 as less WEEE has accumulated than the full 12 days.

A second step then minimises the distance travelled for each route. The initial solutions have the DCFs within each route ordered by periodicity, ignoring their distances apart. To improve the distance travelled, an improvement heuristic was applied to each route to improve the routing beyond just periodicity order. A hillclimbing local search heuristic was implemented that stochastically swaps stops and accepts the swap if it reduces the route length (Figure 7, Figure 8). The local search heuristic was iterated 100,000 times for each route, and the optimised DCF order final solution replaces the original DCF order in the initial solution.

The results of the routing improvement, in terms of collection carbon footprint, were compared to a baseline value calculated for single out-and-back collections to each DCF when they have reached capacity.

The full code for the two stages is detailed in Appendix E.

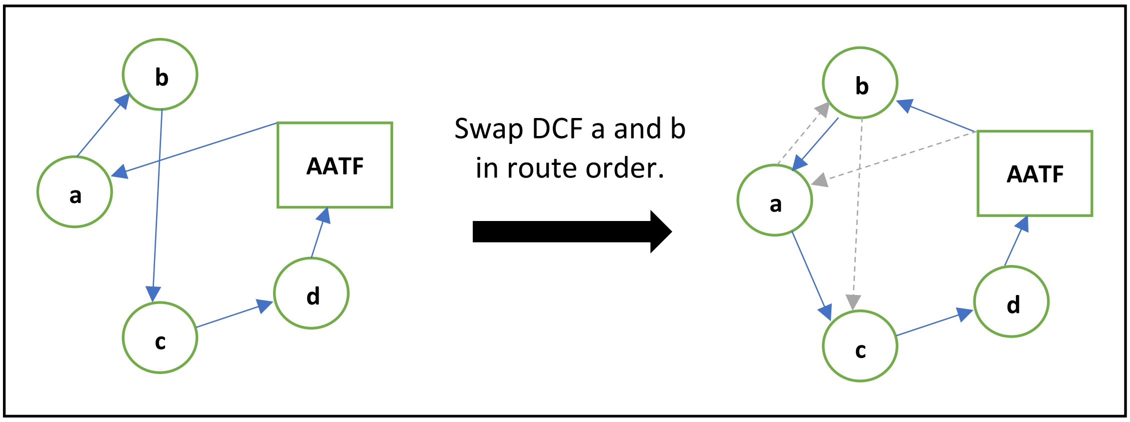


Figure 7: Visualisation of the improvement heuristic. Route with 4 DCFs (a-d). Starts with random route order, route distance = d0, two DCFs' order swapped, new distance calculated = d1, if d1 < d0 keep new order, else keep old order. Repeat for n=100,000 iterations.

```
Load route R
Let n_max represent the number of desired iterations
Let S represent the candidate solution
Let S_best represent the best solution
Generate initial solution from route R ← S_0
S_0 ← S_best
i ← 0
While i < n_max:
    Generate new solution by swapping two DCFs in S_best ← S_i
    If Totalcost(S_i) < Totalcost(S_best) then:
        S_i ← S_best
    i ← i+1
Return S_best
```

Figure 8: Pseudocode for the hillclimbing algorithm

3.5 Methods Summary

The methods presented show the study design, theoretical backing, and data collection that addressed the aims of the study.

In summary, a combined life cycle assessment and material flow calculation was undertaken on REPIC's 2019 WEEE data, following guidance from the European Committee for Electrotechnical Standardization product category rules for LCA of electronic and electrical products and systems. The system boundary covered WEEE from the moment it is collected from a designated collection facility, to the point where it is disposed of, or useful outputs substitute virgin production. A system expansion allows the carbon benefit of avoided virgin production to be incorporated into the calculator. The life cycle impact assessment was calculated for climate change impact, measured in GWP_{100} CO_{2eq}. Primary data was used where possible, increasing accuracy compared to other methods employed in the past in the UK's study of WEEE. Database values from Ecoinvent LCI database data were relied on for the later supply chain stages, in line with other studies.

The following section goes into the full reproducible detail of the carbon calculator structure and displays the data sourced from REPIC, the questionnaires, and secondary sources that populated the calculator for REPIC's 2019 situation.

4 Carbon Footprint Calculator

As detailed in Section 3, the carbon footprint calculator split the WEEE supply chain into 4 stages and calculated the material flow and the carbon footprint of each stage. The model was created in Excel, starting with REPIC's data on WEEE collections in 2019. The following section details how the carbon footprint calculator was constructed and details the data inputs and assumptions made.

4.1 Material Flow Analysis

The carbon footprint data calculated for each process in the supply chain was in units per tonne of WEEE or tonne of material going through that process. Every process needed to be scaled back to the functional unit of 1 tonne of WEEE deposited at the Designated Collection Facility (DCF), so the flow of material through each stage and process in the supply chain was required. A material flow analysis (MFA) was undertaken to track the mass of material going through the supply chain (Hischier et al., 2005).

The MFA starts with the tonnage of WEEE collected from each DCF in 2019 and tracks which Approved Authorised Treatment Facility (AATF) it was sent to. At the AATF stage the WEEE is shredded and separated into multiple different materials that each have different proportions going to each end-of-life process. These proportions were determined using data collected in the AATF residues questionnaire. Data was requested for each WEEE stream separately, to report the following: what % of the WEEE arriving is diverted to reuse; what materials are recovered in the output of the pre-processing of 1 tonne of WEEE and what % by mass do they represent; what % of each material goes to recycling, energy-from-waste, landfill or high-temperature-incineration; and ideally an indication of where the end-of-life process takes place. The responses to this survey covered 53% of WEEE. For the remainder of AATFs that did not respond, REPIC provided information for if there were any close matches of AATFs with similar technology and scale that did respond. Where this was the case, the matching AATF data for the appropriate WEEE stream was used as a data proxy. This allowed a further 21.6% of the WEEE tonnage to be covered by the proxy data. For the remaining 27.0% the average values for appropriate WEEE stream were used. Limited location data was supplied by the AATFs, so this was supplemented with other data sources (Section 4.4). This data allowed the entire material flow from DCF to end-of-life to be ascertained, including geographical location. Figure 9 gives an example of this material flow calculation, with a simplified 2 material output.

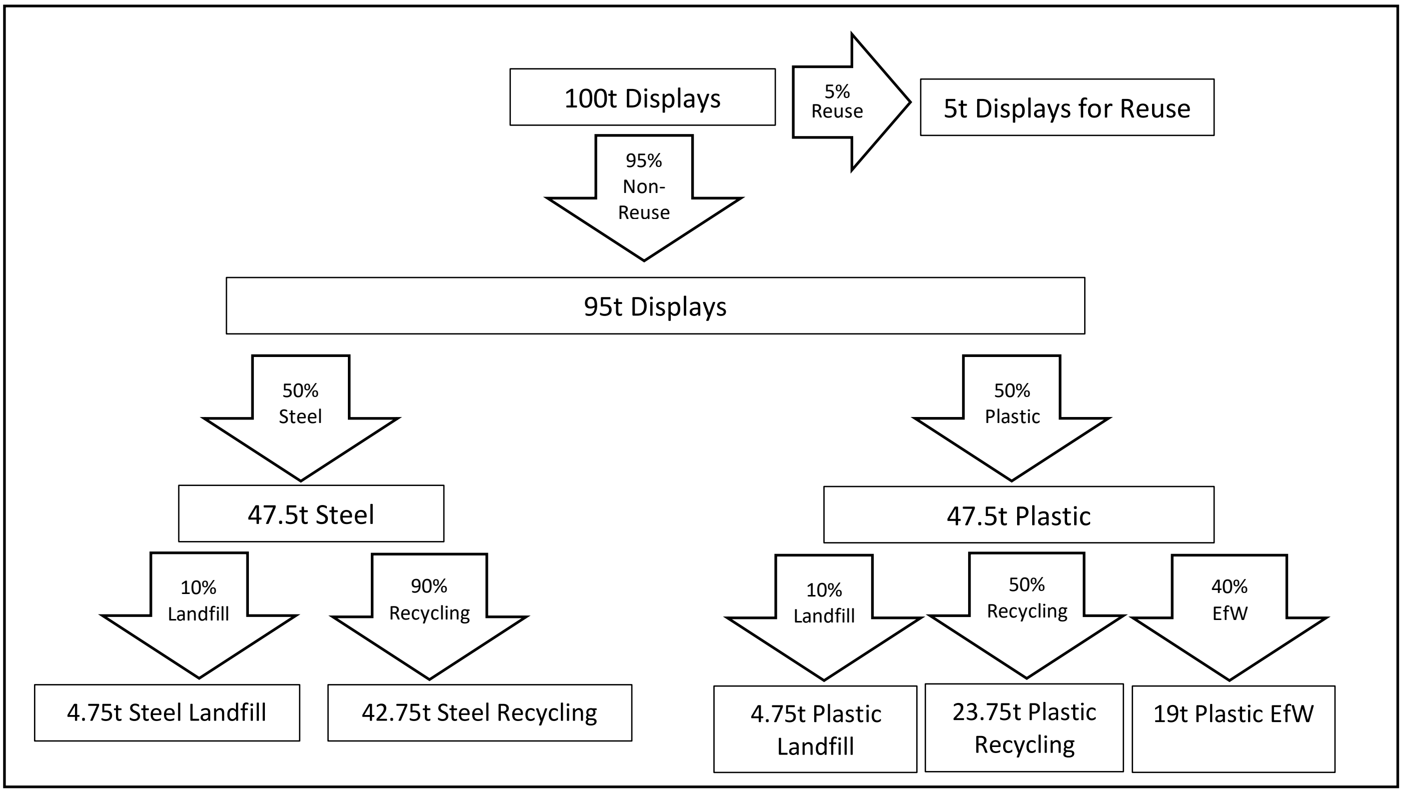


Figure 9: Example material flow calculation for one WEEE stream, simplified to only have two material residues, rather than the >10 used in the actual MFA.

Figure 10 shows the MFA of REPIC's entire 2019 WEEE tonnage, scaled down to 1 tonne of WEEE. In total, 27 different materials were identified by AATFs in the WEEE output (Table 8). The full breakdown of the composition and end-of-life processes for each WEEE stream individually is shown in Appendix C. Steel is the primary material for all WEEE streams except Gas Discharge Lamps (GDL), which is dominated by glass. Other materials that are present in high quantities are mixed metal, hazardous plastic, non-hazardous plastic, polyurethane foam, glass, compressors, circuit boards and concrete. All the WEEE streams, except GDL, contain a common set of materials – steel, stainless steel, copper, aluminium, plastic and residue. Individual WEEE streams then have a set of unique materials that are specific to their function. The Cooling stream contain compressors, polyurethane foam and refrigerant gas;

Displays contains panel glass, cathode-ray tube funnel glass and circuit boards; Large Household Appliance (LHA) contains concrete; Small Mixed WEEE (SMW) contains batteries and motors. The GDL stream has a less varied composition, dominated by glass, with <10% respectively of aluminium and mercury fraction. Figure 11 shows the average WEEE composition post-AATF, showing how steel and plastic dominate the composition.

The end-of-life process of these major materials vary (Table 8). All metals have a high recycling rate of 95-100%. Only a minority of AATFs showed metal going to other end-of-life processes. Plastics span all 4 categories of end-of-life process: non-hazardous plastic is >90% recycled, except for in the LHA stream where it is landfilled; hazardous plastics are 80-100% sent for energy-from-waste (EfW) or high-temperature-incineration (HTI); and PU foam is treated by predominantly EfW, with smaller amounts of landfill and recycling. Glass is either recycled or landfilled – funnel glass from cathode-ray tube TVs contains lead which makes it unsuitable for recycling, so it is landfilled. Compressors are 99% recycled, due to their high metal content. Further data from an AATF indicated that compressors are 89.9% steel, 10% copper and 0.1% aluminium. Circuit boards are processed to separate the plastic backing, which is incinerated, and the metals, which undergo precious metal refining. Finally of the major materials, concrete is entirely recycled.

The amount of WEEE diverted for reuse varies between the streams (Table 9), with displays being reused most at 5.36%, and GDL least at 0%.

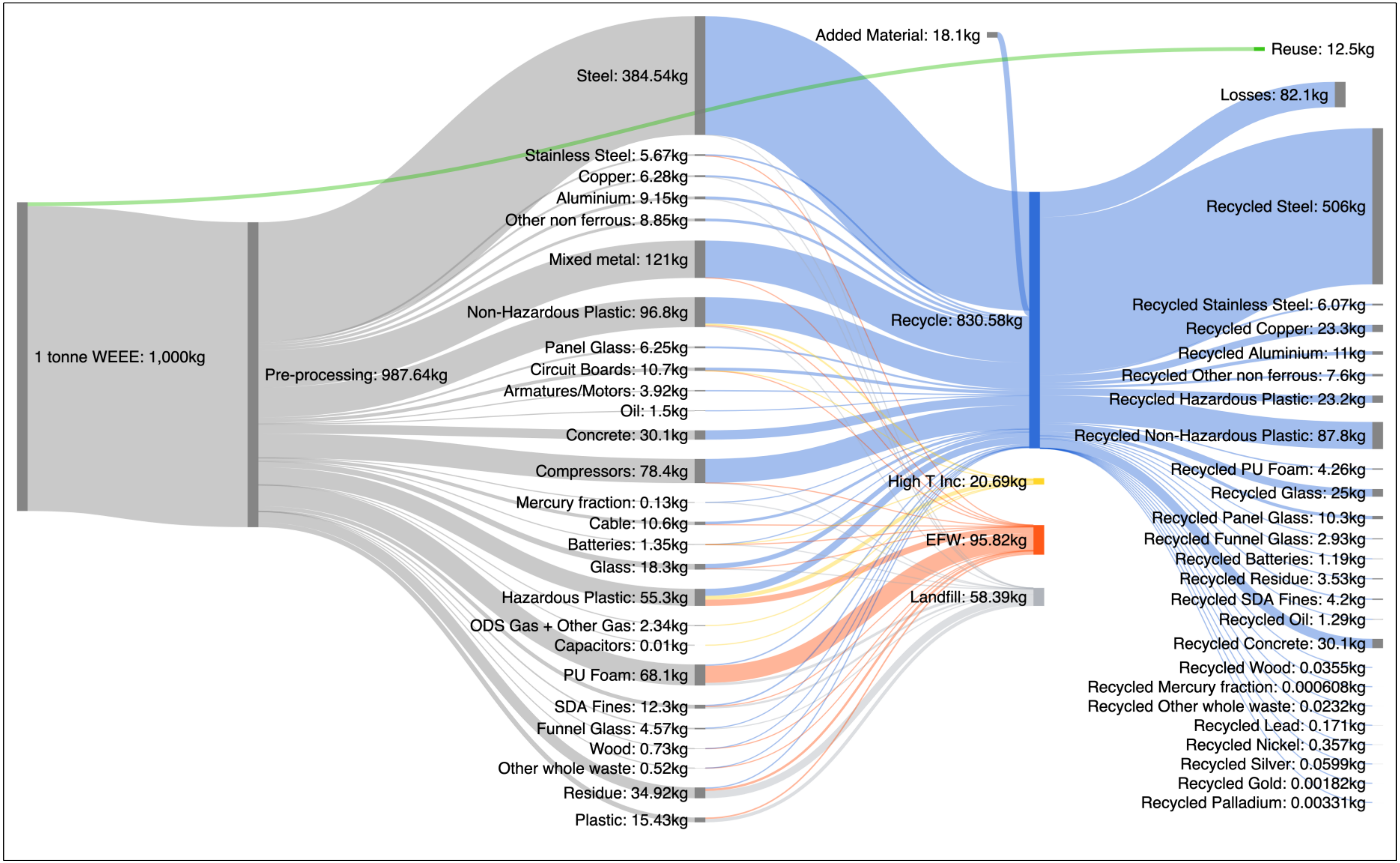


Figure 10: Sankey diagram showing the material flow analysis from 1 tonne of average WEEE through to the useful outputs of recycling and reuse.

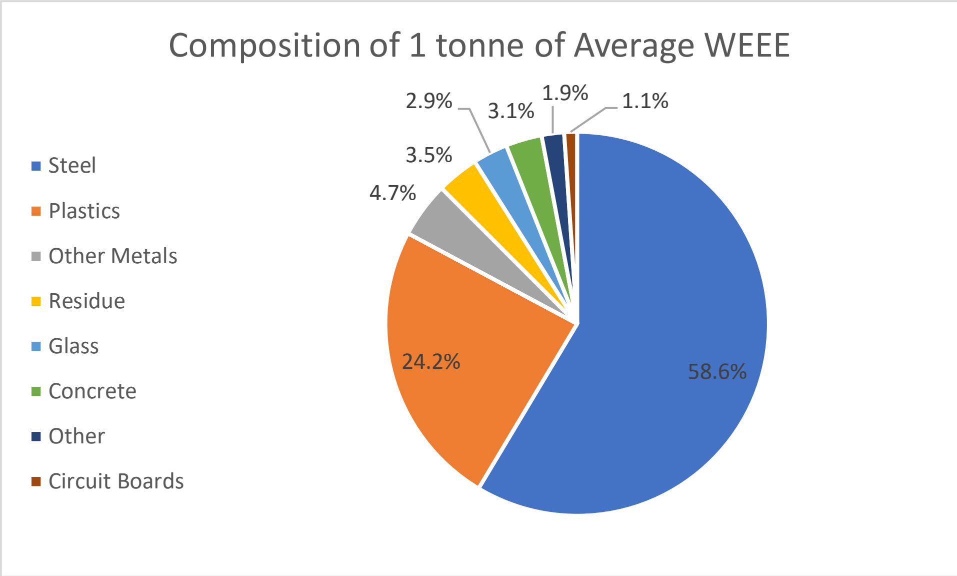


Figure 11: The average composition of REPIC's 2019 WEEE, sampled post pre-processing, as reported from AATFs. Components that are a mix of other materials have been separated into them e.g. compressors to 89.9% steel, 10% copper 0.1% aluminium.

Table 8: The average material composition as reported by AATFs from their outputs, and the proportion of each material sent for the different end-of-life processes.

1 tonne of average WEEE	Composition	Recycle	Energy-from-Waste	Landfill	High-Temperature-Incineration
Steel/Ferrous Metal	38.9%	100%	0%	0%	0%
Stainless Steel	0.575%	100%	0%	0%	0%
Copper	0.635%	100%	0%	0%	0%
Aluminium	0.927%	99%	0%	1%	0%
Other Non-Ferrous	0.896%	100%	0%	0%	0%
Mixed Metal	12.2%	100%	0%	0%	0%
Cable	1.07%	82%	18%	0%	0%
Plastic	1.56%	0%	30%	70%	0%
Hazardous Plastic	5.60%	41%	37%	0%	23%
Non-Hazardous Plastic	9.80%	88%	3%	3%	6%
PU Foam	6.89%	6%	81%	13%	0%
Glass	1.85%	83%	2%	15%	0%
Panel Glass	0.633%	100%	0%	0%	0%
Funnel Glass	0.463%	39%	0%	61%	0%
Batteries	0.136%	89%	0%	7%	4%
Circuit Boards	1.08%	97%	2%	0%	2%
Residue	3.53%	11%	21%	68%	0%
Armatures/Motors	0.397%	100%	0%	0%	0%
Small Appliance Fines	1.24%	38%	11%	52%	0%
Oil	0.152%	100%	0%	0%	0%
ODS Gas + Other Gas	0.237%	0%	0%	0%	100%
Concrete	3.05%	100%	0%	0%	0%
Compressors	7.94%	99%	1%	0%	0%
Wood	0.073%	5%	95%	0%	0%
Capacitors	0.000831%	0%	0%	0%	100%
Mercury Fraction	0.0135%	91%	0%	9%	0%
Other Whole Waste	0.053%	5%	95%	1%	0%
End-of-Life Process %		82%	10%	6%	2%

Table 9: The proportion of WEEE from each stream diverted for reuse.

WEEE Stream	% of WEEE diverted to reuse
Cooling	2.44%
Displays	5.36%
GDL	0%
LHA	0.592%
SMW	0.493%

4.2 Stage 1: Collection and Transport to AATF

The collection stage consists of vehicles picking up WEEE, usually one stream at a time, from DCFs and transporting it to an AATF for pre-processing. The collection is undertaken either by third-party logistics hauliers or by vehicles from the AATF. A variety of types of collection are undertaken using a range of vehicle sizes up to >33T heavy goods vehicles (HGVs). The collections can either be a direct out-and-back collection where a vehicle collects from a single DCF per journey, or a milkround collection where multiple DCFs are collected from. A further division occurs as some collection journeys go straight to the AATF, while others use a consolidation point where WEEE is consolidated to fill a large vehicle to capacity for more efficient transport to the AATF.

The carbon footprint of the WEEE collections, when capital goods are excluded, is simply the tailpipe emissions of the collection vehicles plus the well-to-tank (WTT) emissions of producing the fuel. These emissions were found by multiplying the distance travelled by the emissions per km, itself calculated by applying an emissions factor for the fuel combustion and WTT emissions to the vehicle fuel usage. An allocation factor was then applied so if the journeys carried other freight than REPIC's WEEE, only a proportion of the transport emissions are allocated to REPIC. Route distance was calculated from REPIC's collection data; the vehicle fuel usage and allocation factor were collected from the questionnaire sent out to REPIC's haulier companies; and the fuel emissions factor were from the DEFRA greenhouse gas conversion factors (DEFRA, 2020).

The data on collections was gathered from REPIC's internal reporting where two different sets of data exist. One dataset covering the majority of the 2019 WEEE, which contains full data for every single collection journey including the DCF, AATF, haulage operator, vehicle type and tonnage of WEEE collected. The other dataset covering the remainder of the 2019 WEEE contains limited data which aggregates multiple collections and shows the DCF, AATF and total tonnage collected in 2019 using that DCF:AATF combination. The two datasets required different methods for calculating emissions, which are both detailed below.

For the full data collections, the first stage was to determine the waypoints on the collection route, and calculate the distance of these routes. Data collected in the haulier questionnaire gave the vehicle depot location, which was set as the start and end point of every journey. Next, it was determined whether collections were direct out-and-back direct collections, or milkround collections where multiple DCFs are collected from in a single journey. The collection data from REPIC was listed collection by collection in Excel, but milkrounds were not clearly indicated so had to be inferred from data on the vehicle type and the "waste note" (a unique code for each delivery to an AATF) of each collection. First, any collections using a roll-on-roll-off vehicle were assigned as out-and-back collections – only a single roll-on-roll-off container can be carried at once. The remaining collections were each assigned an ID that contained the date of collection, the waste note, the postcode of the AATF, and the collection vehicle license plate which should be unique for each individual journey. Where multiple collections had the same ID, they were classed as milkrounds, and those with a unique ID were classed as out-and-back collections.

An Excel VBA code was then used to search the list of milkround collections and construct routes that stitch together the collections. VBA use was required due to the complexity of having up to 20 different collections in each milkround, not necessarily adjacent in the data. The output was a list of postcodes, starting with the haulier depot, followed by the DCFs, then the AATF, followed by the depot again.

The milkround routes outputted contain the DCFs in a random order, not representative of the routes that hauliers plan (Anonymous AATF 2021, personal communication, 20 April). To improve the routes' representativeness of the real-world situation, a Travelling Salesman Problem (TSP) was solved for the DCFs within each milkround. First, the great-circle distance (i.e. the shortest arc on the surface of a sphere) between each of the DCFs, the depot and the AATF for each milkround was calculated from the latitude and longitudes. Then, a constructive heuristic algorithm was used to solve the TSP, followed by an improvement heuristic to improve each route further by minimising distance travelled. Full code is in Appendix E. The heuristics used were a nearest-neighbour constructive heuristic, which chooses the next stop by finding the closest option to the prior stop (Laporte, 1992), and a 100,000 iteration Hillclimb improvement heuristic, as detailed in Section 3.4.5. These heuristics are relatively simple to code, and while they produce less optimal solutions than more complex heuristics such as the insertion constructive heuristic (Hassin and Keinan, 2008), the results may actually be more representative of the system being modelled where hauliers are unlikely to create optimal routes every time. Figure 12 shows the improvement in route distance that the heuristics result in.

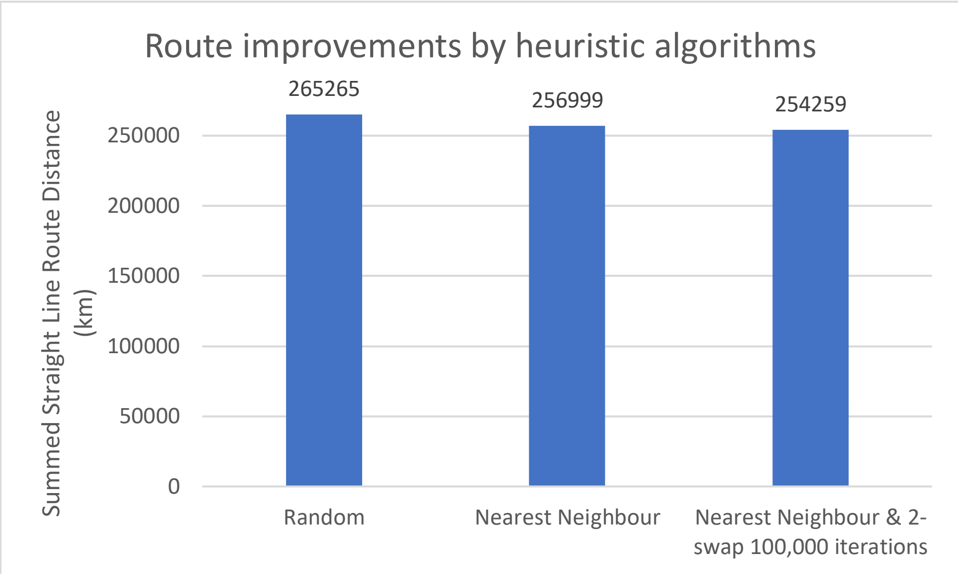


Figure 12: The change in summed straight-line distance of all routes when the travelling salesman problem was solved using heuristics.

After assigning collections to either a milkround or an out-and-back collection, the journeys using consolidation points were considered. These represent 21% of the collections in the full data dataset (a mixture of out-and-back and milkrounds) and use a consolidation point where WEEE is consolidated at intermediate locations between the DCF and AATF so larger vehicles can be completely filled for more efficient transport to the AATF. The second leg of these journeys, from the consolidation point to the AATF, is always an out-and-back collection, so the route waypoints were calculated as they were for normal out-and-back direct collections from the DCF. Due to the consolidation of WEEE, less journeys are made from the consolidation point to the AATF than arrive at the consolidation point, but no data was available for this. To calculate the number of journeys made on each route from consolidation point to AATF, the total tonnage transported in 2019 for each route was calculated and the number of journeys decided based on the average tonnage for each WEEE stream that can be transported in a >33t HGV (Table 10).

Table 10: Tonnage carried per >33T HGV for each WEEE stream, as reported in the haulier questionnaire. GDL is excluded because no GDL collections used a consolidation point.

WEEE Stream	Tonnes per journey
Cooling	7.5
Displays	13
GDL	N/A
LHA	11
SMW	11

The output of these initial stages was a list of waypoints for each collection journey. For direct out-and-back collections the journey was Depot – DCF – AATF or Consolidation Point – Depot, for the milkround journeys it was Depot: DCF_1 – $DCF_{n...}$ – AATF or Consolidation Point – Depot, and for the second leg of consolidated journeys it was Depot – Consolidation Point – AATF – Depot.

The final stage of the collection distance calculation was to find the distance travelled by road for these routes. The Google Maps Directions API was used in Python 3.7 to find the distance by road of each route in kilometres ("Google Maps Directions API overview," 2021). The ordered waypoints of the route are used as inputs for the API, which returns the distance by road considering the road conditions. A driving time 5 months in the future, at 10pm, was used to avoid there being any alterations to the routes due to live roadworks or traffic incidents. Full code is displayed in Appendix E.

0.7% of the collections are made from islands, requiring ferry transport as well as road transport. Ferry transport has a different emissions factor per km travelled, so the road and ferry distances were separated.

To calculate greenhouse gas emissions from the transport, the distance is multiplied by an emissions factor for $kgCO_{2eq.}$ per km. Use of an average database emissions factor, such as Ecoinvent emissions factors for road transport, is common (Baxter et al., 2016; Biganzoli et al., 2015; Clarke et al., 2019; Turner et al., 2016). However, the high level of resolution of REPIC's data, showing which haulage company was used for each journey, allows primary data on fuel usage to be collected from the hauliers and applied to their journeys. Thus giving greater accuracy, and the ability to compare different vehicle types and companies. Miles per gallon of diesel data, the most common fuel consumption unit in UK transport (UK Department for Transport, 2018), was collected in the haulier questionnaire. The emission factor for diesel combustion, including well-to-tank emissions, was taken from the DEFRA greenhouse gas conversion factors (DEFRA, 2020) – a value of 3.17 $kgCO_{2eq.}$ per litre. Thus the emissions factor in $kgCO_{2eq.}/km = (0.112*mpg)^{-1}$. This relies on diesel fuel consumption being directly proportional to CO_2 emissions, which it should be due to the stoichiometry of diesel combustion. This assumption is made in other studies converting from mpg to CO_2 emissions (Jabali et al., 2012).

Ferry emissions factors were taken from the DEFRA greenhouse gas conversion factors entry for "Large RoPax ferry" (which represents a car ferry), with a value of 0.37668 $kgCO_{2eq.}$ per tonne.km (DEFRA, 2020). Database emissions per tonne.km were used here as overall ferry emissions per km would be difficult to allocate between the WEEE and other loads. The emissions factor is ambiguous as to whether the tonne.km tonnage should include the vehicle weight, or just the freight weight. REPIC reported that some ferries transport WEEE in a container, without the lorry, which adds difficulty to deciding on the tonnage. A simplification was assumed that the tonnage is just the weight of WEEE.

The distance and emissions factor calculations allow the emissions of each journey to be calculated using the specific emissions factor of each haulier. A further step was added to allocate to REPIC only the proportion of these emissions that it is responsible for. Each route consists of travel from the haulier depot to the first collection point, then other collection points in the case of milkrounds, followed by the AATF and then back to the haulier depot. The haulier questionnaire returned data on what % of journeys used backloading, where the return journey to the depot was performing another job, and what % of the vehicle load was REPIC's WEEE i.e. if other goods were transported simultaneously, such as another producer compliance scheme's WEEE. An allocation factor takes these into account (Equation 3). The number of waypoints in milkround collections is included in the empty return allocation to reflect that a greater number of waypoints leads to the return leg representing a smaller proportion of the overall journey.

Equation 3: The emissions factor calculated for each haulage company, taking into account vehicle mpg, % backloading of journeys, and the % of vehicle load that was REPIC's.

$$Allocated\ emissions\ per\ km = (\frac{2.8248}{mpg} * 3.172 * \left(\frac{(2 - \%\ backloading)}{1 + no.waypoints}\right) * \%\ REPIC\ WEEE$$

The haulier questionnaire responses cover 54% of the 2019 collection tonnage (Table 11). For the remainder of the collections the mean values for the mpg and allocation factors were applied.

Factor	Mean value	Range of values	Standard Deviation	Sample Size
mpg fuel efficiency	13.1	9.00 to 40.0	3.74	18
% of journeys backloading	20.7%	0% to 100%	33%	18
% REPIC weight	97.4%	50% to 100%	9%	16

Table 11: Range and mean values of miles per gallon (mpg), % of journeys backloading and % weight carried that is REPIC's WEEE, from the haulier survey responses.

The limited data collections, where REPIC's data does not detail the haulier or tonnage transported, required the following assumptions to be made about the tonnage carried per vehicle, the vehicle mpg and the allocation factor. These collections are predominantly bulk collections from retailers, one of which was contacted for further information. The retailer detailed that their collections fill capacity on large vehicles and that backloading is used extensively. Backloading was set to 100% to represent the filling of return leg capacity, and vehicle mpg to 9.9 for >33T HGV. The same average tonnage was used as in the post-consolidation journeys (Table 10). No details of the DCF locations were available, creating difficulty in calculating the distance travelled, so the average distance for the full data collections was used: 295.8km.

The output of Stage 1 is a collection carbon footprint for every tonne of REPIC's 2019 WEEE, and details of which AATF each tonne of WEEE is delivered to.

4.3 Stage 2: Pre-processing at AATF

The pre-processing stage takes place at Approved Authorised Treatment Facilities (AATFs) spread across the UK. Some WEEE is diverted before pre-treatment for reuse, and the remainder is treated as required in the WEEE legislation Best Available Treatment Recovery and Recycling Techniques (Environment Agency, 2021b). The material is then manually dismantled or shredded, and the different materials in the WEEE are separated using a range of machinery such as magnets for separating ferrous metal. The AATF then sends the WEEE for disposal or recycling, either directly, or via a scrap trading organisation. AATFs must record the materials they separate and the proportion that is recycled, energy recovered or landfilled to report against the requirements of the WEEE regulations (*The WEEE Regulations*, 2013).

The emissions of the pre-processing at the AATF, excluding capital goods, are a result of electricity and diesel usage by the machinery, diesel usage by on-site vehicles such as forklift trucks and nitrogen usage for treatment of cooling devices. The carbon footprint was found by finding the usage of these per tonne of WEEE, from each stream, treated at each AATF. Emissions factors were then applied for the carbon emissions from electricity production, diesel combustion and nitrogen production. As with the WEEE collection emissions, primary data that is specific to each company in the supply chain allows more accuracy than averages, and also allows for comparison between different companies. Primary data was used for the consumables usage, and database values for the emissions factors.

The AATF emissions questionnaire requested data for the electricity usage, diesel usage, and nitrogen usage per tonne of WEEE processed in each WEEE stream. Feedback from the AATFs indicated that this data is not routinely calculated, so required approximations to be made in their calculations, such as allocation of electricity usage between other activities that happen in the same premises. The responses to this survey were from the same AATFs who responded to the AATF residues questionnaire, covering 53% of WEEE, and the same proxies were used (Section 4.1). Again, the remainder of the AATFs had the average values for each WEEE stream applied (Table 12).

*Table 12: Mean, standard deviation and sample size of values of electricity consumption (kWh), diesel consumption (L) and nitrogen consumption (kg), all per tonne of WEEE processed, from the AATF survey responses. * Indicates sample size is too small to disclose data.*

	Values per tonne WEEE processed. (Mean ± standard deviation, sample size)		
	Electricity (kWh)	**Diesel (L)**	**N_2 Gas (kg)**
Cooling	114.07 +- 16.4 , n=4	2.11 +- 1.2 , n=3	107.67 +- 34.2 , n=3
Displays	55.49 +- 6.3 , n=3	2.06 +- 0.9 , n=3	/
GDL	* n=1	* n=1	/
LHA	* n=1	* n=1	/
SMW	48.06 +- 11.4 , n=3	1.97 +- 1.1 , n=3	/

Emissions factors were sourced for diesel combustion (including well-to-tank emissions), UK grid electricity and nitrogen production (Table 13). These emissions factors were combined with each AATF's electricity, diesel and nitrogen usage to produce an AATF emissions factor per tonne of WEEE. The tonnage of each WEEE stream processed at each AATF is then multiplied by the AATF CO_2 emissions factor to find the total emissions.

Table 13: The emissions factors and their sources for electricity production, diesel combustion (including well-to-tank) and N2 gas production (DEFRA, 2020; ecoinvent, 2021)

Consumable	Emissions in $kgCO_{2eq.}$	Data Source
Electricity	0.23314 per kWh	DEFRA Conversion Factors
Diesel	3.17214 per L	DEFRA Conversion Factors
Nitrogen	0.23853 per kg	Ecoinvent 3.7

WEEE destined for reuse, either at specific reuse AATFs, or a small percentage of WEEE at regular AATFs, is also assigned the average AATF emissions. While this WEEE does not go through mechanical shredding, there are emissions associated with refurbishment and preparing for resale. Specific data for reuse AATF emissions was not available, making the average emissions the most suitable estimate.

4.4 Stage 3: Transport to End-of-Life

The scrap materials that are outputted from the AATF are then transported in bulk to their end-of-life process, which can be in the UK or abroad. Transport could be by road, train or ship.

The emissions from this stage, again excluding the capital goods of the vehicle/ferry/train, are from the combustion of the diesel or fuel oil in the engine of the vehicle and the well-to-tank emissions of the fuel. This stage of the supply chain is now out of REPIC's control and visibility, so data was obtained from AATFs, industry contacts and literature.

An assumption was made that the same materials going to the same end-of-life process from different AATFs and WEEE streams would have the same pathway post-AATF, and that this is the same as bulk scrap of that material. For example, steel for recycling from 2 different WEEE streams or 2 different AATFs would be indistinguishable from each other and from other scrap steel produced in the UK. Discussion with individuals from the recycling industry supported that this assumption was the best available as data for any more accurate analysis is not accessible (British Metals and Recycling Association 2021, personal communication, 21 June). The differences that could exist are due to different scrap grades of the same material undergoing different recycling processes.

The locations of the end-of-life process vary between the different processes (Table 14). The AATF questionnaire indicated that landfill and high-temperature-incineration take place locally in the UK, as does energy-from-waste in electricity-producing plants. Some WEEE plastic is converted into solid recovered fuel to power cement kilns outside of the UK. AATFs did not differentiate this from electricity-producing energy-from-waste, and until legislation changed in September 2019 little WEEE material went to this end-of-life (Environment Agency, 2020b). For the purposes of this study, based on 2019 data, energy-from-waste is assumed to be in electricity-producing plants in the UK. The location of recycling can be in the UK, Europe, or elsewhere worldwide. This is further complicated by the ever-changing nature of scrap material trading, where the recycling location can change based on price and legislation changes around the world (World Trade Organisation, 2017; WRAP, 2019).

The locations set in the model for the end-of-life processes were decided based on input from AATFs, online sources, and UK government export data provided by a recycling organisation. The distance by road to locations within the UK was calculated by averaging the distances reported by several AATFs that provided landfill and EfW locations. Average round trip values of 218km for landfill, and 430km for energy-from-waste were set. For high-temperature-incineration, no AATFs specified a location, so the energy-from-waste value of 430km was assumed.

For recycling, due to the range of locations worldwide, up to 4 different locations were specified for each material, with a % assigned to each location for how much of the recycling they receive (Table 14). The locations and % were assigned based on a variety of sources, differing for the different materials, detailed in Table 14. Where the data showed >4 recycling locations, the percentages were scaled such that the top 4 locations sum to 100%. Locations within the UK were assumed to be transported to by road, and those out of the UK by bulk shipping. Discussion with AATFs and recycling industry contacts confirmed these are the usual transport methods. In the absence of accessible data on the distance to the UK recycling locations, road transport for recycling in the UK was assumed to be 296km – the average

Material Fraction	% of output	Locations and %'s				Source(s)
Steel and stainless steel	47.9	Turkey: 36%	Pakistan: 26%	UK: 20%	Spain: 18%	BMRA, Liberty Steel
Copper, including cable core	1.83	China: 45%	India: 25%	Germany: 20%	Spain: 10%	BMRA, USGS
Aluminium	1.10	UK: 59%	India: 20%	China: 13%	Germany: 8%	BMRA, Alfed
Other non-ferrous metal	1.10	Assumed = Copper				N/A
Mixed metal	14.9	Assumed = Steel				N/A
Hazardous plastic	4.68	UK: 100%				Estimated
Non-Hazardous plastic	8.65	UK: 39%	Turkey: 36%	Hong Kong: 13%	Netherlands: 12%	WRAP
Polyurethane foam	0.525	UK: 100%				UK carpets...
Glass	2.98	UK: 100%				AATF correspondence
Circuit Boards and Batteries	1.43	Belgium: 25%	Japan: 25%	Sweden: 25%	Canada: 25%	AATF correspondence
Armatures/Motors	0.481	Assumed = Steel				N/A
Oil	0.184	UK: 100%				Estimated
Concrete	3.71	UK: 100%				Estimated
Compressors	9.56	Pakistan: 90%	UK: 10%			AATF correspondence
Mercury Fraction	0.0143	UK: 100%				AATF correspondence
Wood	0.00436	UK: 100%				Estimated
Small Appliance Fines	0.570	UK: 100%				Estimated
Residue/Other waste	0.479	UK: 100%				Estimated

Table 14: The end-of-life recycling locations set for each material. Citations for table: USGS (2020), BMRA (2021, Personal Correspondence, 21 June) , WRAP (2019), LIBERTY Steel UK (2021). Estimations were based on the restrictions on movement of hazardous waste, and the poor economics of moving low value goods such as concrete out of the UK.

WEEE collection distance. Shipping distance was calculated using an online tool (Sea Distances, 2021), calculating the one-way shipping distance between the largest port by cargo tonnage in the UK (Felixstowe) and the largest port in the destination country (Table 15). Ships were assumed to take on a different shipment on the return trip, so only one-way shipping emissions were allocated to the WEEE. Shipped WEEE also had 151km of road transport added for transport to and from the port at either end of the shipping, this distance is the average round trip distance of each of the 10 largest AATFs (by tonnage processed) to their nearest major port.

Emissions factors for each transport method, in tonnes CO_2 per t.km, were sourced from the DEFRA emissions factors and included the direct emissions and well-to-tank emissions. (Table 16) (DEFRA, 2020). These factors were applied to the tonnage and distance for each of the end-of-life locations to find the total carbon footprint of transport to end-of-life for each material.

Table 15: Shipping distances calculated for each of the WEEE residue destinations, starting in Felixstowe.

Shipping Destination	Destination port	Distance (km)
Spain	Algeciras	2400
Portugal	Setubal	1932
Belgium	Antwerp	261
Netherlands	Rotterdam	224
Germany	Hamburg	667
Turkey	Mersin	6025
Pakistan	Karachi	11231
India	Jawaharlal Nehru	11577
China	Shanghai	19365
Hong Kong	Hong Kong	17296
Japan	Nagoya	20389

Table 16: Emissions factors for bulk transport, per tonne.km, including well-to-tank emissions.

Emissions per t.km	DEFRA	Tonnes $CO_{2eq.}$ per t.km
Ship	Average Bulk Carrier	0.00000422
Road	>33T HGV, 100% Laden	0.0000740
Rail	Freight Train, UK	0.0000394

Reused WEEE has no end-of-life transport carbon footprint allocated. The WEEE is assumed to be sold from the AATF, and the transport from that point onwards is no longer part of the waste treatment, instead falling under the next use phase of the WEEE.

4.5 Stage 4: End-of-Life Process

The final stage in the WEEE collection and treatment process is the end-of-life process. WEEE materials are either recycled, landfilled or incinerated in energy-from-waste or high-temperature-incinerators. The choice of end-of-life is dictated by material properties, AATF decisions and legislation, which sets minimum requirements for recycling for different materials and dictates end-of-life for some materials such as POP plastics which must be incinerated (Environment Agency, 2020b, 2020a).

The emissions from the end-of-life processes come from a range of sources – recycling processes use electricity, fossil fuels and raw materials; landfill can produce methane; and incineration emits carbon dioxide directly. Again, this stage is beyond REPIC's control and visibility, so data is collected from secondary sources – primarily the Ecoinvent LCI database. In contrast to the method for the other supply chain stages, the Ecoinvent data includes the emissions from producing capital goods for each process, which cannot be easily separated.

In total 60 different end-of-life processes take place for the WEEE material. Each of the 27 materials had up to 4 different end-of-life processes, but most had only 2 or 3 utilised. Within Ecoinvent 3.7, there are three different system models available that set the rules for how the different impacts are allocated with regards to by-products, waste, recycling and avoided emissions (Table 17). Allocation – cut off by classification was selected as it fits best with the definitions of the research, with the waste treatment burden being allocated to the waste, not the secondary material.

Table 17: Different system models in Ecoinvent and their characteristics. Allocation – cut off by classification was selected for this study.

System Model	Supply considered	Recycling allocation	Uses
Allocation – cut off by classification	Considers all suppliers.	All waste treatment burden allocated to the reference product. Secondary material is burden-free.	Ecoinvent default model. Suitable for assessing the first life of a material, and its recycling process.
Allocation – at point of substitution	Considers all suppliers.	Secondary material receives some of the burden of waste treatment.	Suitable for assessing the environmental impact of secondary material.
Substitution, consequential, long-term	Only considers marginal suppliers.	Includes avoided emissions for recycling.	Suitable for seeing the consequence of changes.

Each of the 60 processes was searched in Ecoinvent, and the closest matching dataset was selected. Full details of each dataset selected are in Appendix D. The emissions factors were extracted from the life cycle impact assessment IPCC 2013 GWP_{100a} category. Where multiple localised datasets were available, the most localised area to the UK was assigned – most often Europe. For 34 out of 60 processes, covering 77% of the material tonnage, an exact process match was found. Exact matches weren't found either: when a material stated by AATFs is composed of a mixture of other materials, each with their own Ecoinvent entry; or when a process was not represented in the Ecoinvent database at all. The following end-of-life processes lacked a perfect match in the database, and the method used to overcome this is stated:

- Mixed metal: assumed to be the proportions of metal reported from other AATFs: 95% steel, 1% stainless steel, 2% copper, 2% aluminium.
- Other non-ferrous metal: assumed to be the proportions of non-ferrous metal reported from other AATFs: 50% copper, 50% aluminium.
- Hazardous/Non-Hazardous Plastic: assumed to be an even mixture of ABS and PP – the most common WEEE plastics that had Ecoinvent entries (APPLiA, 2019).
- PU Foam: 100% recycled polystyrene foam production substituted for polyurethane foam recycling process.
- Cable: Ecoinvent shows this to be 66% copper and 34% plastic, copper is recycled and plastic processed in energy-to-waste.
- Circuit Boards: 3 stages of processing from Ecoinvent were combined for recycling, and 6 different materials for the avoided emissions. See Appendix D for details of the material breakdown of circuit boards.

- Glass/Panel Glass/Funnel Glass: set as “Packaging Glass with 100% Recycled Cullet Production”.
- Batteries: set as “Laptop Residue Incineration” for EfW. Landfill and hazardous waste incineration used generic Hazardous Waste values.
- Residue: Ambiguous term. Assumed to be a mixture of the top 5 materials for recycling, and assumed to be Municipal Solid Waste for EFW and landfill.
- Small Appliance Fines: Assumed to be a mixture of the top 5 materials for recycling, and assumed to be shredder residue for EFW and landfill.
- Oil: No recycling values found in Ecoinvent, applied the ratio of recycled:virgin emissions from Grice *et al.* (2014) to the Ecoinvent primary oil production value.
- Mercury fraction: No similar matches. Waste aluminium recycling and landfill substituted in for mercury. Very low tonnage so value has little impact on results.

If the functional unit for each dataset was not 1 unit of scrap input (recycling datasets are often referenced to 1 unit of useful output), the values were adjusted to equal 1 unit of input. Recycling processes in Ecoinvent account for where the process has material losses, or dilution from added virgin material, so the amount of input scrap and output material is often different. For example, 1kg copper cathode output required 1.31kg copper scrap input, so the recycling emissions factor was divided by 1.31 to find the emissions per kg of input scrap (Figure 13). Some recycling processes take <1 unit of input scrap to produce 1 unit of output raw material, due to dilution with extra raw materials. The same process was used to equal 1 unit of input (Figure 14) and the additional emissions resulting from producing the extra raw materials are already included in the emissions factor.

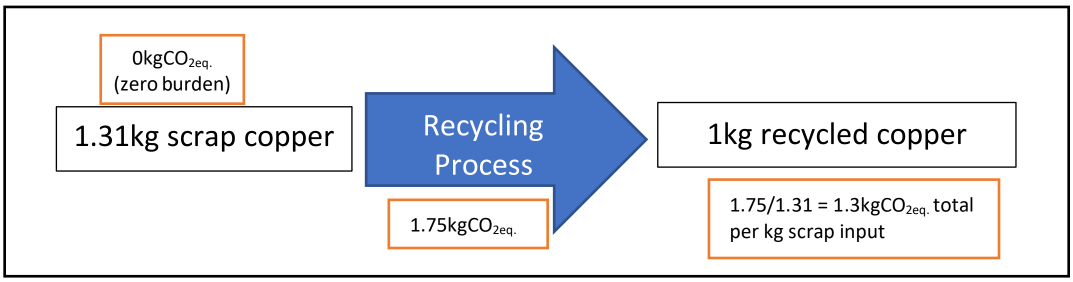


Figure 13: Example of Ecoinvent calculation where recycling losses occur.

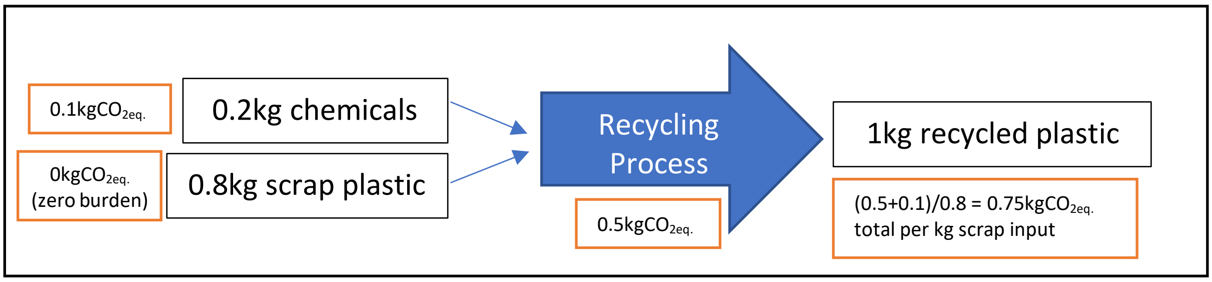


Figure 14: Example of Ecoinvent calculation where recycling dilution occurs.

The resulting value of tCO_2 per tonne of scrap input was multiplied by the tonnage of scrap entering each end-of-life process to find the total emissions for each process.

Full detail of the emissions factors used for recycling, energy-from-waste, landfill and high-temperature-incineration are listed in Appendix D.

4.6 System Expansion: Avoided Emissions

The final stage of the carbon footprint calculation was to calculate the GWP benefit of the WEEE treatment. No actual greenhouse gas removal occurs in the WEEE supply chain, but the useful outputs of the recycling, energy-from-waste and reuse substitute other material being produced, avoiding the emissions that would have otherwise occurred. To capture the benefit of the WEEE treatment process these must be included, so a system expansion of the life cycle assessment (LCA) considers the useful outputs and the substituted processes.

To calculate the avoided emissions from recycled materials, the tonnage of secondary raw material produced, including losses or dilution, is calculated for each recycling process, and the emissions factor for virgin production applied to find the emissions that would result from producing that amount of virgin raw material. This level of emissions is added to the model with a negative sign, so that when total emissions are summed, the avoided emissions value reduces the emissions. The resulting net emissions show the emissions compared to if the WEEE recycling did not take place.

Emissions factors for the virgin production of materials were taken again from the Ecoinvent 3.7 database. The same methodology as in Stage 4 was applied when an exact match wasn't found – requiring substitution of similar processes. Full details of the datasets selected for avoided emissions are shown in Appendix D.

Emissions are also avoided when energy-from-waste processes export electricity to the grid, as this electricity would otherwise have been produced from conventional electricity generators. EfW also has the potential to avoid emissions by exporting heat that would otherwise be produced by conventional boilers. A report by Tolvik Consulting (2020) showed that in 2019 only 4 out of 53 EfW plants in the UK exported >100GWh of useful heat, and only 10 exported any heat at all. Due to this, and the complexity of what type of heat generation is being avoided, EfW plants were assumed to only produce electricity. This is in consensus with Turner et al. (2016, p3) who state that heat produced “would be used internally due to a lack of established district heating networks in the UK”. The Ecoinvent 3.7 datasets for EfW incineration include a net energy production value for electricity production in MJ per kg waste (Appendix D). This is converted to kWh per t waste by multiplication by 277.7. Again following the methodology of Turner, the electricity that is avoided is that of the marginal electricity supply in the UK, as this is what is reduced, rather than the average electricity supply. In the UK, marginal electricity supply is from combined cycle gas turbine power plants (CCGT). A carbon intensity of 490g$CO_{2eq.}$/kWh is taken from IPCC Annexe 3 for the median lifecycle emissions of a CCGT (Schlömer et al., 2014).

WEEE going to reuse also leads to avoided emissions by displacing new WEEE that would otherwise have been produced to meet demand. The emissions of producing a new product were calculated by summing the primary production emissions for the material composition of each product. While this omits the emissions from actual manufacturing and assembly, it allows continuity of the emissions factors throughout the model. Reused WEEE has a shorter lifespan than a new EEE item, so the model allocates less than 100% of the new product emissions to the avoided emission (Jaunich et al., 2020; Turner et al., 2016). Lifespans for new and reused WEEE were taken from Boldoczki et al. (2020), and the proportion of the new product emissions allocated as avoided emissions was equal to the proportion of the new product lifespan that the reused product is expected to have. E.g. 5-year reuse lifespan and 12-year new lifespan = 5/12 of the emissions of a new product are avoided. As discussed in Section 2.4.3, avoided emissions from WEEE reuse is a complex research topic in its own right.

Our method does not capture all of the complexity, but it correctly acknowledges that the avoided emissions are less than that of an entire new EEE product being displaced (O'Connell et al., 2013; Hischier and Böni, 2021).

5 Results

The output of the carbon calculator provides data on the overall carbon footprint of REPIC's WEEE treatment in 2019 and provides specific breakdowns for each supply chain stage and each of the 5 WEEE streams. These output results address Aims 1 and 2 of the research – the calculation of REPIC's 2019 WEEE carbon footprint and the evaluation of the carbon footprint across the whole supply chain. They also provide the input for Aim 3 – the ways in which the carbon footprint logistics can be optimised. The optimisation model results, which address Aim 3, are solutions for logistics problems, along with the carbon footprint that they result in.

5.1 Total WEEE Carbon Footprint

Figure 15 shows the carbon emissions resulting from each stage of the WEEE disposal supply chain in a waterfall chart. This is broken down into gross emissions, that are emitted by the supply chain, shown in blue, and avoided emissions, in orange, that result from the useful outputs of the supply chain displacing more carbon-intensive virgin sources of each output. The overall carbon footprint is displayed as net emissions – combining the gross and avoided emissions. The calculated net emissions for REPIC's WEEE supply chain in 2019 was -2.014 tonnes $CO_{2eq.}$ per tonne of WEEE collected. The average gross emissions per tonne of WEEE collected is 0.903 tonnes $CO_{2eq.}$. The breakdown of gross emissions resulting from each stage of the supply chain are represented by the blue bars in Figure 15. The first 3 stages of the supply chain, where WEEE is collected from the Designated Collection Facility (DCF), pre-processed at the Approved Authorised Treatment Facility (AATF), and transported to its end-of-life (EoL) location, are only responsible for 4.7%, 3.9% and 3.9% of gross emissions respectively. The remaining 87.5% of gross CO_2 emissions are emitted at the EoL process – recycling, landfill, energy-from-waste or high-temperature-incineration. The avoided emissions average value is -2.92 tonnes $CO_{2eq.}$ per t WEEE – over 3 times greater in magnitude than the gross emissions, leading to the negative net emissions. These avoided emissions result from recycled materials substituting virgin material production, reused WEEE displacing new EEE, and energy-from-waste electricity substituting grid electricity production.

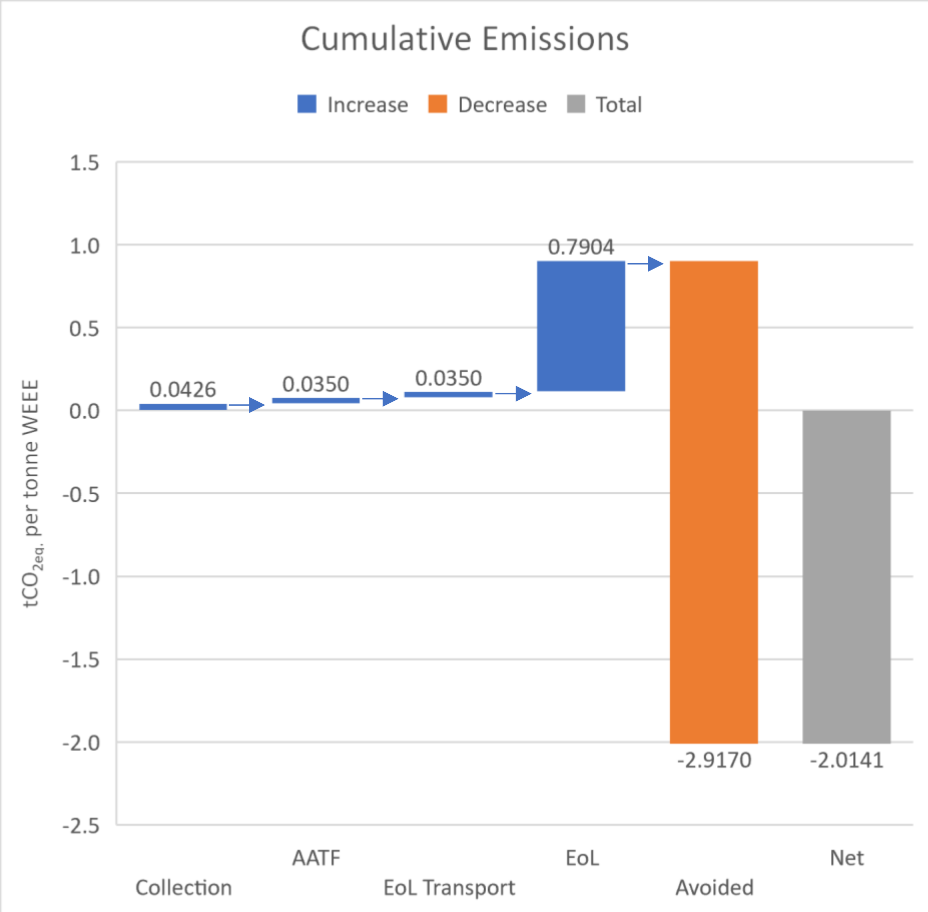
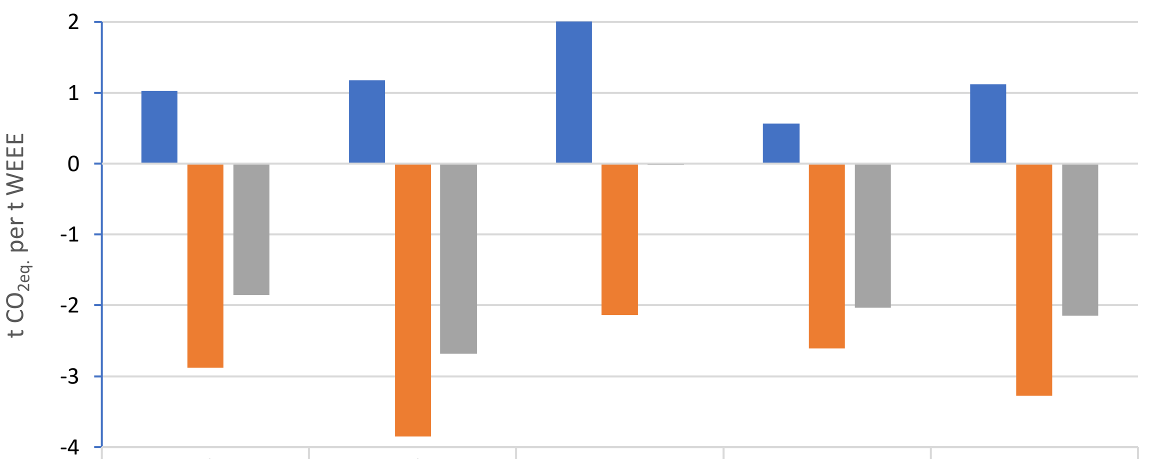


Figure 15: Average carbon emissions in $tCO_{2eq.}$ per tonne of WEEE at each supply chain stage, shown as a waterfall chart where the start of each bar is at the top of the last bar. The grey bar is the overall net emissions, which is the whole chart summed.. Gross emissions are shown as blue bars, avoided emissions as the orange bar.



	Cooling	Displays	GDL	LHA	SMW
Gross	1.023	1.174	2.118	0.567	1.124
Avoided	-2.8792	-3.8528	-2.1371	-2.6043	-3.2733
Net	-1.857	-2.679	-0.019	-2.038	-2.149

Figure 16: Gross, avoided, and net emissions for each of the 5 WEEE streams.

5.1.1 Individual WEEE Stream Carbon Footprint

Figure 16 shows the overall gross, avoided and net emissions for each of the 5 WEEE streams: Cooling, Displays, Gas Discharge Lamps (GDL), Large Household Appliances (LHA) and Small Mixed WEEE (SMW). The WEEE streams show different values of net emissions, but all are negative, indicating a carbon benefit to the WEEE process. The net emissions range from -0.0191t$CO_{2eq.}$for GDL to -2.68t$CO_{2eq.}$ for Displays. GDL appears an outlier compared to the other 4 WEEE streams, with greater gross and lesser avoided emissions.

Excluding GDL, the remaining 4 WEEE streams have a narrow range of net emissions, from -1.86 to -2.68 tonnes $CO_{2eq.}$. Again, excluding GDL, the gross emissions range from 0.567t$CO_{2eq.}$ for LHA to 1.174t$CO_{2eq.}$ for Displays, and the avoided emissions range from -2.60t$CO_{2eq.}$ for LHA to -3.85t$CO_{2eq.}$ for Displays.

The contribution of the different supply chain stages to the gross emissions for each WEEE stream are shown as a % in Figure 17a and as absolute values per tonne in Figure 17b and Table 18. In this data, the end-of-life process is further divided into the emissions from recycling, energy-from-waste (EfW), landfill and high-temperature-incineration (HTI). This shows that the contribution of emissions from each stage varies between the different WEEE streams. The recycling process is the highest CO_2 emitting stage for every stream, but the contribution of the other stages varies greatly:

- Emissions from Cooling WEEE are dominated by the recycling and EfW stages, together responsible for 81.0% of gross emissions. This is also the only WEEE stream where the AATF emissions are greater than both the collection and transport to end-of-life emissions, at 5.95%. The higher AATF emissions are not unexpected due to the additional emissions from producing N_2 gas for the AATF shredding phase for Cooling equipment.

- Emissions from Displays WEEE are also dominated by recycling and EfW, responsible for 87.8% of gross emissions. Collection is the next most emitting stage, at 7.30% of gross emissions.

- GDL WEEE shows a very different distribution, with collection responsible for 38.1% of emissions: over 5x its contribution in the other streams. Most of the remainder is made up of recycling emissions at 60.4%, leaving only 1.47% of emissions from the other stages. No emissions come from EfW. GDL only makes up a small proportion of WEEE, in REPIC's collections, and in the UK as a whole (Environment Agency, 2021d), so the outlier nature of its emissions hardly affect the mean collection emissions.

- LHA WEEE is the most dominated by recycling emissions, at 72.1%, and also has the greatest proportion of all the streams of emissions from landfill, at 5.96%. A comparatively low 8.76% of emissions come from EfW.

- Finally, the SMW stream shows recycling and EfW dominating, with 47.3% and 27.3% of gross emissions respectively. SMW shows the highest of all WEEE streams contribution from HTI, at 14.8%, and the 2nd highest of landfill at 2.60%. The high-temperature incineration (HTI) value is high due to the high incidence of persistent organic pollutants (POPs) in SMW plastic, which then requires destruction at high temperature.

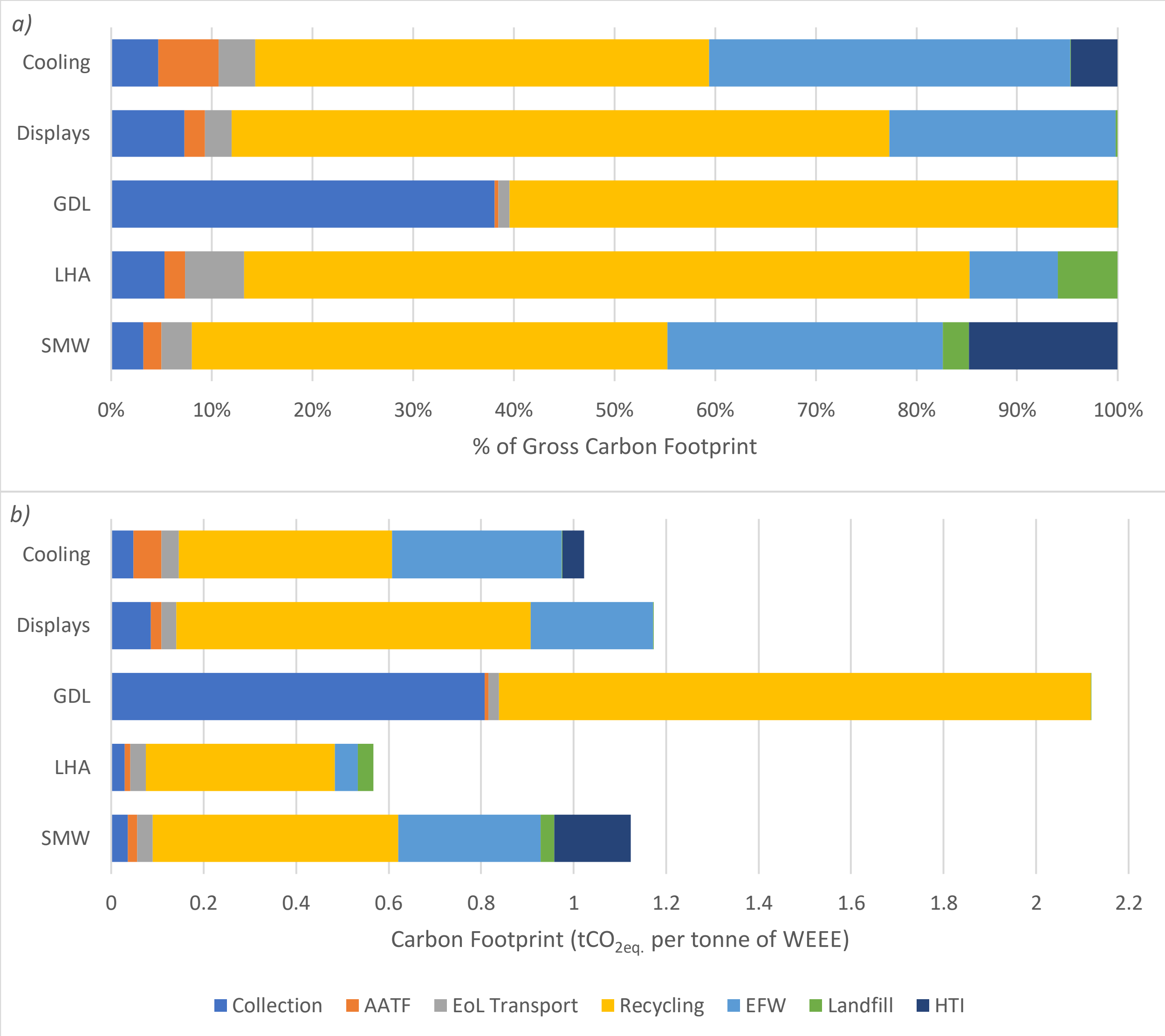


Figure 17: The contribution of each of the WEEE supply chain stages to the gross emissions for each WEEE stream.
a) The contribution as a percentage of the total gross emissions.
b) The contribution in absolute carbon footprint ($tCO_{2eq.}$ per tonne of WEEE).

Table 18: The gross carbon footprint values for each stage of the supply chain for each WEEE stream.

	Carbon Footprint ($tCO_{2eq.}$ per tonne of WEEE)			
WEEE Stream	**Collection**	**AATF**	**EoL Transport**	**EoL Process**
Cooling	0.0480	0.0609	0.0374	0.8763
Displays	0.0857	0.0232	0.0314	1.0334
GDL	0.8070	0.0082	0.0227	1.2802
LHA	0.0299	0.0118	0.0330	0.4920
SMW	0.0362	0.0199	0.0340	1.0341

5.1.2 Carbon Footprint per individual WEEE item.

Data in the format of carbon footprint per item of WEEE may be more relatable than per tonne, and useful for considering the benefit of one item over another. Table 19 shows the net emissions of the WEEE supply chain for a single WEEE item for each of the WEEE streams, using the weights calculated from REPIC's collection data. Except for GDL, each unit of WEEE has greater negative net CO_2 emissions than the mass of the device.

*Table 19: Net Emissions per item of WEEE collected. *The large range of items within the SMW stream make average item weight a misleading metric.*

WEEE Stream	Average Item Weight (kg)	Net emissions per item of WEEE ($kgCO_{2eq.}$)
Cooling	41.0	-76.9
Displays	14.8	-40.0
GDL	0.205	-0.00390
LHA	48.8	-99.6
SMW	N/A*	N/A*

5.2 Carbon footprint by supply chain stage

5.2.1 Stage 1: Collection and Transport to AATF

As shown above the first stage of REPIC's WEEE supply chain, collection, contributes a small amount to the overall carbon footprint, representing less than 8% of gross emissions for all streams, except for GDL where it contributes a far more significant 38%. Averaged across the WEEE streams, collection of WEEE emits 42.6$kgCO_{2eq.}$ per t WEEE, equal to 4.7% of gross emissions.

All the emissions from this stage are from the fuel in vehicles and ships, but the different types of collection are associated with different levels of emissions. Table 20 presents details of the different types of collection and details of their carbon footprint. WEEE is collected in out-and-back collections emits 39.5$kgCO_{2eq.}$ per t WEEE transported, and averages 212km round-trip travel distance. Milkround collection are slightly higher at 43.4$kgCO_{2eq.}$ per t. Collections with consolidation points have higher emissions of 102$kgCO_{2eq.}$ per t WEEE, but this is a result of longer travel distances, emissions per t.km are similar. Journeys with Ferries emit the most CO_2: 193kg per t WEEE. This is attributable to both the long travel distance, and the poor emissions per t.km of short-distance ferry travel; the ferry leg of the journey emits 60% of the total emissions for these journeys, despite only travelling 30% of the distance. The "other arrangements" journeys have the lowest emissions per tonne of WEEE, at 8.94kg$CO_{2eq.}$ per t WEEE – attributable to their shorter distance, and low emissions per t.km. These journeys either use bulk collections or fill excess capacity in vehicles already travelling, both of which reduce the emissions allocated to each tonne of WEEE.

Table 20: Different collection types and their proportion of REPIC's tonnage and carbon footprint information. Simple collections are where a single vehicle transports WEEE from the DCF to the AATF, either from a single DCF (out-and-back), or multiple DCFs (milkround) per journey. Collections with consolidation points are where one vehicle collects WEEE from the DCF, and transports it to a consolidation point where multiple collections are bulked before being transported to the AATF. Collections with ferries are where part of the journey is made by ferry, and can be simple or consolidated collections. "Other arrangements" represents bulk collections, from the 'limited data' section of REPIC's data.

	% of REPIC tonnage	% of total collection carbon footprint	kg CO2 per tonne WEEE	Average distance (km)	kg$CO_{2eq.}$ per t.km
Out-and-back simple collections	38.9%	45.0%	49.2	212	0.230
Milkround simple collections	13.1%	15.7%	54.1	226	0.239
Collections with consolidation points	9.21%	27.3%	127	526	0.240
Collections with ferries	0.307%	1.74%	240	612	0.394
Other arrangements	39.2%	10.2%	11.1	193	0.0573

The collection emissions vary between the different WEEE streams (Figure 18), with GDL being an order of magnitude greater than the other WEEE streams. There are several inputs that can change between WEEE streams including distance travelled, emissions per distance travelled and tonnage carried per vehicle. GDL has high emissions because each collection only transports a small amount of WEEE.

Collection emissions per tonne of WEEE transported also vary between different Local Authority (LA) areas in the UK. REPIC's full data recorded collections show a weak positive correlation (Correlation Coefficient r value = 0.419) between the distance to the AATF and the emissions from collection (Figure 19). Outliers from the trendline include LAs that use a ferry in their collections, whose emissions are higher than expected from the distance, and LAs where tonnage carried per collection is especially high or low, corresponding to lower and higher emissions than expected from the distance respectively.

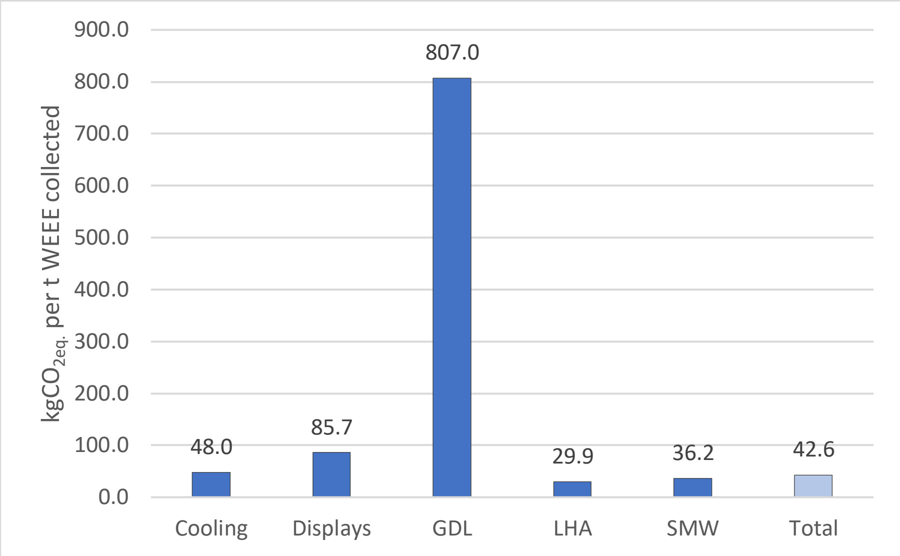


Figure 18: The emissions from collection per tonne of WEEE for each WEEE stream. The pale bar shows the average emissions for REPIC's 2019 WEEE.

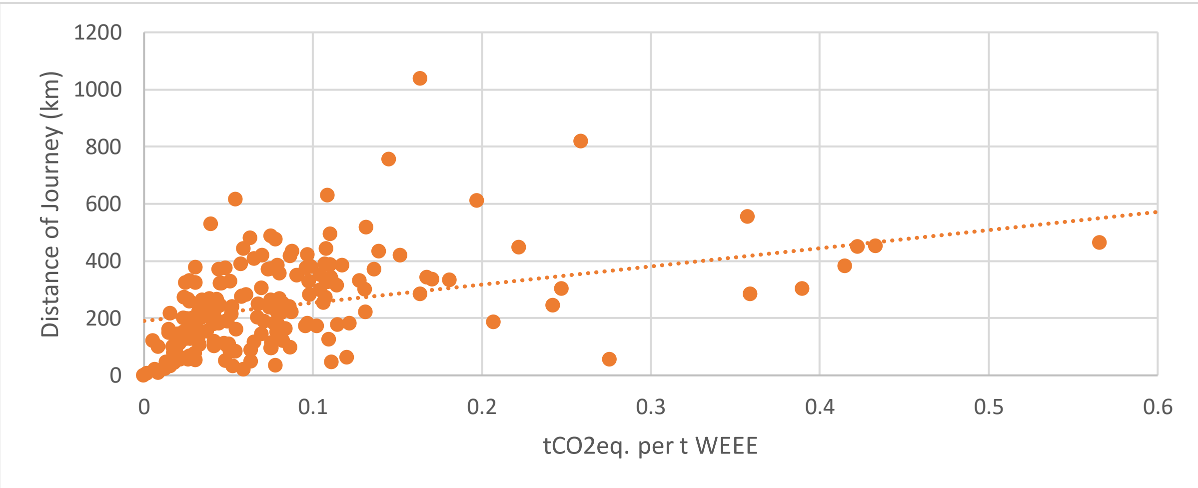


Figure 19: The emissions from collection per t of WEEE plotted against the average distance of the collection journey for each Local Authority Area. Regression line plotted with Correlation Coefficient r = 0.419.

5.2.2 Stage 2 – Pre-processing at AATF

The emissions from the AATF pre-processing stage are of similar magnitude per tonne of WEEE to the collection emissions, with an average value for REPIC's 2019 WEEE of 35.0kg$CO_{2eq.}$ per tonne of WEEE, equal to 3.9% of gross emissions.

AATF emissions in the model are from electricity, diesel and nitrogen usage, with the latter only for the cooling stream. Figure 20 shows the carbon footprint per tonne of WEEE for each WEEE stream, with the breakdown of the emissions from electricity production, diesel combustion and nitrogen production. Emissions from diesel show a narrow range between WEEE streams – a standard deviation of ±0.804kgCO$_{2eq.}$ around the mean of 7.36kg. Emissions from electricity usage show a far greater range, with a standard deviation of ±10.1kg around a mean of 16.9kg. The overall range of emissions is also large, with a standard deviation of ±21.0kg around a mean of 35.1kg, largely due to the high and low values from Cooling and GDL respectively.

Cooling has the greatest emissions per tonne from all 3 emissions sources, with the emissions from N_2 production or Electricity production alone being greater than the overall emissions from the other WEEE streams. GDL has the lowest emissions per tonne, close to an order of magnitude lower than that of Cooling WEEE. Interestingly this reverses the trend seen in the collection emissions where GDL had the highest and Cooling the lowest.

The AATF Emissions vary between different AATFs because of differing electricity, diesel and nitrogen usage (Table 21), by up to a factor of 2.7x. In section 5.4 the impact of the AATF technology on downstream emissions is presented, and far overshadows the difference in the emissions directly from the AATF stage. This is an example where improving one aspect of

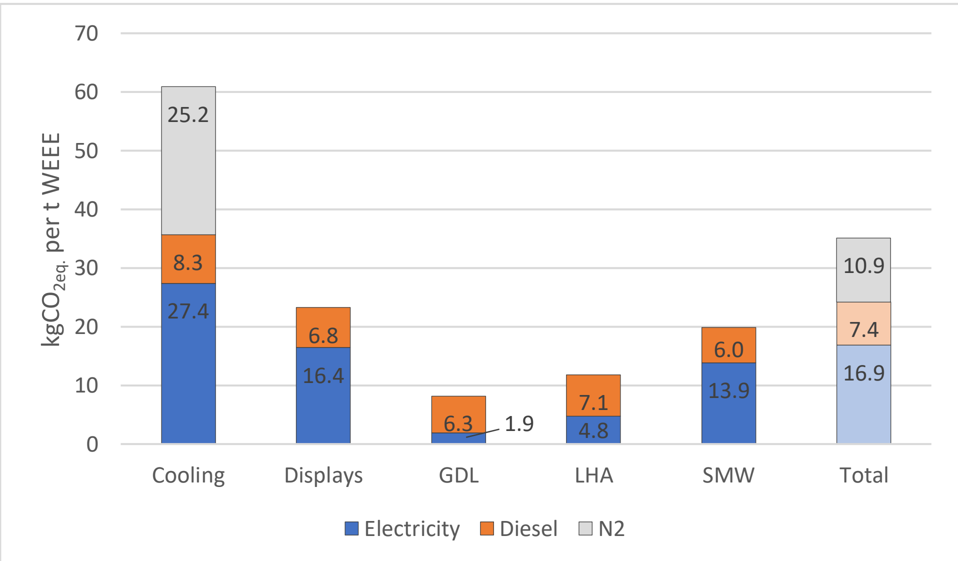


Figure 20: The AATF emissions for each WEEE stream, in kgCO$_{2eq.}$ per t WEEE, broken down into the contribution of electricity, diesel and nitrogen. Labels show the value for each source of emissions. The pale 'Total' bar shows the average emissions for REPIC's 2019 WEEE.

carbon footprint could worsen the overall footprint, i.e. if AATF carbon footprint is improved by changing technology, but the new technology has a lower recovery rate, the resulting overall carbon footprint will be worse.

Table 21: The minimum and maximum carbon footprint for pre-processing for each WEEE stream, $kgCO_{2eq.}$ per t WEEE.

WEEE Stream	**Cooling**		**Displays**		**GDL**		**LHA**		**SMW**	
Range	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
$kgCO_{2eq.}$ per t WEEE	42.5	70.2	17.2	41.5	8.2	8.2	11.1	17.7	17.2	36.8

5.2.3 Stage 3 – Transport to End-of-Life

Stage 3 of the WEEE treatment, the transport of WEEE to its end-of-life process from the AATF, is responsible for 3.9% of the overall emissions per tonne on average, with a value of 35.0$kgCO_{2eq.}$ per tonne of WEEE. Again, this is similar in magnitude to the emissions from the first 2 stages: Collection and Pre-processing. These first 3 stages combined only account for 12.5% of the overall emissions.

Emissions are from bulk carrier ships and road HGVs. Figure 21a shows the emissions per tonne of waste transported to each end-of-life process, and the contribution of road and shipping emissions. Transport to landfill has the lowest emissions, 16.1$kgCO_{2eq.}$ per t, due to it having the shortest travel distance. Recycling has the highest emissions, 37.3$kgCO_{2eq.}$ per t, due to the combined emissions of road transport and shipping that result from a highly international supply chain. Figure 21b shows the end-of-life emissions for the materials from each WEEE stream. Transport to recycling emissions are responsible for at least 80% of the end-of-life transport emissions for each stream, and 98% for GDL. This is mainly due to recycling being the most prevalent end-of-life process, but also contributed to by its higher emissions per t of material transported.

The end-of-life location for the WEEE materials varies from nearby landfill sites in the UK to circuit board treatment in Japan. Figure 22a shows the emissions of transporting a tonne of WEEE to different end-of-life locations, and the distance of transport. Road transport within the UK has 17x higher emissions per km than bulk shipping so, even when 151km of road transport on the UK side of the shipping is included, shipping to China has less than an order of magnitude more emissions than transport to UK landfill, and only 3x the emissions of transport to UK incineration, despite transport being 90x and 45x the distance respectively.

Figure 22b shows the breakdown of destination regions of the WEEE material, by % of 2019 total tonnage, and by % of the total end-of-life transport carbon footprint. 85% of the recycling tonnage is steel or plastic, so the destinations of these materials dominate. Over half of steel is recycled in mainland Europe, with the remainder evenly split between Asia and the UK. Plastic is also recycled in a mixture of UK, European and Asian countries. Transport to Asia is responsible for a greater proportion of the carbon footprint than its proportion of the tonnage – 26% of tonnage and 46% of emissions.

Individual WEEE residues tend to either be treated entirely in the UK for end-of-life, or have a diverse range of export locations spanning Europe and Asia. As such, no single material has the high carbon footprint of transport to East Asia, as some tonnage will also be transported to Europe or stay in the UK. The material with the highest average end-of-life transport carbon footprint is copper, with a value of 61.8kg$CO_{2eq.}$ per t material, and the lowest is for materials that are entirely kept within the UK. Funnel Glass has the lowest carbon footprint, with a value of 21.9kg$CO_{2eq.}$ per t material, as it predominantly goes to landfill in the UK.

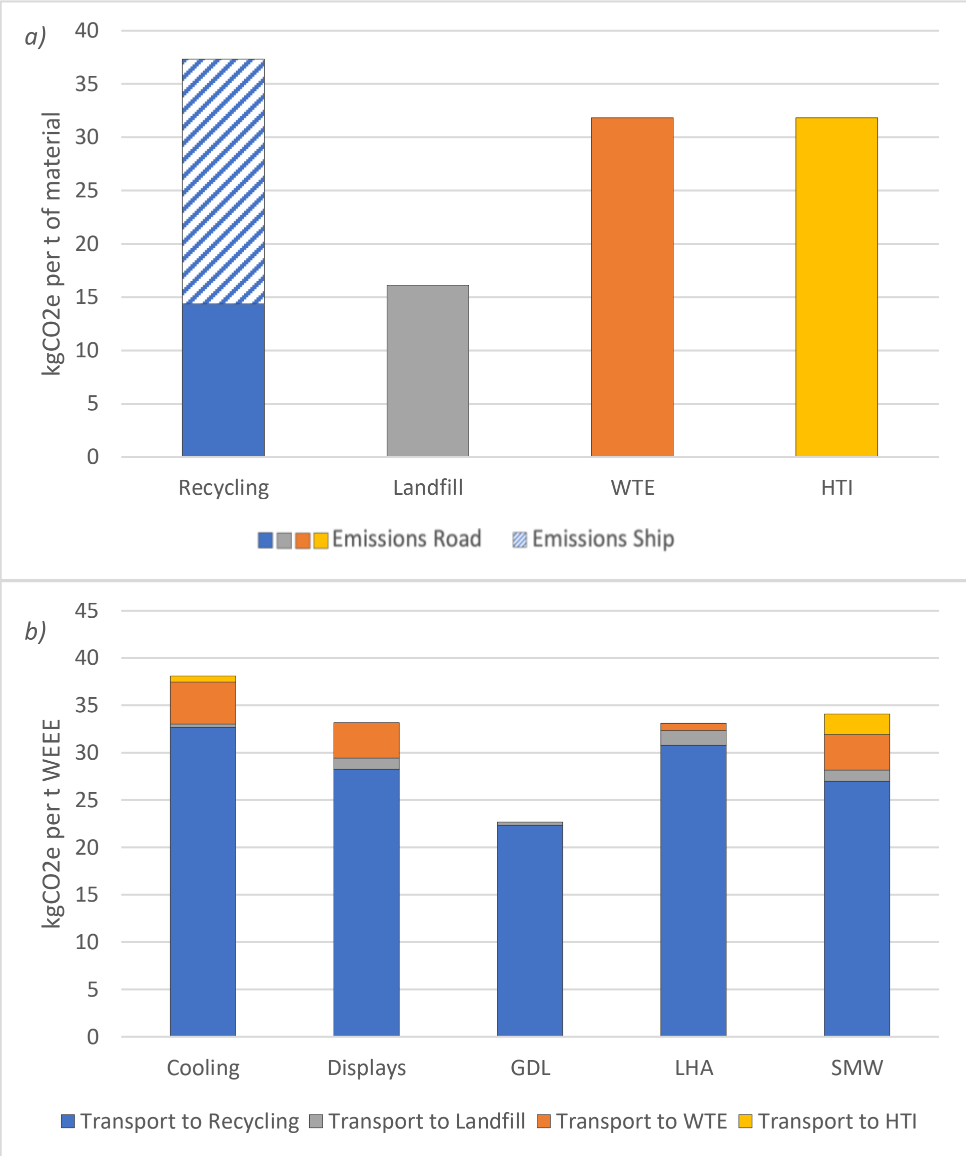


Figure 21:
a) The emissions of transporting 1 tonne of material to each of the different end-of-life processes, and the transport type producing the emissions.
b) The emissions of transport to end-of-life for each of the WEEE streams, per tonne of input WEEE, and the breakdown of the transport to different end-of-life processes.

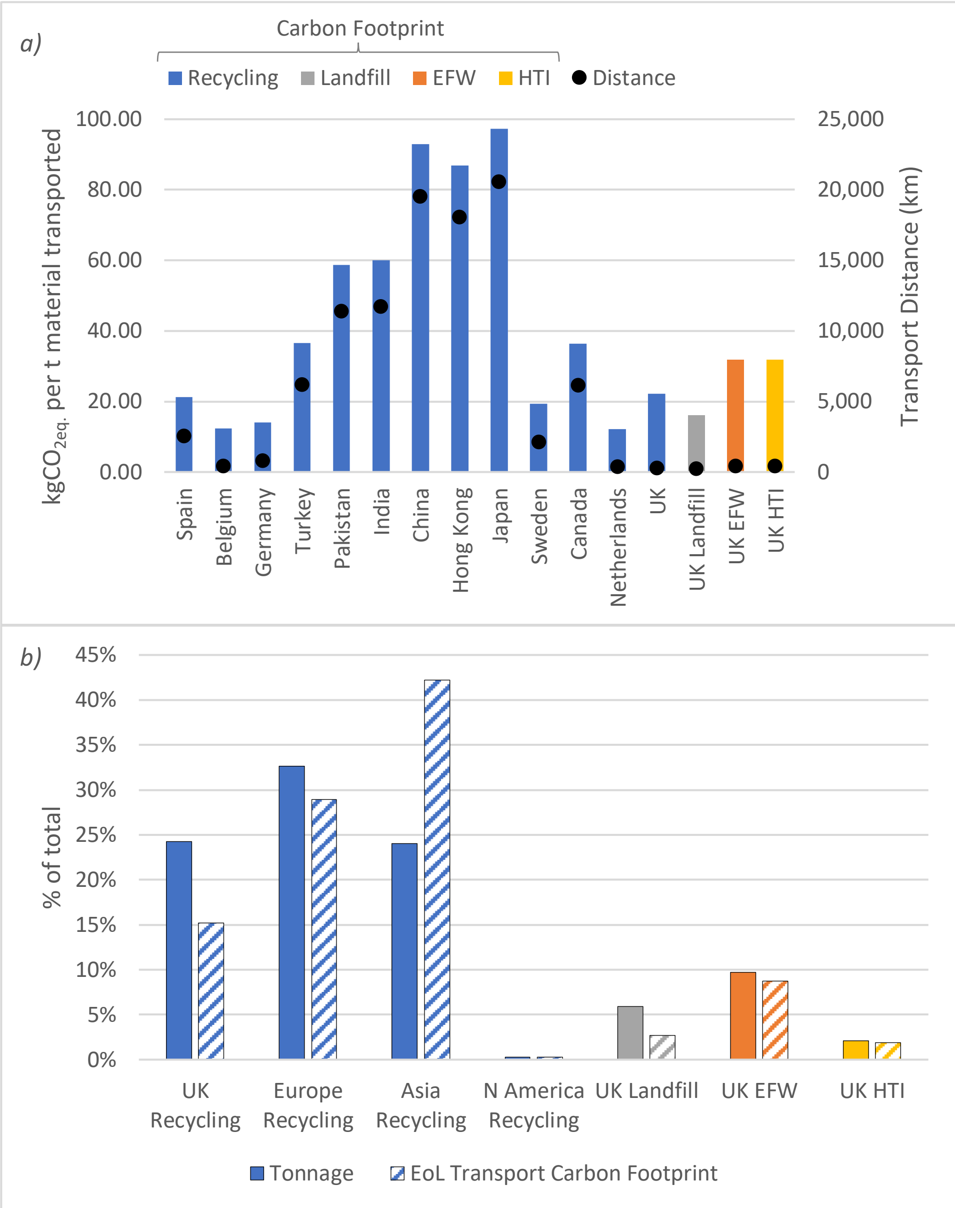


Figure 22:
a) The bars and left axis present the emissions per tonne of material transported to a range of countries around the world where the WEEE end-of-life process takes place. The points and right axis present the travel distance of transport to those countries.
b) The proportion of end-of-life WEEE tonnage (solid bars) and proportion of end-of-life transport carbon footprint (striped bars) for each end-of-life process, with recycling destinations split into 4 regions.

5.2.4 Stage 4: End-of-Life Process

The end-of-life process of the WEEE is responsible for most of the emissions of the WEEE supply chain, averaging 87.5% of the gross emissions. This corresponds to an average of 0.790t$CO_{2eq.}$ per tonne of WEEE, 19x the emissions of the next most emitting stage (collection). This average consists of 0.475t$CO_{2eq.}$ from recycling, 0.247t from EfW, 0.0512t from high-temperature incineration and 0.0169t from landfill.

Figure 23 displays the end-of-life emissions, broken down by each end-of-life process, for each WEEE stream, and for 1 tonne of average WEEE. For every WEEE stream, the recycling process accounts for over 50% of the emissions. As seen in the previous stages, GDL stands out as being different, here we see that glass recycling dominates GDL's carbon footprint, with the glass recycling process alone emitting more $CO_{2eq.}$ per tonne of WEEE than any of the other WEEE streams total end-of-life emissions. Glass makes up 85% of the mass of GDL, and has a reasonably high emissions recycling process, including dilution with virgin raw material, explaining this result. All the other WEEE streams have end-of-life emissions split across a range of different processes.

For the average WEEE composition, the recycling of metals produces the greatest CO_2 emissions of the different end-of-life processes. LHA is particularly dominated by metal recycling, due to its high metal content, and high landfill rate for the remainder of its composition. Landfill has the lowest average emissions per tonne of any of the end-of-life processes, so contributes little to the total carbon footprint. Non-metal recycling has emissions of greater magnitude than metal recycling for GDL, as discussed above, and for Displays, where circuit board recycling contributes 27% of the end-of-life emissions.

Figure 23 also shows that EfW contributes 31% of the end-of-life emissions. Cooling, Displays and SMW all have at least 25% of their emissions from EfW, with >95% of these emissions coming from plastics. Lower values for the other streams are due to GDL lacking plastic in the WEEE composition, and LHA only having 30% of plastic sent to EfW, with the majority going to landfill.

The final end-of-life process is high-temperature-incineration (HTI), responsible for 5.1% of Cooling and 15.5% of SMW end-of-life emissions. In SMW 29% of hazardous plastic is treated by HTI, and for Cooling, 100% of refrigerant gas is treated by HTI.

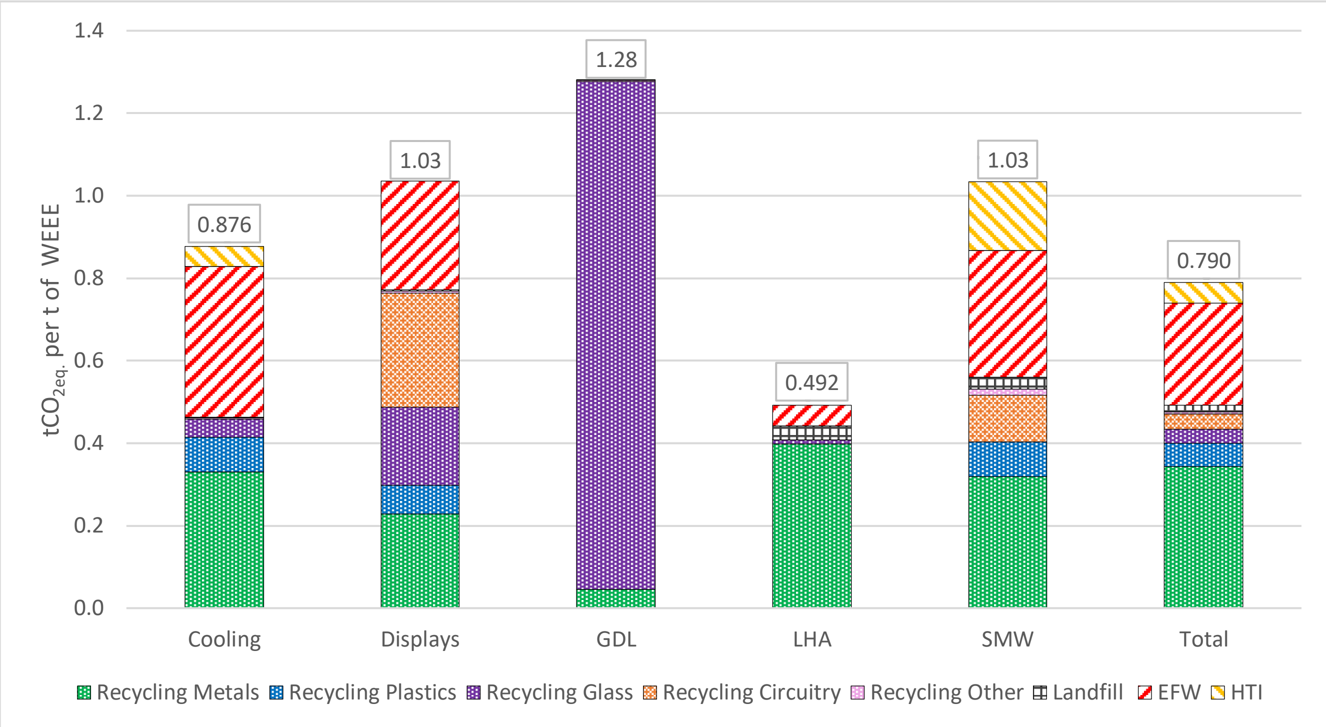


Figure 23: The $CO_{2eq.}$ emissions from each of the end-of-life processes, for the residues of each of the WEEE streams, per tonne of WEEE. The total $CO_{2eq.}$ emissions of end-of-life for each WEEE stream are displayed in the box above each bar.

Different AATFs recover varying amounts of materials from the WEEE and send varying amount of material to each end-of-life process. As a result, WEEE processed at different AATFs has different end-of-life emissions. Table 22 shows the range of gross carbon footprint from end of life between AATFs for each of the WEEE streams. A difference of up to 0.47t$CO_{2eq.}$ per tonne of WEEE can be observed for the output of different AATFs, for the same WEEE stream. This has a more pronounced effect on the avoided emissions, discussed in Section 5.3.

Table 22 – Range of gross carbon footprint of end-of-life process, per tonne of WEEE, for the outputs from different AATFs for each WEEE stream. GDL shows a range of 0 because only a single AATF reported high enough quality data to ascertain the material flow to end-of-life.

WEEE Stream	Cooling		Displays		GDL		LHA		SMW	
Range	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
t$CO_{2eq.}$ per t WEEE	0.67	1.0	0.92	1.08	1.28	1.28	0.51	0.57	0.79	1.26

5.3 Avoided Emissions

The material flow calculation outputs data on the amount of recycled material, energy-from-waste electricity and reused WEEE that the WEEE supply chain produces. These useful outputs of the WEEE treatment substitute the production of the same amount of virgin material and grid electricity, and avoid the associated carbon emissions.

1 tonne of WEEE, mixed in the proportion of REPIC's 2019 WEEE, produces 748kg of secondary material, 87.6kWh of electricity and 12.5kg of reused WEEE. The full breakdown of materials produced includes 1.81g of gold, 3.31g of palladium and 59.9g of silver (Table 23).

The avoided emissions resulting from these useful outputs exceed the $CO_{2eq.}$ emitted by the WEEE treatment process for all 5 WEEE streams, resulting in the net carbon saving. The average avoided emissions are -2.92t$CO_{2eq.}$ per tonne of WEEE. Figure 24 shows how the avoided emissions vary between WEEE streams, and how the source of the avoided emissions varies. The lowest avoided emissions are for the GDL stream, at -2.14t$CO_{2eq.}$, compared to the greatest avoided emissions of -3.85t$CO_{2eq.}$ for the Displays stream.

97.8% of the avoided emissions are from the recycling output. Apart from GDL, where the benefit is dominated by glass, the benefit comes predominantly from secondary metals – both those resulting from the recycled metals and recycled circuitry, which together are responsible for 80.2% of the avoided emissions. Recycled circuitry has a disproportionately large contribution relative to its proportion of mass due to the extremely high avoided emissions of the rare metals; as high as 48,000t$CO_{2eq.}$ per tonne of gold. Secondary plastic makes up a further 15.0% of the average tonne's avoided emissions and a further 2.65% is from the other secondary materials, mainly glass.

The electricity produced by energy-from-waste is only responsible for 1.5% of the total avoided emissions, despite being the end-of-life process for 11.8% of WEEE by mass and being responsible for 31% of gross emissions.

The reuse of WEEE is responsible for the remaining 0.7% of avoided emissions. Of the 5 WEEE streams, Displays is the only WEEE stream where reuse is responsible for >1% of the avoided emissions, at 3.7%. This is due to Displays having both the highest % of WEEE reused, and the highest avoided emissions per tonne reused.

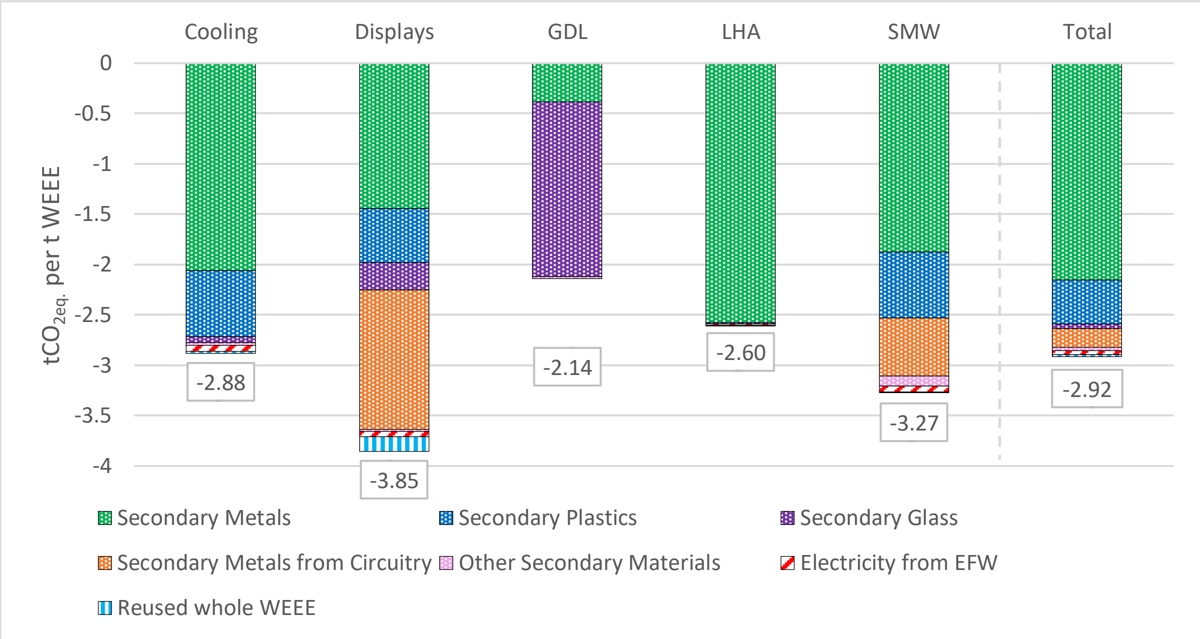


Figure 24: The $CO_{2eq.}$ emissions avoided as a result of the useful outputs of each of the WEEE streams, per tonne of WEEE treated. The avoided emissions are broken down into 5 broad categories of recycling, and energy-from-waste and reuse. The total avoided $CO_{2eq.}$ emissions for each WEEE stream are displayed in the box below each bar.

As alluded to in Section 5.2.4, there are differences in the avoided emissions when WEEE is processed in different AATFs, due to the different recovery rates and amounts sent to each end-of-life process. Table 24 shows the range of avoided emissions between AATFs for each WEEE stream. Whereas the largest range between AATFs in gross emissions from end-of-life was 0.47$tCO_{2eq.}$, the largest range in avoided emissions is 1.94$tCO_{2eq.}$, between the best and worst Displays AATF. The comparison in Displays avoided emissions may not be just comparing AATF performance, because some AATFs specialise in older cathode-ray tube TVs or newer flat panel TVs, leading to a fundamentally different material composition. A more appropriate comparison would be the next largest range – seen in SMW, with a range of 1.37$tCO_{2eq.}$. As a result of this large range, the AATF that WEEE is sent to can lead to a very different net carbon footprint. The significance of this is further investigated in Section 5.4 (Sensitivity Analysis) and Section 5.5 (Optimisation).

Table 23: Amounts of secondary material produced from 1 tonne of each WEEE stream. Materials and Reuse in kg, Electricity in kWh.

	Cooling	Displays	GDL	LHA	SMW
Steel	483	319	0	662	347
Stainless Steel	6.7	0.1	0	7.0	4.9
Copper	22.5	33.5	0	8.14	48.4
Aluminium	8.74	19.9	53.0	8.60	17.5
Other non ferrous	5.85	5.41	0	0	25.9
Hazardous Plastic	0.0	0	0	0	127
Non-Hazardous Plastic	162	145	0	0	48.7
PU Foam	9.90	0	0	0	0
Glass	48.6	0	1377	11.2	0
Panel Glass	0	166	0	0	0
Funnel Glass	0	47.1	0	0	0
Batteries	0	0	0	0	6.5
Residue	6.23	4.64	4.53	0	3.05
Small Appliance Fines	0	0	0	0	23.0
Oil	3.0	0	0	0	0
Concrete	0	0	0	93.1	0
Wood	0.0824	0	0	0	0
Mercury fraction	0	0.00727	0.440	0	0
Other whole waste	0	0.373	0	0	0
Lead	0	1.31	0	0	0.489
Nickel	0	2.74	0	0	1.02
Silver	0	0.460	0	0	0.171
Gold	0	0.0140	0	0	0.00519
Palladium	0	0.0255	0	0	0.00947
Reused WEEE	18.1	53.1	0	2.96	2.46
Electricity	117	113	0	21.8	126

Table 24: Range of avoided emissions, in $tCO_{2eq.}$ per tonne of WEEE, for the outputs from different AATFs for each WEEE stream. GDL shows a range of 0 because only a single AATF reported high enough quality data to ascertain the material flow to end-of-life.

WEEE Stream	Cooling		Displays		GDL		LHA		SMW	
Range	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**	**Min**	**Max**
$tCO_{2eq.}$ per t WEEE	-2.82	-3.25	-2.66	-4.60	-2.14	-2.14	-2.22	-3.12	-2.89	-4.26

5.4 Sensitivity Analysis

The results of a sensitivity analysis testing the sensitivity of the output to each of the inputs to the model is outlined in this section. Knowledge of this sensitivity is useful to understand where the greatest impact can be made in improving the carbon footprint, and also illustrates how sensitive the model is to inaccurate inputs.

Figure 25 shows the % change in the average net carbon footprint with a $\pm$10% change to all the data inputs in each supply chain stage. The sign of the 10% change made to each input was adjusted so that ‘+10%’ corresponded to a higher (worse) carbon footprint output, and ‘-10%’ corresponded to a lower (better) carbon footprint, to stop changes cancelling each other out. The main finding is that the output is most sensitive to changes in the avoided emissions and end-of-life stages, with a 14% change and 4% change in the output respectively when a 10% change to the input is made. The earlier stages of the supply chain have a sensitivity an order of magnitude lower – collection having a change of 0.44%, AATF 0.16% and EoL transport 0.13%, when a 10% change to the inputs is made.

Figure 26 shows the single inputs that the output is most sensitive to, with only three inputs resulting in a sensitivity of >1%. The remainder of the inputs, as listed in Table 25, all have a sensitivity of <0.25%, so changes to these inputs only have small effects on the output. The range in sensitivity of the output to a 10% change in input is from 0.0273% for AATF diesel usage, to 14.0% for the avoided emissions factor for recycling. This demonstrates how a small number of the inputs have a high share of the determination of the output.

Most of the carbon calculator inputs change the output linearly to changes in the input, so the sensitivity values can be scaled up to see the change in output that would result from changes in input other than 10%.

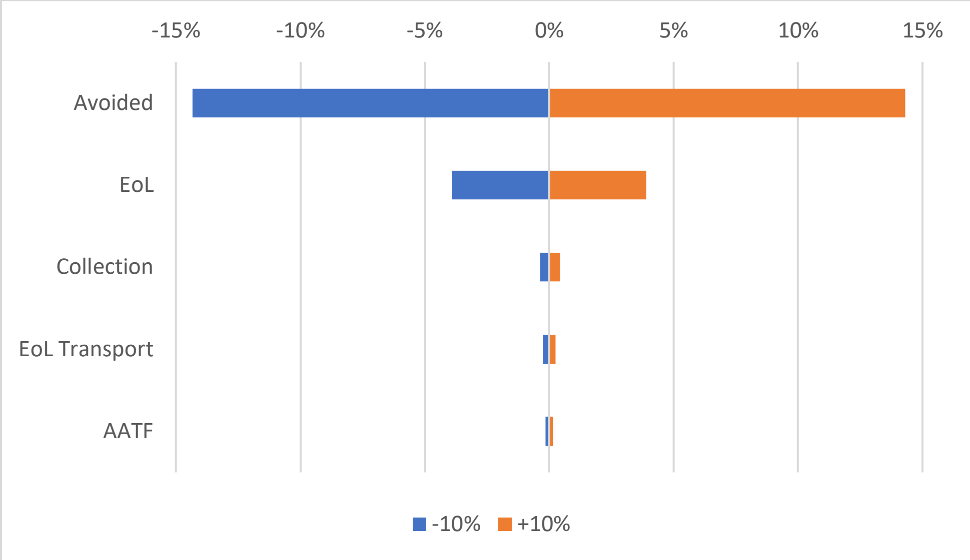


Figure 25: Comparison of sensitivity of average net carbon footprint to changes in the inputs of each supply chain stage. Values are a % change of the average net carbon footprint.

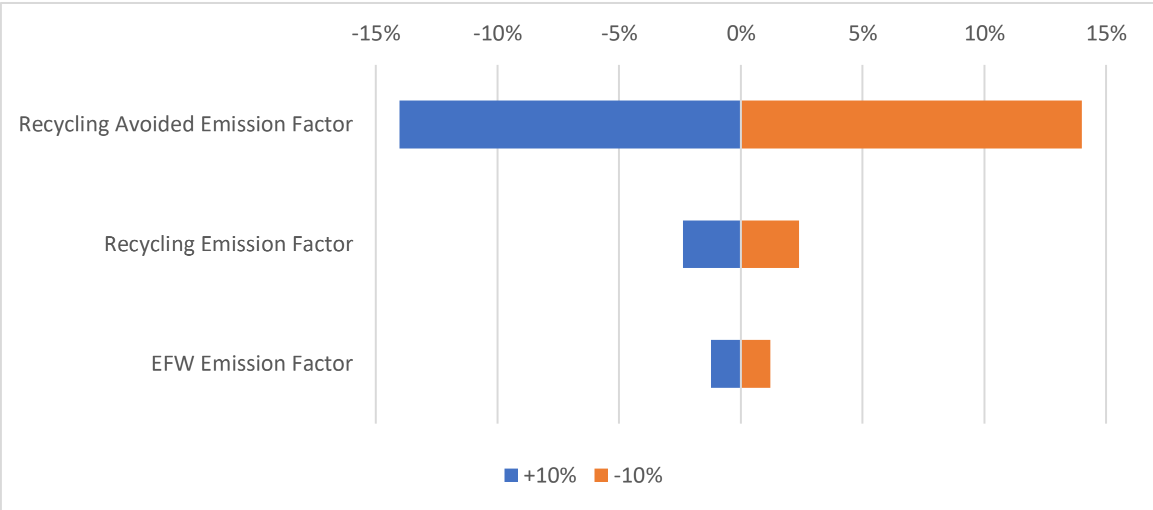


Figure 26: The sensitivity of the output carbon footprint in % change when individual inputs are changed by +/-10%. Only the inputs that change the output by >1% are displayed.

Table 25: Inputs that had sensitivity of <0.25%

Collection vehicle fuel efficiency
Collection distance
% of collection allocated to REPIC
% of journeys using backloading
AATF electricity usage
AATF diesel usage
AATF nitrogen usage
End-of-life shipping distance
End-of-life shipping emissions factor
End-of-life road distance
End-of-life road emissions factor
Landfill emissions factor
EfW avoided emissions factor
Reuse avoided emissions factor

Figure 27 assesses the sensitivity of the output carbon footprint to the choice of AATF. The comparison is made between the carbon footprint when the best AATF is used for each stream, in terms of overall downstream carbon footprint, to that when each stream uses the AATF with the worst downstream carbon footprint (Table 26). The only differences between the AATFs in the comparison are the AATF's own emissions, the material composition of their output and the proportion of each material sent to each end-of-life process. This comparison shows a large range of the output carbon footprint, larger than any of the 10% changes in the inputs. The difference in carbon footprint between using the best and worst AATFs, averaged across the 5 WEEE streams, is 0.83t$CO_{2eq.}$ per tonne of WEEE. This difference, of >40% of the net carbon footprint, shows us that the intra-AATF difference in material composition and recovery rate is highly important in the overall carbon footprint.

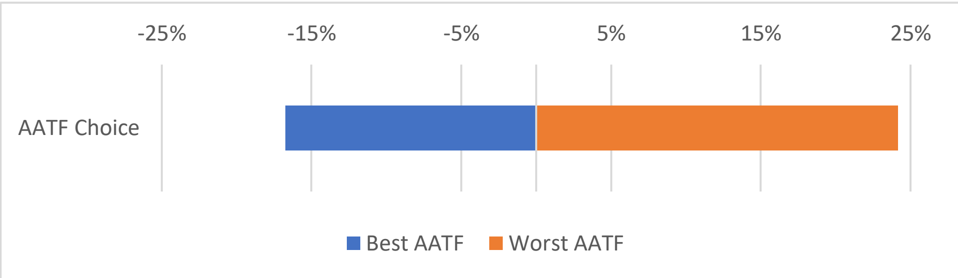


Figure 27: % change in the average net carbon footprint from the 2019 scenario to a scenario if every WEEE stream only used the AATF that results in the best or worst carbon footprint.

Table 26: The output carbon footprint when the best and worst performing AATFs are selected in terms of downstream emissions.

WEEE Stream	**Cooling**		**Displays**		**GDL**		**LHA**		**SMW**	
Range	**Worst**	**Best**	**Worst**	**Best**	**Worst**	**Best**	**Worst**	**Best**	**Worst**	**Best**
t$CO_{2eq.}$ per t WEEE	-1.82	-2.36	-1.65	-3.52	-0.86	-0.86	-1.74	-2.62	-1.72	-3.04

5.5 Optimisation of AATF Allocation and Vehicle Routing

The results of the optimisation model, tested on the cooling stream, are split into two sections. The AATF allocation optimisation, which assessed the carbon footprint when different AATFs were allocated to each DCF's WEEE, and the vehicle routing optimisation, which used the results of the AATF allocation and planned routes to collect the WEEE that minimised the carbon footprint from transport.

The AATF allocation results showed that optimisation based on either distance or overall CO_2 both result in improved net emissions compared to the current REPIC allocation, with and without constrained capacities of AATFs implemented (Figure 28). The best net emissions are reached when no AATF capacity constraints are in place and the objective of the allocation is to minimise the net supply chain carbon footprint, achieving net emissions of -2.08 per tonne of Cooling WEEE, a 12% improvement over the actual 2019 situation. This scenario resulted in all the UK's WEEE being sent to 1 of 2 AATFs, whose downstream carbon benefit exceeded the high transport emissions of receiving WEEE from distant DCFs, and the other 17 AATFs receive no WEEE at all. Changing the objective to only minimising the transport distance, as in conventional vehicle routing optimisation, resulted in a lower improvement of 6%, and spread the WEEE across all 19 of the AATFs.

Adding a capacity to each AATF in the optimisation, of 1.2x the WEEE each AATF treated in 2019, resulted in much smaller improvements over REPIC's 2019 situation. This resulted in an improvement of 2.7% for the capacitated total carbon footprint optimisation and 2.6% when only distance was optimised (Figure 28). In both capacitated cases, WEEE is sent to all 19 AATFs.

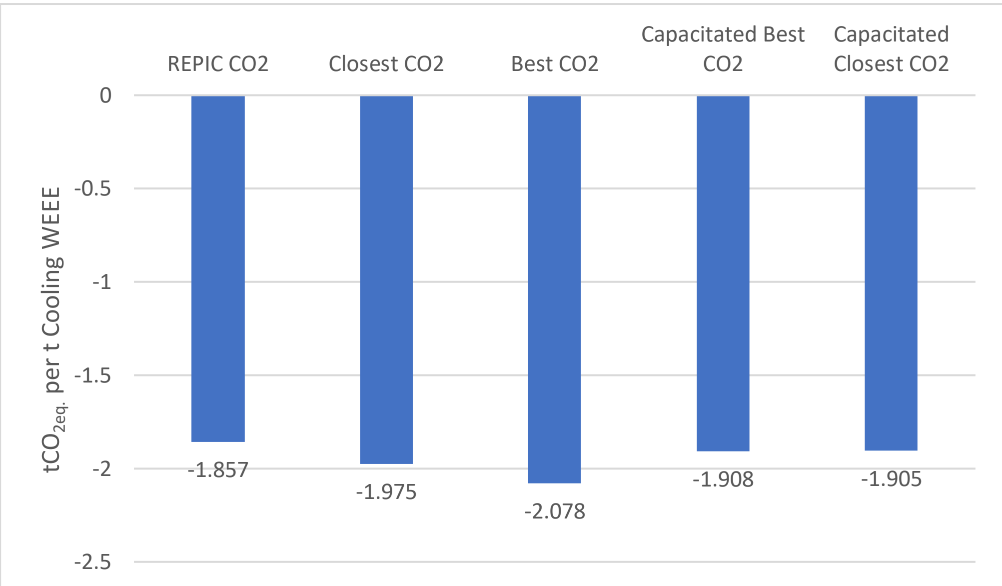


Figure 28: The net carbon footprint per tonne of Cooling WEEE, with the different allocation techniques.

Figure 29 shows the effect of different AATF capacity multiplication factors on the optimised carbon footprint. As the multiplication factor increases, more WEEE is sent to AATFs with the best performance, and the net carbon footprint improves. As discussed in Section 3.4.4, a factor of 1.2x was chosen based on discussion with REPIC considering the short-term inflexibility of AATFs to changes in quantity received from each producer compliance scheme (REPIC 2022, personal correspondence, 11th March).

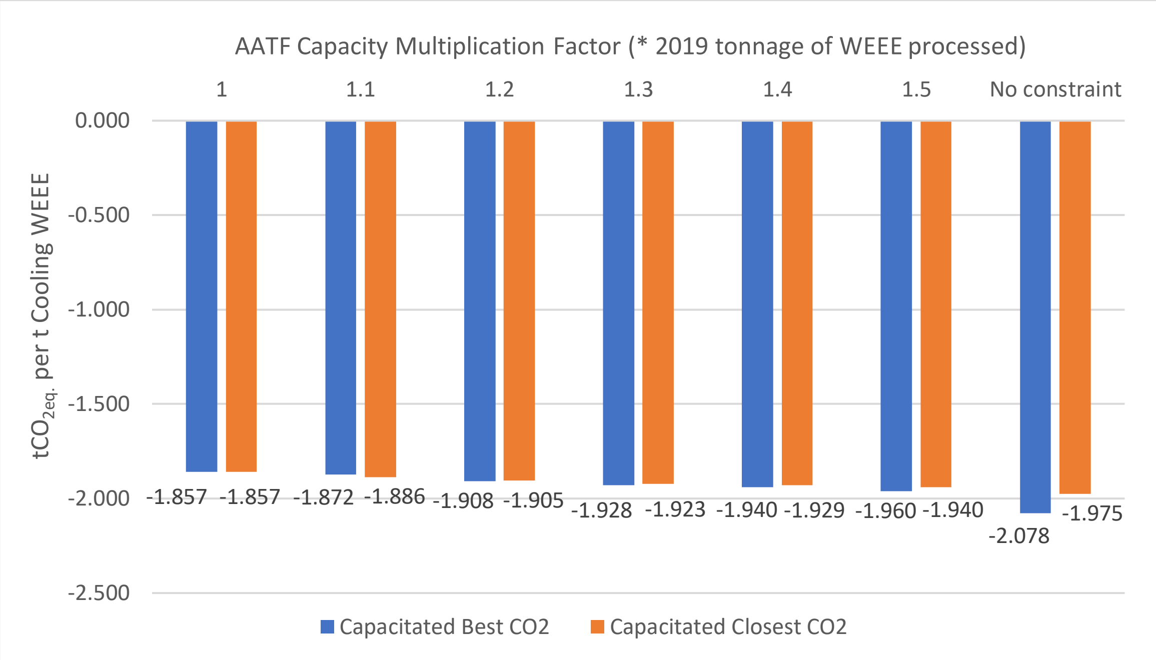


Figure 29: The impact of different AATF capacity multiplication factors on the net carbon footprint per tonne of Cooling WEEE. In blue is AATF allocation aiming to minimise overall CO2 ('Best'), and in orange, allocation minimising just the CO2 from transport ('Closest').

The increase in collection distance when AATFs are allocated based on net carbon footprint would increase the cost of transport, as haulage costs are closely related to distance. Dual objective optimisation with different weightings towards minimising total carbon footprint and minimising distance shows the trade-off between them. In Figure 30, the results of a dual objective optimisation are shown with 11 steps in weighting of the objectives: the two extremes are a weighting that makes the objective only minimising the net carbon footprint, and a weighting that only minimises the distance between the DCFs and their allocated AATFs. The line joining the points represents the Pareto frontier where no improvements can be made to one objective without worsening the other. As the weighting changes from just distance towards just carbon footprint there is an initial steep improvement in net carbon footprint with little increase in distance, which gradually levels out to instead have a small improvement in carbon footprint with a large increase in distance. This indicates that the marginal improvement in net carbon footprint per increase in distance, and cost, becomes worse as the weighting of the carbon footprint optimisation increases. The range is 103kg$CO_{2eq.}$ for total emissions and 120km for collection distance.

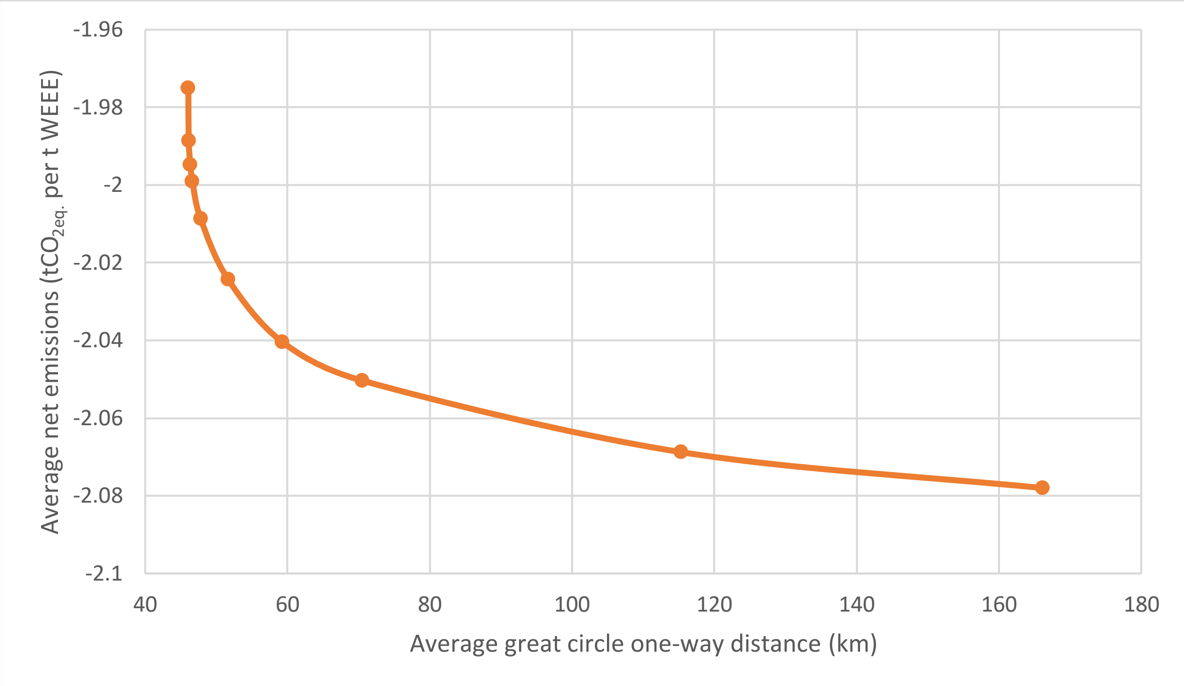


Figure 30: A weighted dual objective optimisation, without capacity constraints, between total emissions and collection distance for the Cooling WEEE Stream in 2019. Average distance is the mean great-circle distance between the DCF and the AATF for all the DCFs. The line represents the Pareto Frontier.

The second stage of the optimisation planned routes for vehicles to collect the WEEE from the allocated DCFs for each AATF, over one whole year based on 2019 data. The aim was to minimise the carbon footprint from the transportation, by minimising the number of journeys and the distance of each journey. Collecting in milkrounds where several DCFs have their WEEE collected in a single vehicle journey reduces the number of journeys compared to the baseline of single DCF out-and-back journeys. Creating milkrounds collecting from DCFs with similar periodicity led to an average of 2.6 DCFs being collected from on each journey. When the DCF order within each route was just based on periodicity the carbon footprint from transport is reduced by 14.3% compared to out-and-back collections (Figure 31). Applying a local search improvement heuristic to minimise the distance of each route by changing the order of the DCFs further reduces the carbon footprint from transport, to an average of 22.5% below the single journey scenario. Due to the stochastic nature of the heuristic, these values were calculated by the mean of 10 runs of the model. It was noted that the 100,000-iteration improvement heuristic failed to further improve the routing beyond 600 iterations (Figure 32).

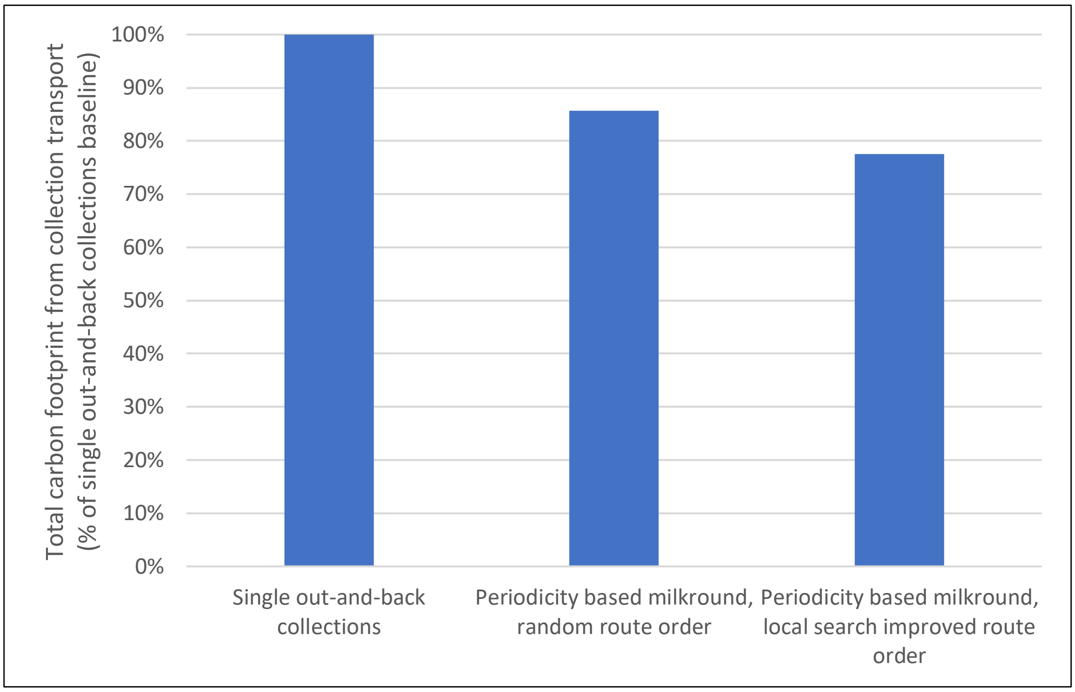


Figure 31: A comparison of different options for route planning for the collections, based on carbon footprint of collection transport.

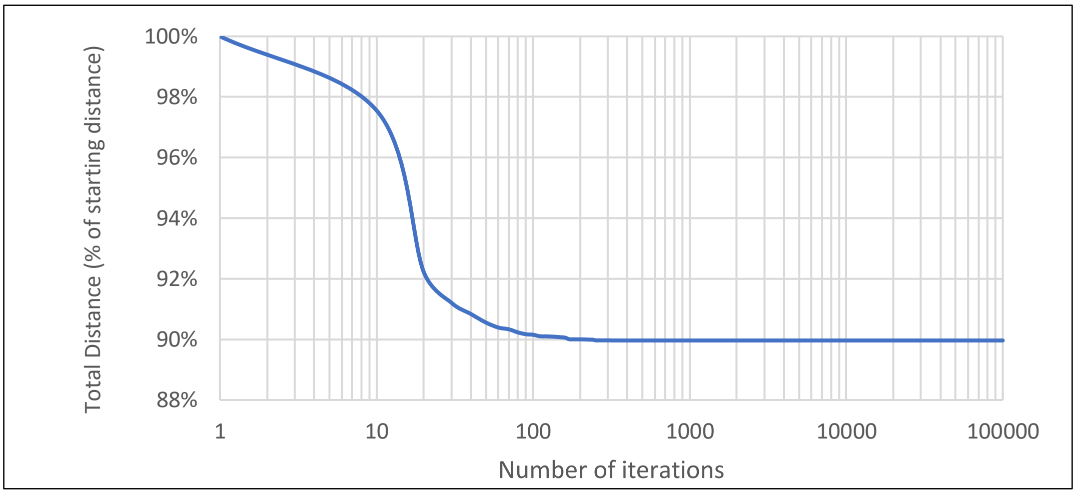


Figure 32: Progress of the improvement heuristic over 100,000 iterations. Data is a composite of 10 runs of the heuristic and on a log scale x-axis for clarity. No further improvement is achieved after 600 iterations.

6 Discussion

This chapter presents the key findings of the research, and discusses interpretations of the results, including how the knowledge gaps highlighted in Chapter 2 have been addressed. The implications of the research from an academic and an industry standpoint are also discussed.

6.1 Key Findings

This study set out with the aim of creating a model that calculates the carbon footprint of REPIC's WEEE treatment supply chain. We produced a model that takes REPIC's data on WEEE collection and treatment in 2019 and combines it with primary data sought from questionnaires and secondary data from the Ecoinvent LCI database to model the WEEE supply chain. The model addresses the gap in the UK WEEE literature for an accurate carbon footprint that makes use of primary data, includes reuse of WEEE and covers all the main WEEE streams. The format of the model makes it updatable with future data.

The modelling of REPIC's supply chain successfully allowed a carbon footprint to be ascertained for the WEEE that REPIC collected evidence for in 2019. The overall carbon footprint output from the model showed that REPIC's WEEE processing has negative net emissions, saving more than twice the weight of CO_2 than the weight of WEEE treated. While the net emissions per tonne of WEEE varied between the 5 WEEE streams, a negative net emissions figure is reached in all cases. The level of data granularity in the model allows identification of where in the supply chain sources of the emissions, and the emissions avoidance, are found, and how they vary between different local areas or operators in the supply chain.

The output of the carbon calculator model allowed optimisation modelling of Approved Authorised Treatment Facility (AATF) allocation and vehicle routing. Allocating AATFs with the objective of maximising carbon benefit rather than distance or REPIC's current allocation results in an increase in the carbon saving of the WEEE treatment, and solving a vehicle routing problem for the WEEE collections reduces the distance travelled and the resulting carbon footprint.

6.2 Interpretation

6.2.1 Overall Carbon Footprint

The main carbon footprint results show that, from a global warming perspective, the recycling of WEEE in REPIC's supply chain is highly beneficial. This confirms the consensus view in the literature, and the findings of the previous UK based studies from Clarke et al. (2019) and Turner et al. (2015). While sharing the overall benefit conclusion, these studies show a less beneficial net carbon footprint than our model – Clarke stating a net footprint of -0.85t$CO_{2eq.}$ per t WEEE, and Turner stating a range from -0.22 to -1.3t$CO_{2eq.}$ per t WEEE. The more detailed EU studies on authorised WEEE disposal show closer results to our own. Wäger et al. (2011) in Switzerland show -2.1t net emissions when compared to landfill, and 0.96t gross emissions, Biganzoli *et al.* (2015) in Italy show a range from -0.826 to -2.187t$CO_{2eq.}$ and Baxter et al. (2016) in Norway show a range from -0.408 to -6.14t$CO_{2eq.}$ per t WEEE.

For interpreting why our model gives a greater emissions saving than the closest other study, Clarke (2019), an evaluation of the differences to Clarke's model was undertaken. Clarke's emissions factors for collection and pre-processing at the AATF are within 10% of the values in our model and only small differences are found in the transport to end-of-life values where Clarke's model assumes all material stays in the UK. The main source of difference is at end-of-life where Clarke assumes recycling rates of less than 50% for metals, less than 20% for plastics and 0% for PCBs, glass, cable and batteries. This differs from the 81% of waste going to recycling in our model, which was based on primary data from AATFs in the UK. There is also a difference in database values, with Clarke using data from sources dating 2007-2010 and crucially, for the most prevalent material – ferrous metal, the avoided emissions value is for substituting pig iron rather than steel. Pig iron production emits 1.75t less CO_2 per tonne than producing steel (ecoinvent, 2021) and since the recycling process of ferrous metal in an electric arc furnace produces steel, the higher avoided emissions factor for steel production should be used, as it is in our study. Adjusting the recycling rate to 81% as in our data, including circuit boards, glass and cable, would more than double the avoided emissions, and setting the ferrous metal avoided emissions to the Ecoinvent 3.7 value for steel would increase the total avoided emissions by 66%. These changes would result in Clarke's conclusion carbon footprint being <-2.0tCO_2 per t WEEE, so appear to explain the difference from our model. This highlights the sensitivity of the model to recycling rate and avoided emissions, especially those of ferrous metal – which in our model made up 58.5% of the WEEE.

The remainder of Section 6.2 interprets individual aspects of the results, including how the results address the debates highlighted in Section 2.4.

6.2.2 Optimisation of AATF Allocation and Vehicle Routing

The results of the optimisation showed that improvements to net carbon footprint of the WEEE supply chain are possible by improving the AATF allocation and by routing the vehicles based on milkrounds that pick up from Designated Collection Facilities (DCFs) with similar required collection frequency.

The optimisation of AATF allocation resulted in the greatest improvement when there was no limit on AATF capacity and the objective was to minimise the net carbon footprint that results from each DCF:AATF pairing, including the carbon footprint of collection, pre-processing, downstream emissions and carbon benefit. This improved the net carbon footprint by 11.8%, but resulted in WEEE only being allocated to the two AATFs with the best downstream emissions, regardless of their distance from the DCF. Applying this solution would face issues with the limited capacity of AATFs and would increase financial and other environmental costs due to the longer transportation distances required. Two alternative ways of optimising the allocation addressed this – by adding AATF capacity constraints, and/or by having a dual objective to minimise both net carbon emissions and distance travelled. The capacitated version can be seen as a solution that would be possible in the short term, without major changes to AATFs, and achieves a 2.3% improvement over REPIC's 2019 allocation and sends WEEE to closer AATFs. The dual objective version shows that if a small sacrifice of net emissions improvement is made, the transportation distance can be greatly reduced –

compared to just optimising net carbon footprint the carbon footprint improvement reduces from 11.8% to 10.4% benefit, while the distance travelled reduces from 166km to 70km. In the longer term, a further conclusion that can be drawn from the improvement in carbon footprint when WEEE is sent to the highest-performing AATFs is that legislation to require a higher recovery rate at all AATFs could achieve improvements in carbon footprint.

The second phase of the optimisation, to improve the vehicle routing, achieved on average a 22.5% reduction in transportation distance compared to single out-and-back collections. Assessing the optimality of solutions produced by heuristics is another field of research in its own right, so we cannot ascertain how close to optimality the solutions were. The hillclimbing heuristic used is unable to escape local optima, so it is possible that further improvements could be achieved if a heuristic that is not stuck at local optima is used. The impact of these improvements on the overall carbon footprint is low, a 22.5% distance reduction corresponding to a 0.4% improvement to the net carbon footprint for cooling, but as discussed above, distance travelled has implications for financial cost, and other environmental impacts such as air pollution, which would be improved with reduced distance.

The use of these results in practice is limited by the reliability of data collected from the AATFs. AATFs indicated that the data they supplied was not regularly collected and that calculation methodology was likely to vary between AATFs. As such, the results which indicated that sending WEEE to certain AATFs resulted in an improved net carbon footprint are not robust enough to be used for commercial decision making, nor was this an intention that was stated when the data was collected. Instead, the results should be taken as an example of the carbon footprint improvements which may be possible with the outlined methodology. For future use of optimised allocation and vehicle routing, more reliable data must be collected that is comparable between AATFs. It is also worth noting that in the short term there is limited capacity for WEEE pre-processing at AATFs in the UK, if REPIC were to re-allocate to the best-performing AATFs, other WEEE may then fill the vacated capacity at the worse-performing AATFs, resulting in no overall change in emissions for the treatment of the UK's WEEE. With a longer-term view, if the worse-performing AATFs are losing business, they will be incentivised to improve their performance. The evidence of a carbon footprint improvement when AATFs have higher recovery rates could also lead to changes in UK legislation to require a higher recovery rate.

6.2.3 Outliers in the Data

Within the model, several outliers stand out from the rest of the data. The Gas Discharge Lamp (GDL) WEEE stream has higher gross emissions and lower avoided emissions compared to the other streams. This is partly explained by GDL's different material composition to the other waste streams, being predominantly glass, with little metal or plastic (Section 4.1). Glass has relatively low avoided emissions relative to its gross emissions; the glass recycling process, as modelled in Ecoinvent, dilutes the scrap with virgin raw materials at a roughly 60:40 ratio, increasing gross emissions of the recycling, and the glass primary production produces less emissions than metal or plastic production, reducing avoided emissions. GDL also stands out in the earlier stages – with high collection emissions and low AATF emissions. The collection data for GDL looks unusual, with only very low tonnages carried per journey – contributing to the high emissions. The AATF emissions factors are also unusual – an order of magnitude lower than the average of other streams' AATF emissions. The low sample size (of 1) for the GDL haulier and AATF questionnaire responses makes it difficult to ascertain if the data is representative of all GDL hauliers and AATFs. Given the very small contribution of GDL to the overall tonnage, both for REPIC and the UK (Environment Agency, 2021d), and the limited time available for data collection, this was not followed up in greater detail. If the carbon footprint of GDL is to be focused on individually, further responses should be sought from GDL hauliers and AATFs to assess the representativeness of our data source.

The Large Household Appliance (LHA) stream also stands out – with low gross emissions and somewhat low avoided emissions. This is mainly attributable to more material going to landfill, where in other streams it would go to energy-from-waste and recycling, and landfill in the model has low gross and no avoided emissions (See section 6.2.7). The concrete fraction of LHA also shows similar characteristics when recycled, of low gross and low avoided emissions.

6.2.4 The Impact of Transport

One of the debates discussed in Section 2.4 is how much impact the transportation of WEEE has on the carbon footprint. The small proportion of the overall carbon footprint that is attributable to transport of WEEE, both at the collection stage (4.7%) and at the transport to end-of-life stage (3.9%), concurs with Baxter *et al.* (2016) and Wäger et al. (2011) in its conclusion that WEEE transport is a minor constituent of the carbon emissions. A different metric for assessing the impact of transport is to calculate the distance of transport required to negate the carbon benefit of the rest of the supply chain, termed the breakeven distance. REPIC's WEEE breakeven distances are far longer than any feasible transport, highlighting how transportation has low impact relative to the overall benefit: 8,942km for collection transport using out-and-back collections, or 27,700km of road/485,000km of shipping for end-of-life transport, assuming in both cases that the other transport stage is kept at average values. This is contrary to Xiao et al. (2016) who concluded a breakeven distance of 590km applied for WEEE transport in China. The difference is explained by the Chinese system having worse initial net emissions, with no CFC capture and coal-powered electricity, and higher emissions from transport than the UK, using electric trains running on coal power. The relative insignificance of the transport distance to overall emissions is also exemplified by our AATF allocation optimisation with the objective of minimising CO_2 which transports all WEEE to one of two AATFs with the best recovery rate, regardless of distance, because the carbon benefit of more material being recycled outweighs the added transport emissions.

6.2.5 The Impact of Pre-Processing

The second debate from Section 2.4 is whether or not pre-processing has a large impact on the carbon footprint. Our results show the emissions from pre-processing only contribute 3.9% to the gross emissions, but also that pre-processing has a strong influence on the gross and avoided emissions downstream in the supply chain. The results of the sensitivity analysis between the best and worst-performing AATFs in terms of downstream emissions showed dramatic differences in the overall carbon footprint, of >40% of net emissions. The sources of difference between the AATFs in the sensitivity analysis are the emissions from the AATFs themselves, the material composition of their output fractions, and the % of each fraction that goes to each end-of-life process (recycling, energy-from-waste (EfW), landfill or high-temperature-incineration (HTI)). The material and end-of-life differences underly the influence of the AATFs on the carbon footprint. The end-of-life processes contribute most of the gross and avoided emissions, and there are large differences in emissions between each material and each end-of-life process. AATFs with high recycling rate and/or low EfW rate result in the best overall emissions. These results support the argument of Unger et al. (2017) who highlighted the importance of AATF recovery rate to carbon footprint. The improvements of carbon footprint seen in the optimisation allocation of up to 12% also rely on differences between AATFs. So, while our findings showing low emissions directly from the pre-processing stage agree with Hischier's 2005 and 2011 findings, the downstream influence means that our findings disagree with Hischier's statement that the sorting and dismantling is of little interest, and instead find that it is an area of opportunity for improving the emissions.

6.2.6 The Impact of Geographical Location of End-of-Life

The findings relating to transport to end-of-life show that emissions only increase by 60kg$CO_{2eq.}$ (3%) if 1 tonne of material is transported to China for recycling as opposed to staying in the UK. An implication of this is that sending WEEE to the location in the world with the best recycling process in terms of net emissions would be beneficial, even if the distance of transport to end-of-life is further. An example of this would be sending ferrous metal to countries with low electricity carbon intensity for recycling, as electricity usage in an electric-arc-furnace can be a considerable fraction of the gross emissions. The Ecoinvent database showed 384kWh of electricity usage for recycling a tonne of scrap steel. Generating this electricity in a low grid carbon intensity nation could save over 200kg$CO_{2eq.}$ compared to a high grid carbon intensity nation (208kg$CO_{2eq.}$ in Turkey, the UK's greatest export location, or 7.3kg$CO_{2eq.}$ in Norway (EEA, 2020)). The limited information in the Ecoinvent database on country-specific emissions didn't allow this hypothesis to be tested fully. While the decision of where to send material for recycling is currently operated on a cost basis within the countries permitted for export, this finding highlights that carbon emissions could be reduced by looking beyond just cost. The relatively low, and dropping, grid carbon intensity in the UK could make the UK an attractive recycling destination using this metric.

6.2.7 The Impact of Energy-from-Waste and Landfill

A finding highlighted in our results was the detrimental contribution of energy-from-waste to the overall carbon footprint. The avoided emissions from displacing electricity from the grid only offset 1/5 of the gross emissions, meaning that a tonne of WEEE material going to EfW has net emissions of over 2t$CO_{2eq.}$ emitted (2.58t$CO_{2eq.}$ gross, -0.452t$CO_{2eq.}$ avoided).
Another way of looking at the benefit of EfW is the emissions per kWh of electricity produced compared to conventional sources. Electricity generated from EfW treatment of plastic, which makes up 89% of the WEEE material going to EfW, works out at 2.92kg$CO_{2eq.}$ per kWh, comparing poorly to 0.82kg for coal, 0.49kg for natural gas and 0.012kg for offshore wind (Schlömer et al., 2014).

The EfW values are dependent on the Ecoinvent database values for the amount of electricity produced by each material, which assumes a net electrical efficiency of 12.9%. Tolvik Consulting (2020) report a net efficiency of 17% for UK EfW plants, but this is not specific to plastic. Changing the EfW efficiency to 17% would improve the net emissions of EfW by 7.4%, and the overall WEEE net emissions by 0.75%, but would still give emissions per kWh over four times that of electricity from natural gas, the marginal electricity source in the UK. The exclusion of the heat produced by EfW plants from the system boundary will have excluded some additional avoided emissions from the model, but the magnitude will be small due to the poor usage of this heat in the UK (Tolvik Consulting, 2020; Turner et al., 2016).

These findings contrast to Merrild et al. (2012) who came to a very different conclusion in Denmark, showing that in some cases plastic has lower global warming potential when sent to EfW over recycling. This contrast is explained twofold: Denmark utilises far more of the energy from the plastic, through extensive district heating networks using the heat produced (Fruergaard et al., 2010); and Merrild used coal-powered electricity as the marginal source that was displaced by the EfW electricity, as opposed to more efficient CCGT plants that are the marginal source in the UK and in our study. While the UK could improve its use of heat from EfW in the future, this will likely be offset some degree as the avoided emissions decrease due to the electricity grid and heat production decarbonising in line with the UK's ambitions of net zero electricity production by 2035 (Department for Business, Energy & Industrial Strategy, 2021).

In contrast to the net emissions of 2.13t$CO_{2eq.}$ per tonne of EfW WEEE, one tonne of material going to landfill results in net emissions of 0.290t$CO_{2eq.}$, and specifically for plastic 0.116t$CO_{2eq.}$. This low value is because the slow degradation of plastic in landfill keeps the carbon in the ground, and produces very little methane, which usually constitutes the majority of emissions from waste in landfill (ecoinvent, 2021). For EfW to equal this net emissions value, its net efficiency would need to be 65%. Electrical net efficiency from EfW is limited to ~27% (DEFRA, 2013), so greater use of heat, as is the case in Denmark, would be required for EfW to surpass landfill in terms of $CO_{2eq.}$. The main implication for this is that in the UK, from a global warming potential perspective, landfill would be preferable to EfW for the disposal of non-recyclable WEEE materials; landfill net emissions are 86% lower than those of EfW, despite the EfW avoided emissions.

6.2.8 The Resource Benefit

The other way of assessing the useful outputs of the WEEE treatment process is to compare the carbon footprint of virgin material production with that of secondary material production through the WEEE recycling process. Table 27 shows, for the major WEEE materials, the carbon footprint of the virgin material, and how it compares to the carbon footprint of the recycled material from the WEEE treatment process. The virgin carbon footprints are the Ecoinvent values used in the carbon calculator for the avoided emissions. The recycled material carbon footprint assumes no burden from the previous life of the EEE, and includes the emissions from collection to end-of-life, allocated to the different materials by mass.

There is a general trend that materials with higher virgin carbon footprint having a greater % reduction in carbon footprint between virgin and WEEE recycled production (Figure 33). The greatest reduction is for stainless steel which has a carbon-intensive method of virgin production. The lower the virgin carbon footprint, the less opportunity for reduction there is due to the shared stages of the WEEE treatment– the collection, pre-processing and end-of-life (EoL) transport – which emit around 0.1t CO_2 per t of material. This is most clearly seen with wood and concrete, the only two materials where the recycled material has a worse carbon footprint than the virgin material. For concrete, the EoL recycling process only emits 0.00401t$CO_{2eq.}$ per t of concrete, but the rest of the WEEE supply chain emits 25 times more CO_2 (0.101tCO_{2eq}). PCBs show the highest virgin carbon footprint, but do not show the greatest % reduction. This is likely because included in the recycling process is the burning of the PCB support, which emits a large amount of CO_2, whereas the other materials have the recycling process separated from EfW, and only recycling is considered here.

*Table 27: A comparison of the carbon footprint of secondary materials made from recycled WEEE, and virgin materials. *recycled output is 29.3% of mass of circuit boards; 1 tonne of recycled output from circuit boards is composed of: 811kg Copper, 114kg Nickel, 54.7kg Lead, 19.2kg Silver, 1.06kg Palladium and 0.581kg Gold, and requires 3.4t of circuit boards to produce.*

Material	t$CO_{2eq.}$		% Reduction in $CO_{2eq.}$ when material is recycled from WEEE
	Virgin Carbon Footprint per t	Recycled Carbon Footprint per t	
Steel	3.654	0.692	81%
Stainless Steel	5.719	0.692	88%
Copper	6.582	1.930	71%
Aluminium	7.298	0.988	86%
Hazardous Plastic	3.738	0.573	85%
Non-Hazardous Plastic	3.738	0.595	84%
PU Foam	5.108	0.751	85%
Glass	1.258	0.955	24%
Oil	0.446	0.253	43%
Concrete	0.0084	0.1054	-1156%
Wood	0.142	0.147	-4%
1t of circuit board recycled output*	56.4	11.6	79%

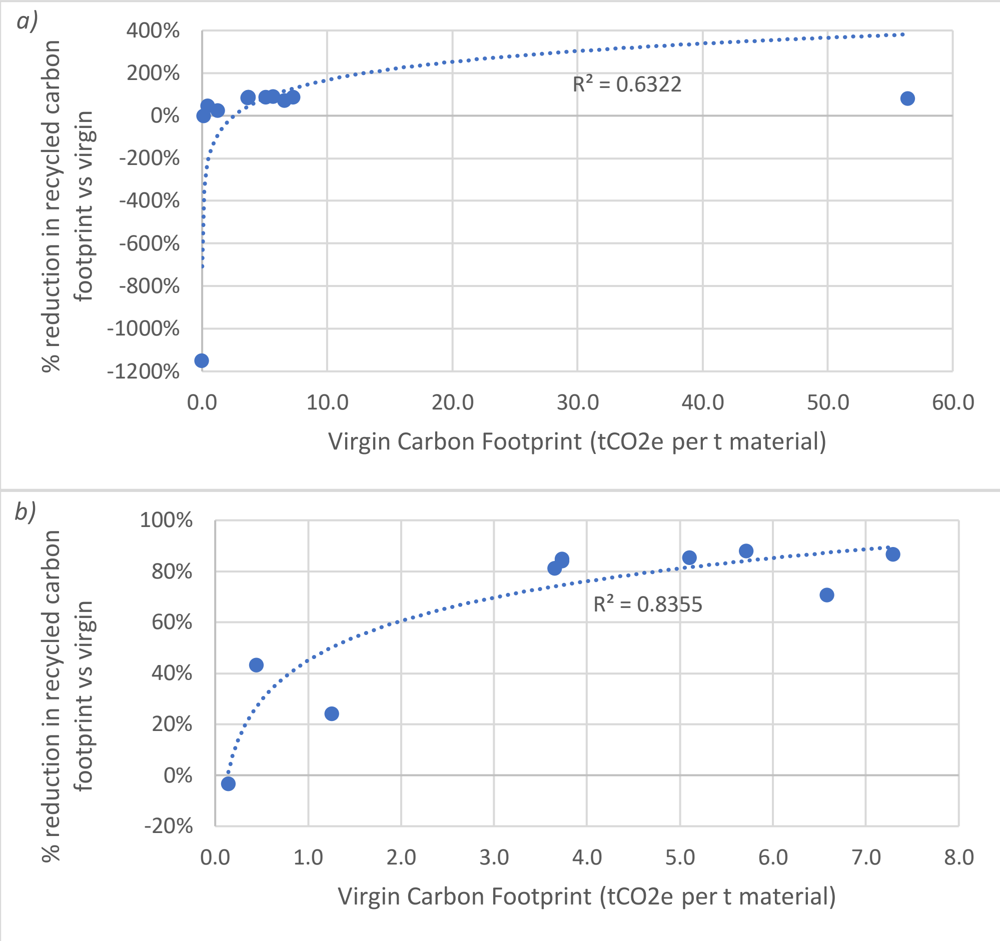


Figure 33: Plot of the virgin carbon footprint of each of the major materials in WEEE, plotted against the % reduction in carbon footprint when the material is produced from recycled WEEE.
a) shows all of the major materials, and is fitted with a logarithmic trendline with an R^2 value of 0.632.
b) repeats this but excluding the two extreme points – concrete and PCBs. This results in a stronger correlation with an R^2 of 0.836.

6.2.9 The Impact of Refrigerant Gases

As detailed in Section 2.4.4, inclusion of the avoided emissions of refrigerant gases in a WEEE carbon footprint depends on the system boundary, and whether there is a reference scenario compared to where refrigerants are emitted. The avoided emissions in our life cycle assessment (LCA) were only considering the useful products produced by the WEEE treatment, by system expansion, so refrigerant avoided emissions were not included. If instead the LCA considered the current treatment compared to non-authorised WEEE treatment, such as the light iron waste stream, the system boundary for Cooling WEEE would expand to include avoided emissions for the refrigerant gases that are captured by the best available treatment recovery and recycling techniques, which are emitted to the atmosphere in the other scenarios. This is worth noting because this change would increase the avoided emissions for the Cooling Stream by between 1.2 and 3.9t$CO_{2eq.}$ per t WEEE depending on the charge of refrigerant per fridge, based on an approximation of the composition of refrigerants in the waste stream (Appendix B). For fridges containing the legacy R12 refrigerant this upper bound would rise to -117t$CO_{2eq.}$. Baxter *et al.* (2016) included the refrigerant avoided emissions in their LCA, assuming R134a refrigerant, and concluded a net emissions improvement of 11.0 t$CO_{2eq.}$ per t Cooling WEEE.

Even in the authorised WEEE system, some refrigerant emissions to air are likely to occur in the supply chain due to improper handling, fugitive emissions (leaks) from AATFs and from theft. Expanding the system boundary to consider refrigerants would allow these emissions to be included and highlight the importance of correct handling and treatment of refrigerant containing WEEE. Compressor theft to recover the valuable steel and copper content is an example of where considering refrigerant emissions highlights an issue. Compressor removal releases the refrigerant gases from the compressor circuit into the atmosphere, which as shown above can lead to up to greenhouse gas emissions of up to 117t$CO_{2eq.}$ per tonne of WEEE. Data from 2018-19 from 4 UK regions showed on average 23% of cooling devices are missing their compressors, but in major urban areas it is as high as 73% (Sayers et al., 2020). At the up-to-date refrigerant composition (Appendix B), 73% compressor removal would result in the release of over 1.5t$CO_{2eq.}$ per tonne of cooling WEEE, almost negating the carbon benefit of the rest of the supply chain. Thus, considering the carbon emissions from refrigerants makes tackling theft a greater priority than just the loss of recyclable material.

6.2.10 The Benefits of Reuse

The benefit of reuse, and how to incorporate it into carbon footprint calculations, is another of the debates in the WEEE carbon footprint literature. Our model used a similar methodology to Jaunich et al. (2020) and Turner et al. (2016), where the expected lifetime of the reused EEE device relative to the lifetime of a new EEE device is accounted for in the avoided emissions, rather than simply assuming an entire new device’s emissions are avoided as in

Clarke et al. (2019). The result of this method was that reuse of a tonne of WEEE had a worse net carbon footprint than recycling the WEEE. The low tonnage of WEEE to reuse for REPIC in 2019 (1.25%) meant that reuse wasn't a main focus of the research, hence applying the method as used in previous literature. For the specific study of reuse by producer compliance schemes and government, a more detailed reuse model that takes into account the age or energy efficiency rating of the WEEE being considered for reuse should be developed, in line with the research by Hischier and Böni (2021) and O'Connell et al. (2013).

6.2.11 Wider context

It is worth noting that these results should not be viewed in isolation for a product life-cycle point of view, for instance by the EEE producers in product design. When considering product design, the end-of-life should be assessed alongside the manufacturing emissions to ensure the original carbon footprint of using a material is included. This is to avoid incorrect conclusions being reached, such as that increasing the amount of aluminium and circuit boards in a product will benefit carbon footprint due to these materials having the best net emissions at end-of-life. When viewed as part of the whole product life cycle, we see that aluminium and circuit boards have high virgin production emissions, so increases in their use may worsen the life cycle carbon footprint.

6.3 Implications

6.3.1 Theoretical Contributions

Theoretically, contributions have been made through the development of a carbon footprint calculation methodology, specific to the UK, that can be updated and adjusted as new or improved data is collected, and through the development of a novel form of WEEE logistics optimisation.

The methodology of the carbon footprint model advances the WEEE field by explicitly showing how primary data can be combined with database emissions factors to evaluate the carbon footprint of each individual operator in the collection and pre-treatment stages of the supply chain. A method for evaluating the net emissions of reuse has also been incorporated in the model – a part of the supply chain that in previous studies is either lacking (Biganzoli et al., 2015), or simplified (Clarke et al., 2019).

The contribution to the field of WEEE logistics optimisation is from this study expanding beyond the common field of vehicle routing logistics to develop a method that includes the downstream net carbon footprint of the supply chain and how changes to logistics decision-making impact this net carbon footprint. It has also demonstrated that, with data provided by a producer compliance scheme, data granularity is sufficient to optimise carbon footprint through logistics changes. While optimisation outcomes were only investigated briefly in this project, it opens the possibility of a more detailed operational logistics study to inform decision making.

6.3.2 Empirical Contributions

Empirically, the main carbon footprint output of the model updates and increases the accuracy of carbon footprint research analysing the collection and treatment of WEEE in the UK. The use of extensive primary data on a WEEE carbon footprint study in the UK, including all WEEE streams, reuse and precious metals, addresses the knowledge gap identified in Section 2.8.

The collated primary data within the model also updates and improves the accuracy of available data on each of the stages of the supply chain, most relevant to the UK due to the UK-based data collection and the limited data available in published sources, but also relevant to other nations using similar recycling processes. Advances over current published UK data have been made in the accuracy of data for WEEE collection distance, AATF pre-treatment facility emissions, treatment facility material recovery rates, and end-of-life locations. The WEEE composition data is also the only UK data available for all 5 of the main WEEE streams. Previously the best data for these stages in the UK was from sources over 8 years old (WRAP, 2012), and was not specific to individual operators, and for some data was not specific to the UK at all (Clarke et al., 2019).

6.3.3 Implications for Industry and Policy

The implications of the research for industry and policy stem from a better understanding of the carbon footprint of the WEEE treatment process and how to improve it. The model indicates where the main carbon emission impacts and benefits are in the supply chain, and how the carbon footprint varies between different scenarios. The results of this study, and the carbon footprint tool going forwards, were intended to inform industry through REPIC's planning of future operations and its external communications, including a whitepaper, and aid policy through REPIC's consultation by DEFRA for the ongoing review of WEEE regulations in the UK. Here, the overall implications of reducing WEEE carbon footprint are discussed for industry and policymakers in the UK, before summarising key recommendations that could be made to each to bring about a reduced carbon footprint.

Industry, including REPIC, other producer compliance schemes, and the WEEE supply chain, can benefit from reduced carbon footprint for several reasons. Many of REPIC's producer members, who can be seen as key stakeholders in the entire supply chain, have their own carbon reduction targets and whilst targets often exclude end-of-life, expansion to cover scope 3 emissions would incorporate the end-of-life emissions in targets, allowing the WEEE industry to add further value by reducing these emissions. REPIC, and companies in the supply chain, could gain a competitive advantage by offering a lower carbon service that helps fulfil producers' targets. Evidence of reducing emissions would also add to the offering that producer compliance schemes provide for Local Authorities during the tendering process for WEEE collections, with Local Authorities frequently having their own carbon reduction targets. Finally, companies in the supply chain would benefit if future policy were to evolve to target improving carbon footprint of the WEEE system. One example would be a change to the WEEE targets, that producer compliance schemes aim to fulfil, from being weight-based collections target to being emissions-reduction-based targets where lower carbon footprint is incentivised.

Policymakers across the government in the UK are aiming to reduce emissions across the economy to meet the UK's legally bound target of 'net zero' by 2050, with an interim target of 78% by 2035 (Department for Business, Energy & Industrial Strategy, 2021). Reductions in the carbon footprint of the waste industry will be required to meet these targets, and in the case of the UK are particularly relevant to the Department for Environment, Food and Rural Affairs (DEFRA).

Specific implications of the carbon footprint research and what it means for industry managers and policymakers follows below.

The main finding that WEEE treatment is highly beneficial from a climate change perspective adds a further lever for increasing the uptake of the authorised WEEE system in the UK. An estimated 300kt of WEEE was disposed of through residual household or commercial non-recycled waste in 2019 (Sayers et al., 2020). If this residual waste is assumed to release no carbon emissions, the carbon saving possible if it were treated in the authorised system is 604 KtCO2eq.. Managers in producer compliance schemes can use this carbon saving data in consumer awareness campaigns, of the like seen from Material Focus in the UK, to encourage consumers to divert WEEE away from residual waste and unofficial waste treatment pathways, towards the authorised system. Policymakers can also use this finding to add priority to government policy that will increase the use of the authorised WEEE system, such as tackling illegal WEEE exports and theft.

Reducing emissions from the collection of WEEE is possible through changes made by managers in the WEEE supply chain, including REPIC. The implications of the vehicle routing optimisation are that shorter routes and milkround collections can reduce total distance travelled, and so reduce both cost and carbon footprint. Even greater savings are possible by using arrangements that fill capacity on return journeys of vehicles already travelling, with the most efficient example of this being a special case of journey backloading where a delivery vehicle delivering new EEE picks up the WEEE item being replaced. Managers could encourage the use of route optimisation tools and logistics optimisation to ensure vehicles are being filled to capacity and taking the most efficient journeys, paying particular attention to the special case of backloading mentioned above. While these improvements reduce the emissions of collection, the small magnitude of the collection emissions means there is little scope to reduce the overall carbon footprint by improving collection.

Improving net emissions at the pre-treatment stage of the WEEE supply chain (at the Approved Authorised Treatment Facilities (AATFs)) can be influenced by managers and policymakers. A key finding of this research was that AATFs that recover and recycle greater amounts of material result in a greater carbon benefit downstream in the supply chain. The finding that when sending WEEE to more distant but higher-performing AATFs, the additional transport carbon footprint is often overshadowed by the downstream emissions improvements was one that was not readily obvious without the carbon footprint data. Managers at producer compliance schemes could incorporate data on AATF carbon footprint performance into the decision making of where to send WEEE, to maximise the use of AATFs with better downstream emissions. In the short-term, limited AATF capacity and REPIC's contracts could limit the extent of change that is possible. With a longer-term view, managers selecting AATFs based on their total downstream carbon emissions would put pressure on poorer performing AATFs to improve their emissions performance to maintain competitiveness. For policymakers, there is opportunity to bring about improvements in the carbon performance of AATFs through changes to the government regulation of AATFs, for example by changing the best available treatment, recovery and recycling techniques (BATRRT), increasing the minimum required recycling rate, and/or discouraging the use of energy-from-waste.

Improving net emissions at the final end-of-life stage of the supply chain is beyond control of producer compliance schemes, but could be influenced by policymakers. The main relevant findings here were that maximising the use of recycling is the best end-of-life in terms of emissions; that energy-from-waste (EfW) is worse than landfill from a carbon perspective; and that emissions from recycling can be improved by recycling taking place in countries with the best emissions from the recycling process. For the comparison of EfW and landfill, policymakers could consider whether the current preference for EfW over landfill in the WEEE regulations is suitable as CO_2 emissions become a key government focus, and commission work to further investigate this (The WEEE Regulations, 2013). Landfill has its own disadvantages relating to land-use, extremely slow degradation of plastics, and water pollution (Teuten et al., 2009), meaning that some materials are not suitable for disposal by landfill, however, from a purely carbon footprint perspective it is advantageous to EfW. These conclusions need further confirmation regarding the efficiency of EfW in the UK, but this is certainly worthy of further investigation as carbon emissions become more of a government priority, and as the benefit of electricity substitution decreases in the future (Section 6.2.7). Finally, the investigation showing that the location of recycling could be prioritised in countries with the best net emissions from the recycling process (Section 6.2.6), shows that considerable carbon footprint reductions could be achieved. This lies in control of the exporting companies, and government export policy. Policymakers could investigate incentives for sending recycling to nations where the carbon footprint is minimised, or restricting recycling in the worst performing nations – there is scope to bypass World Trade Organisation rules when protecting the environment or health (WTO, n.d.).

7 Conclusion

Here we return to the aims defined in Chapter 1 and consider how the research has addressed each of them. We then consider the limitations of the research in terms of the overall method, and the data itself. The chapter concludes by stating future research directions that would lead on from our findings.

7.1 Carbon Footprint Calculator

The model created takes inputs from REPIC's 2019 WEEE collection records, primary data collected from haulage and treatment operators and secondary data from the Ecoinvent LCI database. The output of the model is carbon footprint in tCO_2 equivalent per tonne of WEEE, for the whole supply chain and broken down into the different stages and WEEE streams. The method followed is based on the CENELEC rules for life cycle assessment (LCA) of electronic and electrical products and systems, itself closely based on ISO14044. The usage of primary data represents an advance on previous research in the UK from Clarke et al. (2019) and Turner et al. (2015), but less specific database values are still relied on in the later stages of the supply chain. The model is updatable to allow future years of WEEE collection to be modelled.

The model follows every tonne of WEEE that REPIC collected in 2019 through a material flow analysis to a cut-off when it is either disposed of or the recycled material substitutes virgin production. Only a small proportion of REPIC's 2019 WEEE was destined for reuse, while the majority goes through pre-treatment and on to recycling, landfill, energy-from-waste incineration or high-temperature incineration. The output of the material flow analysis shows that 1 tonne of WEEE produces 748kg of recycled secondary material, 12.5kg of reused WEEE and 88kWh of electricity.

7.2 Evaluating Carbon Footprint

The second aim, to evaluate the carbon footprint/benefit of the WEEE supply chain, was achieved by analysing the detailed outputs of the model.

The main output of the carbon calculator showed the average net carbon footprint to be -2.01t$CO_{2eq.}$ per t WEEE collected in 2019, showing that REPIC's WEEE supply chain has a clear benefit from a carbon footprint perspective. This net carbon benefit held true for all 5 WEEE streams assessed. The average carbon footprint can be broken down into 0.903t$CO_{2eq.}$ of gross emissions from the supply chain, and -2.92t$CO_{2eq.}$ of avoided emissions from the useful outputs of the supply chain.

The gross emissions are broken down into 4 stages of the supply chain – collection, pre-processing, transport to end-of-life and end-of-life process. The gross emissions are dominated by the end-of-life processes; recycling, incineration and landfill; which contribute 88% of the emissions. The recycling processes are responsible for just over half of these emissions, and most of the remainder is from incineration – either energy-from-waste (EfW) or high-temperature incineration (HTI). In contrast, landfill contributes very little to the emissions.

The avoided emissions are key to the benefit of the WEEE treatment from a carbon footprint perspective. The majority of the avoided emissions are from the recycling of the metal fractions of the WEEE, and the remainder mainly from the recycling of plastics and circuit boards. Of note is the minimal contribution of energy-from-waste and reuse to the avoided emissions – only responsible for 1.5% and 0.7% of the total respectively.

The combination of the gross and avoided emissions shows that the end-of-life processes in order of worsening net carbon footprint are Recycling < Landfill < Energy-from-Waste < High-temperature-incineration. This is contrary to the traditional waste hierarchy where energy recovery is preferred over landfill. Energy-from-waste has large gross emissions due to the burning of material, which are only slightly improved by the avoided emissions of electricity production due to the low net electrical efficiency. In contrast, landfill of WEEE material has low gross emissions as most material does not degrade and simply stays in the ground.

Despite contributing less than 4% to the gross emissions, the pre-processing stage is key to the end-of-life gross and avoided emissions as it dictates how much material is recovered from the WEEE and how much is recycled. The range of emissions between the different Approved Authorised Treatment Facilities (AATFs) at the pre-processing stage is only up to 0.028t$CO_{2eq.}$ per tonne of WEEE, but the range in whole supply chain net emissions can exceed 1t$CO_{2eq.}$ per tonne due to the range in recovery rates. This emphasises the importance of AATF recovery rate for the carbon footprint of the supply chain, and makes it a key opportunity for improving emissions in the future.

An additional finding when the emissions of the supply chain are analysed was that there were marked differences between the 5 WEEE streams in the emissions at each stage of the supply chain. The Gas Discharge Lamp (GDL) stream consistently showed very different results, with higher collection emissions and end-of-life emissions, but lower AATF emissions compared to the other streams. The other 4 WEEE streams also show a 3-fold range in collection emissions, a 5-fold range in pre-processing emissions and a 2-fold range in end-of-life process emissions. This highlights the importance of analysing the WEEE streams separately, as focusing on just one could give unrepresentative results.

7.3 Optimisation of AATF Allocation and Vehicle Routing

The optimisation of AATF allocation and vehicle routing both achieved an improved carbon footprint. The first stage of the optimisation, optimising AATF allocation with the objective of minimising the entire supply chain net carbon footprint, was found to improve the net carbon footprint of the Cooling WEEE supply chain by up to 11.8%. The improvement is due to greater avoided emissions, achieved by only sending WEEE to 2 AATFs which had the best recovery rate. This allocation increases the gross emissions of the collection stage as WEEE is sent to more distant AATFs, but the magnitude of avoided emissions improvement is far greater than the increase in transport emissions. The longer collection distances would, however, have cost implications, and worsen other environmental indicators such as air pollution. This method of optimisation is only possible with the granular, AATF specific, data calculated in the carbon footprint model.

A compromise between carbon footprint improvement and transport distance was reached by adding a second objective to the optimisation that minimises transport distance. Setting a weighting mostly towards minimising the carbon footprint halved the transport distance while only reducing the carbon footprint improvement from 11.8 to 10.4%.

The second stage of the optimisation, the more conventional vehicle routing optimisation, achieved a 22% reduction in distance travelled and carbon footprint compared to single out-and-back collections. A constructive algorithm produced milkround collection routes that collect from multiple Designated Collection Facilities (DCFs) with similar required collection capacity until the vehicle reaches capacity, visiting on average 2.6 DCFs per journey. This improved the carbon footprint by 14%. A hillclimbing improvement heuristic then improves the route order and further improved the reduction in carbon footprint from 14 to 22%.

The optimisation was only applied to a single WEEE stream, Cooling WEEE, and was intended mainly as an example of how these methods could be used in the context of WEEE management. Further development of the data inputs and methods is required to allow the optimisation to be used as an operational planning tool for REPIC's logistics.

7.4 Limitations

While this study represents the most accurate and up-to-date carbon footprint study of the UK's household WEEE supply chain, limitations in data accuracy and the methodology were identified that still limit the accuracy.

7.4.1 Data Limitations

One overall limitation was that data was only collected from a single producer compliance scheme. This limits the study's representativeness of the entire UK WEEE supply chain. While REPIC is the largest WEEE producer compliance scheme in the UK, multiple others exist, and while much of the WEEE system is dictated by legislation, the collection and AATF choice could vary between them. In the implications for policy the results of this study are assumed to be representative of the UK system, but to increase the confidence in this, data should also be collected from other UK producer compliance schemes.

The primary data collected from REPIC's partners for the collection and pre-treatment stages of the supply chain, while more specific to REPIC and more granular than previous UK studies (Clarke et al., 2019), suffered from subjectivity due to the assumptions required in the calculations made by treatment operators, limiting the data accuracy and reliability. Several AATFs pointed out that the required data was not routinely calculated and required assumptions to be made, which different AATFs may have interpreted differently. This created difficulty in discerning what is actual differences between AATFs and what is only methodological inconsistencies. It is also possible that data was exaggerated, either implicitly or explicitly, to improve the appearance of each operator. Considering the high sensitivity of the net carbon footprint to the AATF recovery rate, it is recommended that before policy or commercial decisions are made with the data, the accuracy and comparability of AATF data is improved. This limitation also affected the AATF allocation optimisation because the stated recovery rate data from each AATF underlay the optimisation.

The accuracy of the haulier and AATF data was also limited by the response rate to the questionnaires. The data collected covered just over 50% of REPIC's tonnage. Non-responders were matched to the closest proxy in terms of technology and scale, but despite this, the accuracy is lower than if primary data had been collected. This is expected to have an impact on the validity of the overall carbon footprint, as it assumes the 50% of responders are representative of the entire industry. This also limited the optimisation modelling, as non-responding AATFs had to be excluded from the optimisation model where the differences between AATFs are the main basis of the improvement.

The primary data collected also left some gaps that needed filling, for example exact route data for collections is not recorded by hauliers, so collection routes were estimated based on the known waypoints and Google Maps directions. It is likely that there is additional complexity that is not considered in the model such as intermediate locations, road restrictions for heavy goods vehicles and sub-optimal routing.

Primary data collection became increasingly difficult the more steps away from REPIC in the supply chain the data was being sought. REPIC's direct contracts with hauliers and AATFs facilitated the sharing of data, but this was not possible further along the supply chain. As a result, the carbon footprint is still dependent on database values for some of the most sensitive inputs to the model – the emissions factors for end-of-life and avoided emissions. The use of secondary data from LCI databases is widespread in the literature (Hischier et al., 2005; Biganzoli et al., 2015; Baxter et al., 2016) but is still a simplification of the reality, where WEEE fractions are sent to multiple facilities in a range of countries. The limited number of datasets in the Ecoinvent database resulted in some materials having to be approximated to similar materials, requiring subjective judgements, and limiting the validity of the end-of-life emissions data. Thankfully over 75% of the WEEE material was covered by closely matching datasets, minimising the impact of the approximations on the overall carbon footprint. The LCA dataset accuracy was also limited by the lack of country-specific LCA datasets for each material's recycling process. UK or European values were used for consistency, but this fails to capture the differences in emissions of each process taking place in different countries with different technologies and electricity generation sources.

Finally, there was a lack of data on the use of WEEE fractions as solid recovered fuel for powering cement kilns. It was indicated by REPIC that this has recently become an alternative to electricity-generating EfW, but AATFs did not distinguish between these 2 types of energy-from-waste, and the Ecoinvent database lacked a full dataset for the use of waste plastic in cement kilns. As a result, all EfW was assumed to be in electricity-generating plants.

7.4.2 Methodology Limitations

The overall method of LCA has limitations in its accuracy of the total emissions of the processes it models. An issue, termed truncation error, exists due to the necessity for a system boundary that limits the scope of the upstream processes considered (Lenzen, 2000). As a result, part of the life-cycle environmental impact of the system is excluded. The effect of truncation error on this study is particularly unclear due to the error affecting both the gross emissions and avoided emissions. Because of the larger absolute value of the avoided emissions, it is possible that truncation error results in a worse net carbon footprint than the true carbon footprint.

Additionally, the use of an LCA functional unit of 1 tonne of WEEE can hide changes to the overall carbon footprint from changes in the total amount of WEEE (Ekvall et al., 2007). If a greater proportion of WEEE is treated in the authorised WEEE pathway, this will be beneficial from a carbon footprint perspective, but would not be reflected in the per tonne values. The solution to this is also calculating and considering the total carbon footprint values. Total carbon footprint values are not displayed in this thesis for data confidentiality, but are included in the output of the carbon calculator for REPIC’s use.

The specific methods used in the calculation of the inventory for use in this project also possess limitations:

- The material flow analysis that calculates how much of each material leaves the pre-processing stage is calculated at the output of the AATF by applying the percent of each material in the output to the input tonnage of WEEE. This assumes that there are no losses of material during the pre-processing step which aren’t captured in the output percentages. If mass is lost, and not listed in the outputs, then the calculation will overstate the amount of each material that leaves the AATF.
- The reuse calculation does not account for the entire life cycle impact of reuse due to the complexity of energy efficiency and product lifetime. The small proportion of reuse in REPIC’s supply chain limits the effect of this on the overall carbon footprint, but for individually assessing the benefit of reuse, a more comprehensive method would be required, as discussed by Hischier and Böni (2021).

- The method of calculating the emissions from the recycling process was also limited in its accuracy by the selection of just a single dataset to represent the end-of-life. As discussed above, this is partly a problem of data availability, but our method also chose to only use one value per end-of-life process for each material to reduce the complexity of the model. The impact of this again depends on the intended use of the carbon footprint. The location of end-of-life process is beyond REPIC's control and influence, so this limitation has little effect on REPIC's decision making, but if the results were intended for use in policy to choose which countries WEEE materials are sent for recycling, the recycling processes would need to be updated to be country-specific to allow comparisons to be made.

Finally, the vehicle routing model was simplified to fit the scope of the project. It assumes only one size of collection vehicle, and doesn't consider drivers' hours, timings of collections or real road routes. It also relies on the hillclimbing heuristic, which is quick to implement and run, but it is limited by getting stuck in local optima, resulting in less optimal results than more complex heuristics. The level of simplification was suitable for providing an initial overview of the type of improvements possible, but at this time is limited in its application to operational decision making.

7.5 Future Research

The future research recommended following this study can be split into research that would further advance this project and the carbon calculator, and that which would improve knowledge in the overall subject area.

7.5.1 Recommendations Future Research to Advance This Project

- Collection of more reliable data from AATFs, with auditing of the calculation method, would reduce the limitations of data reliability and allow more confident comparisons to be made between different AATFs as a basis for logistics planning. A suggestion for achieving this was to instate an annual, auditable requirement for REPIC's AATFs to report the data, which would result in more reliable and accurate calculations.

- Collection of primary data on the net efficiency at energy-from-waste plants in the UK when they are using plastic as a fuel. This would increase the specificity of the data to the UK and allow assertions to be made more confidently about the benefit of sending WEEE material to EfW.
- Adding a separate EfW end-of-life process to account for the WEEE material being converted to solid recovered fuel to power cement kilns. Its addition would ensure all the current end-of-life processes are accurately represented in the model.
- Comparison of several life cycle inventory databases. The database values are key to the overall carbon footprint and an understanding of how much the carbon footprint changes based on database choice would help in assessing the validity of the results.
- Addition of refrigerant emissions within the supply chain to the carbon calculator. Damage to cooling WEEE or heat-pump tumble dryers at the DCF and while in transit, and emissions to air from the AATF all release refrigerant into the atmosphere, although the earlier stages are hard to quantify.
- Replace the heuristic used in the optimisation model with a more advanced heuristic that can escape local optima, and apply it to all 5 WEEE streams (Altiparmak et al., 2003).
- Expand the vehicle routing problem to include further constraints such as drivers' hours and opening times at the DCF and AATF.

7.5.2 Recommendations Future Research in the Subject Area

- Research into another producer compliance scheme to assess how much variation there is from the results concluded from REPIC's data.
- Research into heat-pump tumble dryers in the waste stream, and how they can be ensured to be separated from the rest of the Large Household Appliance waste stream and treated in a manner that stops the emission of the refrigerant gases into the atmosphere.
- Evaluation of reuse of WEEE in the UK and whether the encouragement of reuse should distinguish between devices based on their efficiency compared to a new

device, and the corresponding difference in their benefit from a life cycle environmental impact perspective (O’Connell et al., 2013).

- Evaluation of whether stricter legislation on AATF recovery rate, to improve all AATFs to the level of the best-performing current AATFs, could improve the carbon footprint of WEEE treatment.

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Appendices

Appendix A – The End-of-Life Processes and Virgin Production Processes

A brief discussion of each of the main materials' dominant end-of-life process – recycling, energy-from-waste or landfill, and where recycled material is produced, how this compares to the primary production process.

Material	End-of-life process	Comparison to virgin production process
Iron/Steel	<u>Recycling</u>: 60% in electric arc furnace and 40% in oxygen steelmaking.	Virgin production requires iron ore mining and transport, then smelted to iron/steel mostly by blast furnace and oxygen steelmaking – emissions from chemical reduction process and from heating of furnace. Electric arc furnace is more energy efficient, avoids direct chemical process emissions, and can decarbonise if electricity grid carbon intensity reduces.
Aluminium	<u>Recycling</u>: Remelted and impurities removed by salt. Further purification can remove alloying elements.	Virgin production requires ore mining and transport, followed by electrolysis to produce pure aluminium, which requires a huge amount of energy. Remelting uses around $1/10^{th}$ of the energy.
Copper	<u>Recycling</u>: High-grade scrap is remelted. Low-grade enters the same process as virgin copper at the converter, which outputs 99% copper, followed by electrolytic refining to pure copper.	Virgin production requires ore mining and transport, then smelting followed by refining in a converter followed by electrolytic refining to produce pure copper. Low-grade recycling has lower energy use and emissions due to skipping the first few steps of production, and high-grade has lower emissions still.
Plastic	<u>Recycling</u>: Plastic is cleaned, compounded and extruded with heat to form pellets. <u>Energy-from-waste</u>: high calorific value allows heat and electricity to be produced from burning plastic, or allows use as a fuel for cement kilns as solid recovered fuel.	Virgin production of plastics uses hydrocarbon feedstock, derived from crude oil or natural gas, which are chemically altered in a polymerisation reaction. Different plastics use different reactions, but commonly a catalyst is used at high temperature and/or pressure. The plastic then undergoes a similar compounding and extruding process to the recycled plastic. The feedstock production and polymerisation process is avoided in recycled plastic, along with their emissions.
Printed Circuit Board (PCB)	<u>Recycling</u>: Mostly pyrometallurgical treatment – metals recycled, and plastic board burnt.	Virgin production of precious metals requires large amounts of raw material to be mined and purified due to the low percentage composition in most ores.
Glass	<u>Recycling</u>: Glass is remelted but requires primary material to improve quality.	Virgin production uses silica sand, lime and soda ash as the main inputs. These are melted at high temperature and then formed into the glass

	Landfill: Leaded CRT glass is landfilled.	product, either with compressed gas to produce containers or floating on a bath of molten tin to produce flat 'float glass'. The remelting of scrap glass avoids the need for virgin material extraction and uses slightly less energy to melt. The result is a lower carbon footprint by 30%.
Concrete	Recycling: Mechanical treatment to produce aggregate.	Virgin production of aggregate from quarried stone has relatively low emissions per tonne as done in extreme bulk, with mainly mechanical processes involved.
Wood	Energy-from-waste: burnt as biomass to produce heat and electricity.	Electricity production in the UK comes from a mixture of renewable, nuclear and fossil sources with a carbon intensity of 220g/kWh on average.
Refrigerant Gas	High-temperature-incineration: CFCs, HCFCs and HFCs are destroyed at high temperature.*	N/A – no useful output.

Appendix B – Refrigerant Gases in WEEE

Refrigerants are gases contained in the sealed compressor circuits of Cooling devices and in heat pump tumble-dryers. Changes to legislation on refrigerants have led to a timeline of different gases being used since the mid 20th century (Figure 33). The older gases have extremely high global warming potential (GWP), of up to 12,000 times that of CO_2, and contribute to ozone depletion, and, although dramatically improved, even modern refrigerants can have a GWP of up to 1,430. The wide range of ages of EEE being disposed of means that cooling devices could contain any one of the refrigerant gases.

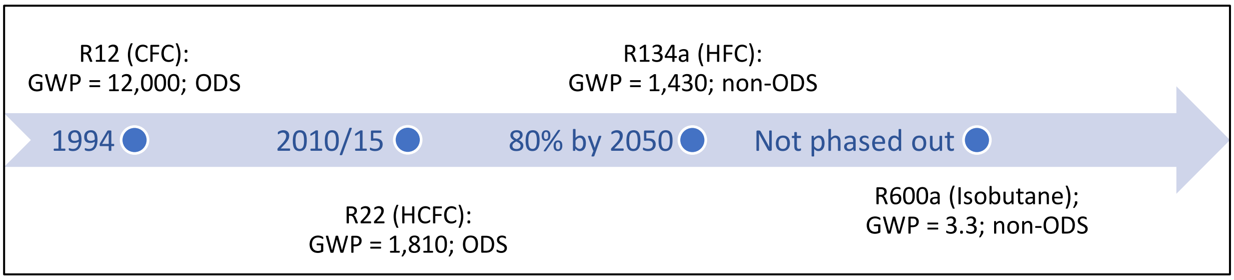

Figure 34 – A timeline of refrigerant history with the date of worldwide phase-out in the centre, and the name, global warming potential and ozone-depleting substance status adjacent (ODS = Ozone-depleting substance).

A refrigerator contains between 20 and 250g of refrigerant (United Nations Environment Programme, 2018), so the incorrect disposal of a single R134a fridge could release up to 357kg$CO_{2eq.}$ of gas, a number which rises to 3000kg$CO_{2eq.}$ for R12, equivalent to driving 1,600 and 13,000 miles respectively (DEFRA, 2020). A UN Report on ozone-depleting substances (United Nations Environment Programme, 2010) reported that in 2008 in Western Europe 76% of new cooling devices put on the market used the low GWP R600a refrigerant, and 24% use R134a (GWP=1,430). The same report estimated that the bank of in use cooling devices in 2006 consisted of 24% R12 (GWP=12,000), and the remainder a mix of R134a and R600a. These data combined with the average cooling device lifespan of 14 years (Bakker et al., 2014) suggest that of cooling devices disposed of today roughly three quarters will use R600a as the refrigerant, one quarters will use R134a and very few use R12. This would give refrigerant in WEEE an average GWP of approximately 400.

Appendix C – the Material Flow Analysis Output

The average material composition of cooling WEEE, as reported by AATFs from their outputs, and the proportion of each material sent for the different end-of-life processes.

Cooling	Composition	Recycle	Energy-from-waste	Landfill	High-temperature-incineration
Steel	37.9%	100%	0%	0%	0%
Stainless Steel	0.520%	100%	0%	0%	0%
Copper	0.690%	100%	0%	0%	0%
Aluminium	0.915%	100%	0%	0%	0%
Other non ferrous	0.770%	100%	0%	0%	0%
Cable	0.115%	33%	67%	0%	0%
Non-Hazardous Plastic	18.5%	92%	4%	0%	4%
PU Foam	17.0%	13%	70%	17%	0%
Glass	2.06%	100%	0%	0%	0%
Residue	1.46%	41%	50%	9%	0%
Oil	0.310%	100%	0%	0%	0%
Refrigerant Gas	0.518%	0%	0%	0%	100%
Compressors	19.3%	99%	1%	0%	0%
Wood	0.0200%	20%	80%	0%	0%
Capacitors	0.000925%	0%	0%	0%	100%
End-of-Life %		82%	14%	3%	1%

The average material composition of display WEEE, as reported by AATFs from their outputs, and the proportion of each material sent for the different end-of-life processes.

Displays	Composition	Recycle	Energy-from-waste	Landfill	High-temperature-incineration
Steel	32.7%	99%	0%	1%	0%
Stainless Steel	0.0160%	100%	0%	0%	0%
Copper	0.455%	100%	0%	0%	0%
Aluminium	1.99%	89%	0%	11%	0%
Other non ferrous	1.10%	100%	0%	0%	0%
Cable	1.32%	92%	8%	0%	0%
Hazardous Plastic	8.69%	0%	100%	0%	0%
Non-Hazardous Plastic	15.0%	97%	3%	0%	0%
Panel Glass	14.1%	100%	0%	0%	0%
Funnel Glass	10.1%	25%	0%	75%	0%
Circuit Boards	8.13%	94%	0%	0%	6%
Residue	2.98%	21%	68%	11%	0%
Armatures/Motors	0.312%	100%	0%	0%	0%
Small Appliance Fines	1.96%	0%	0%	100%	0%

Wood	0.636%	0%	100%	0%	0%
Mercury fraction	0.146%	89%	0%	11%	0%
Other whole waste	0.0460%	90%	0%	10%	0%
End-of-Life %		77%	12%	10%	1%

The average material composition of GDL WEEE, as reported by AATFs from their outputs, and the proportion of each material sent for the different end-of-life processes.

GDL	**Composition**	**Recycle**	**Energy-from-waste**	**Landfill**	**High-temperature-incineration**
Aluminium	5.52%	98%	0%	2%	0%
Glass	85.0%	98%	0%	2%	0%
Residue	0.510%	98%	0%	2%	0%
Mercury fraction	8.97%	98%	0%	2%	0%
End-of-Life %		98%	0%	2%	0%

The average material composition of LHA WEEE, as reported by AATFs from their outputs, and the proportion of each material sent for the different end-of-life processes.

LHA	**Composition**	**Recycle**	**Energy-from-waste**	**Landfill**	**High-temperature-incineration**
Steel	46.5%	100%	0%	0%	0%
Stainless Steel	0.500%	100%	0%	0%	0%
Copper	0.250%	100%	0%	0%	0%
Aluminium	0.250%	100%	0%	0%	0%
Mixed metal	32.4%	100%	0%	0%	0%
Plastic	4.20%	0%	30%	70%	0%
Non-Hazardous Plastic	1.00%	0%	0%	100%	0%
Glass	1.45%	41%	6%	53%	0%
Residue	5.25%	0%	15%	85%	0%
Concrete	8.20%	100%	0%	0%	0%
End-of-Life %		89%	2%	9%	0%

The average material composition of SMW WEEE, as reported by AATFs from their outputs, and the proportion of each material sent for the different end-of-life processes.

SMW	**Composition**	**Recycle**	**Energy-from-waste**	**Landfill**	**High-temperature-incineration**
Steel	28.0%	100%	0%	0%	0%
Stainless Steel	0.854%	100%	0%	0%	0%
Copper	2.21%	99%	0%	1%	0%

Aluminium	2.00%	100%	0%	0%	0%
Other non ferrous	2.42%	100%	0%	0%	0%
Mixed metal	11.0%	99%	1%	0%	0%
Cable	3.14%	71%	29%	0%	0%
Hazardous Plastic	21.5%	20%	50%	0%	30%
Non-Hazardous Plastic	13.0%	99%	1%	0%	0%
Batteries	0.626%	74%	4%	15%	7%
Circuit Boards	3.37%	83%	10%	0%	7%
Residue	6.59%	11%	45%	44%	0%
Armatures/Motors	1.62%	100%	0%	0%	0%
Small Appliance Fines	2.60%	46%	28%	26%	0%
Wood	0.224%	0%	100%	0%	0%
Other whole waste	0.786%	0%	100%	0%	0%
End-of-Life %		72%	17%	4%	7%

Appendix D – Emissions Factors

The Ecoinvent emissions factors for each main material and end-of-life. These are the values after conversion to reference value of 1 tonne of input scrap

Material & End-of-life	$tCO_{2eq.}$ per t input scrap	Ecoinvent Dataset
Steel Recycling	0.498	Steel production, electric arc, low alloy
Steel Avoided	3.23	Pig iron production + steel production, converter, low alloy
Steel Landfill	0.00527	Scrap steel inert landfill
Stainless Steel Recycling	1.55	Steel production, electric arc, low alloy
Stainless Steel Avoided	5.05	Pig iron production + steel production, converter, chromium alloy
Stainless Steel EfW	0.0109	Scrap steel municipal incineration
Copper Recycling	1.34	Copper scrap electrolytic refining
Copper Avoided	5.02	Copper cathode production
Copper Landfill	0.0138	Waste Al in *sanitary* landfill
Aluminium Recycling	0.854	Aluminium scrap in refiner
Aluminium Avoided	7.15	Aluminium ingot production, primary
Aluminium Landfill	0.0138	Waste Al in *sanitary* landfill
Plastic Recycling	0.487	50:50 Plastic flake from consumer electronics, 100% Recycled PS Foam
Plastic Avoided	3.84	33:33:33 ABS:PP:PS
Plastic EfW	3.09	Electronic plastic incineration
Plastic Landfill	0.116	Electronics plastic waste sanitary landfill
Plastic HTI	2.42	Hazardous waste incineration
PU Foam Recycling	0.650	PS Foam production, 100% recycled
PU Foam Avoided	5.11	PU Rigid Foam Production
PU Foam EfW	2.67	waste polyurethane, municipal incineration with fly ash extraction
PU Foam Landfill	0.00527	Waste PU Inert Landfill
Glass Recycling	1.478	Packaging glass production w cullet
Glass Avoided	2.08	Packaging glass production w/o cullet
Glass EfW	0.0162	Waste glass incineration with fly ash extraction
Glass Landfill	0.00927	Waste Glass *sanitary* landfill
Batteries Recycling	1.72	Used Li- battery Pyro-metallurgical treatment
Batteries Avoided	9.65	27% Fe, 19.2% Co, 5.04% Cu, 1% MnO2
Batteries EfW	2.83	Laptop residue incineration
Batteries Landfill	0.0106	Inert waste, sanitary landfill
Batteries HTI	2.42	Hazardous waste incineration
Residue Recycling	0.515	Mix
Residue Avoided	3.38	Mix
Residue EfW	0.519	MSW Incineration
Residue Landfill	0.640	MSW Sanitary Landfill

Small Appliance Fines Recycling	0.515	Mix
Small Appliance Fines Avoided	3.38	Mix
Small Appliance Fines EfW	2.46	Shredder residue incineration
Small Appliance Fines Landfill	0.0106	Inert waste, sanitary landfill
Oil Recycling	0.116	Carbon Footprint of Re-refined vs virgin base oil
Oil Avoided	0.383	Light fuel oil production
Oil EfW	2.85	Incineration with energy recovery of waste mineral oil
ODS Gas + Other Gas HTI	2.88	Treatment of used refrigerant
Concrete Recycling	0.00401	Recycling of non-reinforced waste concrete
Concrete Avoided	0.00839	Crushed gravel production (virgin)
Wood Recycling	0.0452	Waste wood shredding
Wood Avoided	0.142	Wood pellet production
Wood EfW	0.0151	Treated wood incineration
Capacitors HTI	2.46	Capacitor Haz Waste Incineration
Other whole waste Recycling	0.515	Mix
Other whole waste Avoided	3.38	Mix
Other whole waste EfW	0.519	MSW Incineration
Other whole waste Landfill	0.116	Electronics plastic waste sanitary landfill

The electricity generation in kWh per tonne of materials going to EfW

Material	**kWh electricity per tonne**	**Ecoinvent Dataset**
Stainless Steel EfW	0.0109	Scrap steel municipal incineration
Plastic EfW	1241	Electronic plastic incineration
PU Foam EfW	847	waste polyurethane, municipal incineration with fly ash extraction
Glass EfW	0	Waste glass incineration with fly ash extraction
Batteries EfW	1136	Laptop residue incineration
Residue EfW	386	MSW Incineration
Small Appliance Fines EfW	980	Shredder residue incineration
Oil EfW	678	Incineration with energy recovery of waste mineral oil
Wood EfW	483	Treated wood incineration
Other whole waste EfW	386	MSW Incineration
Stainless Steel EfW	0.0109	Scrap steel municipal incineration

The emissions factors for materials in circuit boards

	Useful output (t per t circuit board)	Avoided emissions ($tCO_{2eq.}$ per t of each material)	Avoided emissions ($tCO_{2eq.}$ per t circuit boards)	Gross Emissions (tCO_2 per t circuit boards)
Recycling Processes				1.46
Copper slag (plastics to EFW)			0.375	1.91
Lead	0.0160	1.37	0.0220	
Copper (cathode)	0.237	6.62	1.57	
Nickel	0.033	19.8	0.661	
Silver	0.00560	453	2.54	
Palladium	0.000310	11291	3.50	
Gold	0.000170	48263	8.21	
SUM	0.293		16.9	3.36

Appendix E – Code

Google Maps API Route Distance Calculator

```
# This requires an input Excel sheet with columns:
# Origin eg. "SP5 4ND", Destination eg. "KT11 3HT", Waypoints eg. "CB3 0DG | SP5 4ND | LA1 1AA" and
Number of Waypoints eg. 2
import googlemaps
from datetime import datetime
def distance_calculator(origin, destination, waypoint_parameter, number_waypoints):
    gmaps = googlemaps.Client(key='N/A')
    depart = datetime(2021, 12, 8, 22, 0, 0)
    d = 0
    directions_result = gmaps.directions(origin, destination, waypoints = waypoint_parameter,
mode="driving", departure_time=depart)
    for j in range(0,number_waypoints):
        d += float((directions_result[0]['legs'][j]['distance']['value'])/1000)
        #return d
    return d

# Read file where we are getting postcodes from, making it a dataframe called df.
import pandas as pd
df = pd.read_excel("/Users/matthewbond/Lancaster Python/GoogleMaps API Input.xlsx")

# Create empty parameter that will be added to the spreadsheet
df["route distance"] = ""

for i in range(0,100): #,len(df)
    origin1 = df["Origin"].iloc[i]
    destination1 = df["Destination"].iloc[i]
    waypoint_parameter1 = df["Waypoints"].iloc[i]
    number_waypoints1 = df["Number of Waypoints"].iloc[i] + 1
    df.at[i,"route distance"] = distance_calculator(origin1, destination1, waypoint_parameter1,
number_waypoints1)

# Save to file. Gives distance in kilometres
df.to_excel("/Users/matthewbond/Lancaster Python/Route_distance_output.xlsx")
```

Milkround Travelling Salesman Code

```
import random

def totalcost(current_best):
    total_distance = 0
    for j in range(0,len(current_best)-1):
        total_distance += distance(current_best[j].latitude, current_best[j].longitude,
current_best[j+1].latitude, current_best[j+1].longitude)
    return(total_distance)

def SwapOperator(current_best,stop1,stop2):
    current_best[stop1], current_best[stop2] = current_best[stop2], current_best[stop1]

def HillClimbing(current_solution, nonAATFlength):
    solCost = totalcost(current_solution)
    for i in range(100000):
        s1 = random.randint(1, nonAATFlength-1)
```

```
        s2 = random.randint(1, nonAATFlength-1)
        SwapOperator(current_solution,s1,s2)
        solCost_new = totalcost(current_solution)
        if solCost_new <= solCost:
            solCost = solCost_new
        else:
            SwapOperator(current_solution,s1,s2)

#Define function that finds distance on a globe between two coordinates
import math
def distance(lat1, lon1, lat2, lon2):
    radius = 6371 # km
    dlat = math.radians(lat2-lat1)
    dlon = math.radians(lon2-lon1)
    a = math.sin(dlat/2) * math.sin(dlat/2) + math.cos(math.radians(lat1)) \
        * math.cos(math.radians(lat2)) * math.sin(dlon/2) * math.sin(dlon/2)
    c = 2 * math.atan2(math.sqrt(a), math.sqrt(1-a))
    d = radius * c
    return d

#Define class 'Location' that includes postcode, latitude and longitude
class Location:
    def __init__(self, postcode, latitude, longitude):
        self.postcode = postcode
        self.latitude = latitude
        self.longitude = longitude

#Define function that is the nearest neighbour TSP heuristic algorithm
def nearest_neighbour(stops_trimmed, stops_full):
    output = [stops_trimmed[0]]
    stops2 = stops_trimmed[1:len(stops_trimmed)]
    random.shuffle(stops2)
    random.shuffle(output)
    nearest = output[0]
    min_distance = 100000
    final = []
    while len(stops2) > 0:
        for x in stops2:
            current_distance = distance(output[len(output)-1].latitude, output[len(output)-1].longitude,
x.latitude, x.longitude)
        nearest = x
        output.append(nearest)
        stops2.remove(nearest)
        min_distance = 100000
    nonAATFlength = len(output)
    if stops_full[-1].postcode!=stops_full[-2].postcode:
        output.append(stops_full[-2])
        output.append(stops_full[-1])
    else:
        output.append(output[0])
    HillClimbing(output, nonAATFlength)
    print(totalcost(output))
    for x in output:
        final.append(x.postcode)
    return(final)

# Read file where we are getting postcodes from, making it a dataframe called df.
import pandas as pd
df = pd.read_excel("/Users/matthewbond/Lancaster Python/Milkrounds_TSP_Input.xlsx")
```

```
# Create empty parameter that will be added to the spreadsheet
df["Final_Route"] = ""

# For loop that iterates through each row of the input spreadsheet.
# Looks in df for the postcode, lat and long (max journey length 14 stops).
# Trims the journey to only include the correct number of stops, and removes the AATF, end depot and
any duplicate stops.
for i in range(0,len(df)):
  potential_journey = []
  for a in range (0,14):
    potential_journey.append(Location(df["Stop " + str(a+1)].iloc[i], df["Lat " + str(a+1)].iloc[i],
df["Long " + str(a+1)].iloc[i]))
  journey_1 = [j for j in potential_journey if isinstance(j.postcode, str) is True]      #removes any blank
stops
  journey = journey_1.copy()
  journey.pop()
  journey.pop()

  df.at[i,"Final_Route"] = nearest_neighbour(journey, journey_1)

# Save to file.
df.to_excel("/Users/matthewbond/Lancaster Python/Milkrounds_output.xlsx")
```

Basic Allocation and Vehicle Routing with Hillclimbing Local Search

```
import math
import random
def distance(lat1, lon1, lat2, lon2):
  radius = 6371 # km
  dlat = math.radians(lat2-lat1)
  dlon = math.radians(lon2-lon1)
  a = math.sin(dlat/2) * math.sin(dlat/2) + math.cos(math.radians(lat1)) \
    * math.cos(math.radians(lat2)) * math.sin(dlon/2) * math.sin(dlon/2)
  c = 2 * math.atan2(math.sqrt(a), math.sqrt(1-a))
  d = radius * c
  return d

import pandas as pd
df = pd.read_excel("/Users/matthewbond/Lancaster Python/Problem_Instance3.xlsx")

working_hours = df["C"].iloc[0]
speed = df["C"].iloc[1]
num_vehicles = df["C"].iloc[2]
num_AATF = df["C"].iloc[num_vehicles+4]
num_DCF = df["C"].iloc[num_vehicles+4+num_AATF+2]
vehicles = []
aatfs = []
dcfs = []
initial_distance = 0
annual_initial_distance = 0
hillclimb_distance =0
annual_hillclimb_distance = 0
total_weight = 0
number_routes = 0

class Vehicle():
```

```
  def __init__(self,ID,vtype,capacity,emissions,variable_cost,fixed_cost,loading_time,unloading_time):
    self.ID = ID
    self.vtype = vtype
    self.capacity = capacity
    self.emissions = emissions
    self.variable_cost = variable_cost
    self.fixed_cost = fixed_cost
    self.loading_time = loading_time
    self.unloading_time = unloading_time

class AATF():
  def
__init__(self,ID,name,latitude,longitude,co2,capacity,assigned_dcfs,dcf_matrix,route_list,distance_matrix,di
stance_vector):
    self.ID = ID
    self.name = name
    self.latitude = latitude
    self.longitude = longitude
    self.co2 = co2
    self.capacity = capacity
    self.assigned_dcfs = assigned_dcfs
    self.dcf_matrix = dcf_matrix
    self.route_list = route_list
    self.distance_matrix = distance_matrix
    self.distance_vector = distance_vector

class DCF():
  def
__init__(self,ID,name,latitude,longitude,generation,capacity,intercollectiontime,vtypes,assigned_aatf):
    self.ID = ID
    self.name = name
    self.latitude = latitude
    self.longitude = longitude
    self.generation = generation
    self.capacity = capacity
    self.intercollectiontime = intercollectiontime
    self.vtypes = vtypes
    self.assigned_aatf = assigned_aatf

class Journey():
  def __init__(self,ID,route,distance,loading):
    self.ID = ID
    self.route = route
    self.distance = distance
    self.loading = loading

class Route():
  def __init__(self,ID,AATF,list_DCF,periodicity,weight,trips_per_year):
    self.ID = ID
    self.AATF = AATF
    self.list_DCF = []
    self.list_DCF.extend(list_DCF)
    self.periodicity = periodicity
    self.weight = weight
    self.trips_per_year = trips_per_year

for i in range(4,4+num_vehicles):
  vehicle_ID = df["A"].iloc[i]
  vehicle_type = df["B"].iloc[i]
```

```
    vehicle_capacity = df["C"].iloc[i]
    vehicle_emissions = df["D"].iloc[i]
    vehicle_variable_cost = df["E"].iloc[i]
    vehicle_fixed_cost = df["F"].iloc[i]
    vehicle_loading_time = df["G"].iloc[i]
    vehicle_unloading_time = df["H"].iloc[i]
    vehicle =
Vehicle(vehicle_ID,vehicle_type,vehicle_capacity,vehicle_emissions,vehicle_variable_cost,vehicle_fixed_cos
t,vehicle_loading_time,vehicle_unloading_time)
    vehicles.append(vehicle)

for i in range(6+num_vehicles,6+num_vehicles+num_AATF):
    aatf_ID = df["A"].iloc[i]
    aatf_name = df["B"].iloc[i]
    aatf_latitude = df["C"].iloc[i]
    aatf_longitude = df["D"].iloc[i]
    aatf_co2 = df["E"].iloc[i]
    aatf_capacity = df["F"].iloc[i]
    assigned_dcfs = []
    dcf_matrix = []
    route_list = []
    distance_matrix = {}
    distance_vector = {}
    aatf =
AATF(aatf_ID,aatf_name,aatf_latitude,aatf_longitude,aatf_co2,aatf_capacity,assigned_dcfs,dcf_matrix,route
_list,distance_matrix,distance_vector)
    aatfs.append(aatf)

for i in range(8+num_vehicles+num_AATF,8+num_vehicles+num_AATF+num_DCF):
    dcf_ID = df["A"].iloc[i]
    dcf_name = df["B"].iloc[i]
    dcf_latitude = df["C"].iloc[i]
    dcf_longitude = df["D"].iloc[i]
    dcf_generation = df["E"].iloc[i]
    dcf_capacity = df["F"].iloc[i]
    dcf_intercollectiontime = df ["G"].iloc[i]
    dcf_vtypes = df["H"].iloc[i]
    dcf_assigned_aatf = ""
    dcf =
DCF(dcf_ID,dcf_name,dcf_latitude,dcf_longitude,dcf_generation,dcf_capacity,dcf_intercollectiontime,dcf_vt
ypes,dcf_assigned_aatf)
    dcfs.append(dcf)

def totalcost(list_DCF):
    total_distance = 0
    if len(list_DCF) >1:
        for i in range(0,len(list_DCF)-1):
            total_distance += aatfs[index].distance_matrix[list_DCF[i].ID][list_DCF[i+1].ID]
    total_distance += aatfs[index].distance_vector[list_DCF[0].ID]
    total_distance += aatfs[index].distance_vector[list_DCF[-1].ID]
    return(total_distance)

def SwapOperator(sol,stop1,stop2):
    sol[stop1], sol[stop2] = sol[stop2], sol[stop1]

hillclimb_distance = 0

#HillClimbing
def HillClimbing(current_solution):
```

```
    solCost = totalcost(current_solution)
    for i in range(100):
        if len(current_solution)>1:
            s1 = random.randint(0, len(current_solution)-1)
            s2 = random.randint(0, len(current_solution)-1)
            SwapOperator(current_solution,s1,s2)
            solCost_new = totalcost(current_solution)
            if solCost_new <= solCost:
                solCost = solCost_new
            else:
                SwapOperator(current_solution,s1,s2)

#Construct Matrix
for index, each_DCF in enumerate(dcfs):
    for each_AATF in aatfs:
        df.at[(index)+8+num_vehicles+num_AATF,"DCF Distance to "+str(each_AATF.ID)] =
distance(each_AATF.latitude, each_AATF.longitude, each_DCF.latitude, each_DCF.longitude)

#Assign closest AATF
for index, each_DCF in enumerate(dcfs):
    min_distance = 100000
    min_distance2 = 100000
    for each_AATF in aatfs:
        current_distance = distance(each_AATF.latitude, each_AATF.longitude, each_DCF.latitude,
each_DCF.longitude)
        if current_distance < min_distance:
            min_distance = current_distance
            nearest = each_AATF
    each_DCF.assigned_aatf = nearest.ID
    df.at[(index)+8+num_vehicles+num_AATF,"Closest AATF"] = nearest.ID

#Listing DCFs that are allocated to each AATF
for index, each_AATF in enumerate(aatfs):
    for each_DCF in dcfs:
        if each_DCF.assigned_aatf == each_AATF.ID:
            each_AATF.assigned_dcfs.append(each_DCF)
    new_list = []
    for each_assigned_DCF in each_AATF.assigned_dcfs:
        new_list.append(each_assigned_DCF.ID)
    df.at[(index)+num_vehicles+6,"H"] = new_list
    df.at[(index)+num_vehicles+6,"DCF Distance to AATF1"] = len(new_list)

#Sum capacity required at AATF for allocated DCFs
for index, each_AATF in enumerate(aatfs):
    utilised_capacity = 0
    for each_DCF in dcfs:
        if each_DCF in each_AATF.assigned_dcfs:
            utilised_capacity += each_DCF.generation
    df.at[(index)+num_vehicles+6,"I"] = utilised_capacity

#For each AATF, rank the assigned DCFs by their intercollection time
#For every AATF produce a list of lists that stores the distances between each assigned DCF
for index, each_AATF in enumerate(aatfs):
    aatfs[index].assigned_dcfs.sort(key=lambda x: x.intercollectiontime, reverse=False)
    aatfs[index].dcf_matrix = []
    for index_1, each_DCF in enumerate(aatfs[index].assigned_dcfs):
        aatfs[index].dcf_matrix.append([])
        aatfs[index].dcf_matrix[index_1].append(each_DCF.ID)
```

```
        aatfs[index].dcf_matrix[index_1].append(distance(each_AATF.latitude, each_AATF.longitude,
each_DCF.latitude, each_DCF.longitude))
        for every_DCF in aatfs[index].assigned_dcfs:
            aatfs[index].dcf_matrix[index_1].append(distance(every_DCF.latitude, every_DCF.longitude,
each_DCF.latitude, each_DCF.longitude))
    current_route = []
    current_weight = 0
    current_index = 0
    current_periodicity = aatfs[index].assigned_dcfs[0].intercollectiontime
    aatfs[index].route_list.clear()
    for i in aatfs[index].assigned_dcfs:
        current_DCF_weight = (i.generation/365)*current_periodicity
        trips_per_year = math.ceil(365/current_periodicity)
        current_weight += current_DCF_weight
        if current_weight <= vehicles[0].capacity:
            current_route.append(i)
        elif len(current_route) == 0:
            current_route.append(i)
            current_periodicity = math.floor(current_periodicity/(current_DCF_weight/vehicles[0].capacity))
            current_DCF_weight = (i.generation/365)*current_periodicity
            current_weight = current_DCF_weight
            current_index += 1
        else:
            current_weight -= current_DCF_weight
            previous_route =
Route(current_index,aatfs[index],current_route,current_periodicity,current_weight,trips_per_year)
            aatfs[index].route_list.append(previous_route)
            current_route.clear()
            current_route.append(i)
            current_periodicity = i.intercollectiontime
            current_DCF_weight = (i.generation/365)*current_periodicity
            if current_DCF_weight > vehicles[0].capacity:
                current_periodicity =
math.floor(current_periodicity/(current_DCF_weight/vehicles[0].capacity))
                current_DCF_weight = (i.generation/365)*current_periodicity
            current_weight = current_DCF_weight
            current_index += 1
    previous_route =
Route(current_index,aatfs[index],current_route,current_periodicity,current_weight,trips_per_year)
    aatfs[index].route_list.append(previous_route)

for currentAATF in aatfs:
    for originDCF in currentAATF.assigned_dcfs:
        currentAATF.distance_matrix[originDCF.ID] = {}
        for destinationDCF in currentAATF.assigned_dcfs:
            currentAATF.distance_matrix[originDCF.ID][destinationDCF.ID] = distance(originDCF.latitude,
originDCF.longitude, destinationDCF.latitude, destinationDCF.longitude)
    for currentDCF in currentAATF.assigned_dcfs:
        currentAATF.distance_vector[currentDCF.ID] = distance(currentDCF.latitude, currentDCF.longitude,
currentAATF.latitude, currentAATF.longitude)

for index, each_AATF in enumerate(aatfs):
    for index1, each_route in enumerate(aatfs[index].route_list):
        initial_distance += totalcost(aatfs[index].route_list[index1].list_DCF)
        annual_initial_distance +=
totalcost(aatfs[index].route_list[index1].list_DCF)*aatfs[index].route_list[index1].trips_per_year

    for index1, each_route in enumerate(aatfs[index].route_list):
        total_weight += aatfs[index].route_list[index1].weight
```

```
    number_routes += len(aatfs[index].route_list)
print(initial_distance)
print(annual_initial_distance)
print(total_weight)
print(number_routes)

for index, each_AATF in enumerate(aatfs):
    for index1, each_route in enumerate(aatfs[index].route_list):
        HillClimbing(aatfs[index].route_list[index1].list_DCF)
        hillclimb_distance += totalcost(aatfs[index].route_list[index1].list_DCF)
        annual_hillclimb_distance +=
totalcost(aatfs[index].route_list[index1].list_DCF)*aatfs[index].route_list[index1].trips_per_year

print(hillclimb_distance)
print(annual_hillclimb_distance)

#Save to Excel
df.to_excel("/Users/matthewbond/Lancaster Python/Coding Output.xlsx")
```

Appendix F – Questionnaires

Haulier Questionnaire:

From REPIC's WEEE reporting data, we have information on the route that WEEE takes from collection, sometimes via consolidation sites, to the AATF for treatment. This has allowed an approximate transport distance to be calculated for each tonne of WEEE.
The following questions collect data that will allow this distance to be converted into a carbon footprint, using information about fuel consumption, route planning/scheduling, and vehicle loading.
Please provide data from 2019 where possible. As the most recent 'normal' year we are basing initial calculations on 2019.
We are aware that the data collection has limitations, and that many values will be approximations. Please indicate where approximations/generalisations have been made and the data will be treated accordingly.

Your input into this calculation is vital and much appreciated.
The results will quantify the huge environmental benefit of WEEE recycling, and we hope will encourage further uptake of the WEEE recycling schemes available.
REPIC will circulate information about the calculated carbon footprint and benefit of the WEEE recycling system once the work has been finalised.

1. Routing Questions for collections from HWRCs or retailer sites:

If differences exist between collections in different local authority areas, break down the details e.g. Area 1 = 100% REPIC WEEE, Area 2 = 50% REPIC & 50% other WEEE.

1.1 – Do your vehicles operate out of a depot? Provide postcodes if so:

Yes –
Multiple Depots –
No –

1.2 – How are your WEEE collections scheduled? How flexible is the schedule?
(Is there a fixed schedule eg. weekly collection, or is collection only when notified by the recycling site?)

1.3 – Is each collection from a DCF made in a single out and back journey, or are multiple WEEE collections made in each journey? Please provide details of any multiple collections.

1.4 – How loaded are vehicles on WEEE collections on average?
(please provide % loading, or full/less than full).

1.5 – Is only REPIC WEEE collected, or is other, non-REPIC, WEEE collected simultaneously (if so, indicate a rough % of the load which is REPIC's).

1.6 – Are the other legs of the journeys (e.g. to the HWRC before waste collection) made empty, or are other, non-REPIC, loads transported?
Indicate a rough % of the proportion of legs journeys made empty

2. Routing Questions for collections from consolidation sites:

2.1 – If you use a consolidation site(s), provide the postcode(s) below.

2.2 – How are collections from the consolidation sites scheduled?
(Is there a fixed schedule eg. weekly collection, or is collection only when notified by the consolidation site/treatment facility)

2.3 – Similar to question 1.6, are the other legs of the journey made empty? Indicate a rough %.

2.4 – What tonnage of WEEE is transported per journey (average values are fine).

____Tonnes per journey

3. Vehicle Questions:

3.1 – What vehicle type do you use? (tonnage, rigid/articulated, tail-lift/roll-on-roll-off).

Rigid	<7.5t
	7.5-17t
	>17 t
Articulated	<33t
	>33t

If multiple types used, give the number of each type (e.g. 3 of Truck A, 2 of Truck B) and what each is primarily used for.

3.2 – What is the real life fuel consumption of your vehicles?
If multiple types used, give a fuel consumption of each type.
(if mpg not recorded, just provide vehicle age and emissions level)

Actual mpg –
Euro emissions level –
Vehicle age –

4. Any additional notes:

<u>AATF Questionnaire:</u>

For sites that treat REPIC WEEE.

From REPIC's WEEE reporting data, we have calculated the tonnage of each stream of WEEE that was received in the year of 2019 at each AATF. The following questions collect data that will allow an <u>approximate</u> carbon footprint for the AATF treatment stage of this WEEE to be estimated. We are aware of the limitations of this approximate data, and it will be treated as a rough estimate.
The attached 'Residues Form' Excel sheet intends to collect data on the proportion of material being recycled, energy recovered and landfilled, which allows the carbon *benefit* of the WEEE recycling system to be calculated. This has more impact on the overall carbon footprint, so requires <u>more accurate data</u>.
Please provide data from 2019 where possible. As the most recent 'normal' year we are basing initial calculations on 2019.

Where your organisation runs more than one WEEE treatment location, please provide separate responses (multiple copies of this form and the 'residues form') if the process is different between the locations. E.g. if you run a fridge recycling plant at a separate location from the rest of your WEEE treatment, please fill in a separate form for each. Or if one location uses a more modern technology with higher recovery rate, please fill in a separate form for each location.

Your input into this calculation is vital and much appreciated.
The results will quantify the huge environmental benefit of WEEE recycling, and we hope will encourage further uptake of the WEEE recycling schemes available.
REPIC will circulate information about the calculated carbon footprint and benefit of the WEEE recycling system once the work has been finalised.

Type of WEEE Processing:

1. Does your facility use manual disassembly, mechanical shredding, or a combination of both. Please give a brief description of your process below for each WEEE stream as appropriate:

LHA: Cooling: Small Mixed WEEE: Displays: Lamps: Reuse:

Energy Usage:

1. If possible, please provide data on the energy usage per tonne of WEEE treated at your facility, for each WEEE stream processed (LHA, Cooling, Small Mixed WEEE, Displays, Lamps).
   Energy usage should include electricity consumption and any fuel usage (diesel, natural gas), for cooling it should include nitrogen usage.

Energy Usage **per tonne of WEEE**	Diesel (l)	Electricity (kWh)	Nitrogen (l)	Other Consumables
LHA			N/A	
Cooling				
SMW			N/A	
Display			N/A	
Lamps			N/A	

Brief description of how this was calculated:
If any electricity is supplied by diesel generators provide details below: How were the generators accounted for in the table above? : Percentage of total electricity supplied by generators: Diesel usage per kWh electricity:

If your data does not allow this, please follow the steps in section 2 on the next page for manual calculation, otherwise proceed to section 3:

2. Manual energy usage calculation:

2.1 – What is the total electricity consumption of your facility? (available on energy bills)

_____kWh of electricity per year

2.2 – What is the total fuel consumption of your facility? (Diesel for generators and vehicles, gas for heating).

____Litres of diesel per year
____kWh of gas per year

2.3 – What is the total tonnage of waste received for recycling annually at your facility. We will use this to work out the proportion of your tonnage that is REPIC's WEEE.

_____Tonnes of waste received for recycling

2.4 – Are there any processes that take place within your plant that you believe should be deducted from the energy usage, or bared in mind for the carbon footprint estimation?

e.g. further disassembly/reprocessing; producing nitrogen on site...

3. Further Energy Questions:

3.1 – Does your facility produce its own electricity, or purchase electricity through a 'green electricity tariff'? Please provide details if so.

Any additional notes:

AATF Residues Questionnaire:

(attached as pdf)

WEEE RESIDUES

In order for this Lancaster University research project to quantify REPIC's carbon footprint, and that of the full supply chain, details of the outcome of treatment of REPIC's WEEE is required. Different carbon footprints are associated with reuse, recycling, energy recovery and landfill, and the carbon footprint also varies by country for the final recycling. This form aims to collect data on these to inform the carbon footprint. Please complete, as best possible, each sheet that is applicable to the WEEE streams you treat for REPIC. Where you treat other WEEE than just REPIC's, data from your aggregate treatment is sufficient. Thank you for your support in this research and the aim of reducing the carbon footprint of the WEEE system.
Where your organisation runs more than one WEEE treatment location, please provide separate responses (multiple copies of this spreadsheet) if the process is different between the locations. E.g. if you run a fridge recycling plant at a separate location from the rest of your WEEE treatment, please fill in a separate form for each. Or if one location uses a more modern technology with higher recovery rate, please fill in a separate form for each location.
Please Note - A confidentiality agreement between the researcher and REPIC ensures that any information created, received, held, or transmitted is handled confidentially. Any published work will only include aggregated data that cannot be used to identify individual data sources, unless express permission has been given.
Please provide data from 2019 where possible. As the most recent 'normal' year we are basing initial calculations on 2019.
TABLE A: WEEE prepared for re-use By your organisation- The information recorded in this table should relate to appliances that have **entered your site as waste and which leave your site as non-waste only.** These appliances should be suitable for direct use by consumers without any checking, cleaning, testing or repair being first required. The percentage of your site input for the relevant stream to which this applies should be completed in cell B3.
TABLE B: WEEE supplied to another UK organisation for preparation for reuse- The information recorded in this table should relate to appliances that have **entered and have left your site as waste and which you have supplied to another UK organisation for the purpose of reuse.** This may include appliances which you have inspected, or undertaken some preparatory reuse work on yourself, but require further checking, cleaning, testing or repair before they can be classed as non-waste. The percentage of your site input for the relevant stream to which this applies should be completed in Cell B7.
TABLE C: WEEE Treated by your organisation The information recorded in this table should be the percentages applicable to only the appliances that you have treated. The percentages provided should not encompass appliances that you have prepared for reuse, supplied to another organisation for this purposes, nor any whole appliances you have supplied to another organisation for treatment. The recycling and recovery percentages provided in columns D and E must incorporate the processing efficiencies of the downstream processors to which you have supplied each product listed. An example of how to do this is provided under the heading "Recycling and Recovery Percentages" below. The total under the headings J, O and in cell at the base of column B should be 100%. Please add in other residues, inserting as many additional rows as is needed in which to record this information.
TABLE D: WEEE Treated by your organisation (Cooling only) Please ensure that the units of measure are included in columns E and F for example mg/kg. If you have had only one analytical result in the relevant quarter, please complete the highest result column only and enter "N/A" in the lowest result column. Please enter "N/A" if you have not had any analytical results in that quarter. You may wish to use column G to provide further details, either in relation to the results or the analysis. It will be particularly helpful if you would include any unusual operating conditions that may have affected your results and for Cooling Appliances, please provide details of the abatement system used in Cell G47 (e.g. bag filter).
Recycling and Recovery Percentages This is the proportion of each output that is ultimately recycled. This is unlikely to be 100% for all outputs since not all downstream processors will meet the "acceptable reprocessor recycling efficiencies" published for Defra for all outputs. To calculate the recycling and recovery percentage, you need to ascertain the percentage of each output that is recycled by downstream processors and where there is a published "acceptable reprocessor recycling efficiency", which this falls below, you need to apply the downstream reprocessor's efficiency to that output, rather than declaring it is 100% recycled. For illustrative purposes, if you supply mixed plastic to a plastic recycler, this does not necessarily mean that 100% of your plastic is recycled; the plastic recycler may seperate the BFR plastics and send these for recovery. The plastic recycler advises you that 65% of the weight of plastics you send them is recycled, they send 20% on for recovery and 15% are contraries that they send for disposal. The acceptable recycling efficiency publised by Defra for plastic is 75%, so you cannot record 100% of your plastic as recycled since it is below this level. The percentages you would enter in column C and D for plastics would be 65% and 20% respectively. NB* although your overall recovery rate includes the proportion you recycle, please record in column D only the percentage sent for a recovery activity.

REUSE

Table A - Large Household Appliances prepared for reuse by your organisation

		Of the total Reuse, please identify % split by destination				
% of total WEEE input prepared for Reuse by your organisation		**UK** Customer	**EU** Customer	**Non – EU** Customer	If Non EU State(s) Please Specify Country (is)	Total
This is where whole appliances arrive with your organisation as waste and leave as non-waste						0%

TREATMENT: PRODUCTS AND WASTE

Table C - Large Household Appliances treated by your organisation or supplied to another UK organisation for treatment

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
										Final destination for recycling material recovery (if known) e.g. Portuguese iron smelter				
WEEE Residue Description	% of material from the WEEE stream being treated	% Recycled	% Energy Recovered	Energy Recovery Details	% Landfill	Landfill Site Location	% Other	If Other - Please Specify	Total	**UK** Processed	**EU** Processed	**Non – EU** Processed	If Non-UK Please Specify Country	Total
Name	%	%	%	eg. Teeside Energy from Waste Plant	%	e.g. Veolia Portsmouth	%		%	%	%	%		%
Light Iron									0%					0%
Stainless Steel									0%					0%
Aluminium									0%					0%
Copper									0%					0%
Other non-ferrous metal									0%					0%
Cable									0%					0%
Concrete									0%					0%
Plastics									0%					0%
Glass									0%					0%
Residue									0%					0%
									0%					0%
Other - Recyclables or Waste (please specify below)														
									0%					0%
									0%					0%
									0%					0%
									0%					0%
Total	0%													

% of total mass recycled	% of total mass energy recovered
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%	0.00%
0.00%	0.00%
0.00%	0.00%
0.00%	0.00%
0.00%	0.00%
0.00%	0.00%

How were your recovery rates calculated: a) Mass balance data. b) Batch testing of each waste stream c) Other (please describe)	

LDA recycling rate	0%
LDA recovery rate	0%

Additional Notes

Appendix G – Research Ethics Form

(Attached as PDF)

FASS-LUMS Research Ethics Committee

Ethical Approval Form for UG and taught PG students

This form should be completed for each project involving the collection of data from human participants that you undertake on your UG or MA programme (including as part of your taught modules, self-directed study and UK/MA dissertation). The form must be approved and signed by your dissertation supervisor PRIOR to any data collection taking place. A completed copy of your form should be included in the appendix of your dissertation. When you submit the completed form to your supervisor, you must give them time to read it carefully and suggest amendments. You must allow time to make any amendments they might suggest before beginning your data collection. When you complete this form you may want to consult relevant guidelines for ethical research, such as by the British Sociological Association, the British Education Research Association or the ESRC. **Please note:** if your study involves the use of data from social networking sites or other online data, you are still being asked to complete this form, in particular if the data you will use could be considered private and/or is dealing with sensitive or personal topics.

Name of student, Department, e-mail address

Matthew Bond

Department of Entrepreneurship and Strategy

m.bond@lancaster.ac.uk

Module this application is related to:

MSc by Research Innovation Thesis (Centre for Global Eco Innovation)

Name of dissertation supervisor

Dr Burak Boyaci, Dr Lingxuan Liu, Dr Ahmed Kheiri, Dr Alison Stowell

Project title

Development of a Carbon Calculator for Waste Electronic and Electrical Equipment

Overall aim of the project and research questions (please be brief, no more than 4-5 sentences)

The overall aim is to develop an Excel tool that calculates the carbon footprint of the different stages of an e-waste recycling supply chain, on behalf of REPIC, a client who commissioned the Masters. The data will then be used to calculate improvements to the logistics, using an optimisation model. Data will be collected for each stage of the recycling supply chain's energy consumption and emissions. Data collection from the supply chain will allow the tool to accurately represent the up-to-date UK supply chain, in a level of detail not reached in the research literature.

What will be the research methods?

There are three modes of data collection:

1. Quantitative data collected by the sponsoring company on carbon metrics and measurements
2. Questionnaires sent by the sponsoring company to their supply chain.
3. Secondary data drawn from academic publications and life cycle analysis databases.

Who are the intended participants and how will you recruit them?

The questionnaires are to be filled in with details of entire companies rather than specific individuals, all company contacts are over the age of 18. REPIC will contact each of the companies in its supply chain, outlining the details of the project and asking if they give permission for their details to be shared with the researcher (me). Participation is voluntary and there will be no obligation to take part.

Where will the research be carried out and do you have permission from the organisation(s) concerned (e.g., the school you want to work in)?

The research will be carried out working from home for the duration of the project, with regular meetings over Microsoft Teams with LUMS supervisors and the client company (REPIC). Questionnaires will be sent out by email from REPIC, with permission from the Chief Executive.

Do any of the aspects of the study pose any risks to the participants' physical or emotional well-being (e.g., might they find taking part embarrassing or may they be asked to discuss topics which are emotionally upsetting)?

No

Does your project involve people or groups who may be vulnerable, in particular in the context of the planned research (e.g., children in schools who may be vulnerable to feeling under pressure to consent to taking part in the study)?

No

Does your project involve covert methods or any form of deception or limited disclosure (this may be necessary in some forms of experimental research)?

No

How will you ensure that data participants share with you will only be used in such a way that they cannot be identified? (e.g. will you use pseudonyms; will you use aggregated data so that individuals' views cannot be identified; will you use anonymised quotes?) How will you ensure that participants' personal data will be kept confidential (e.g. that it will be stored securely and separate from the research data)?

Aggregated data will be used so individual companies' commercially sensitive data cannot be identified. Only with express permission from each company will specific quotes or data be published. No personal data is collected in the questionnaires. Questionnaire data is sent directly to the LU Researcher by email. The company contact named in the email will not be shared with REPIC (the sponsoring company). All data collected will be held in encrypted files on a password protected laptop, and the emails containing the data deleted. Upon completion of the research, expected to be 31/10/2021, the individual companies' data will be deleted, unless express permission is granted by the participant companies for REPIC to have access to the data.

Will participants be given accessible information explaining: the general aim of the study; what they will be expected to do; how their data will be stored and how you will use their data in the essay/dissertation?

The first page of each questionnaire informs the companies the aim of the study, why their input is required, the confidentiality agreement that the data will be held under, and states that any published work will only include aggregate data that does not allow individual sources to be identified, unless express permission is given. This page, and the full questionnaire are attached at the end of the document.

<u>Please include a participant information sheet and consent form with this application</u>

<u>Student signature</u>	**Date**
Matthew Bond	**20/08/2021**
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Approval

Dissertation Supervisor | **Date**

Burak Boyaci	**20/08/2021**
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Approval

Dissertation Supervisor	**Date**
Lingxuan Liu (e-signed)	**20/08/2021**
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Approval

Dissertation Supervisor	**Date**
Ahmed Kheiri	**20/8/2021**
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Approval

Dissertation Supervisor	**Date**
Alison Stowell	**19th August 2021**
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[Name
[Address]

25th October 2020

Dear [name],

Lancaster University REPIC Carbon Footprint Research - Request to provide data and information

I am writing to request your support for a project REPIC is undertaking with Lancaster University. The aim of the research is to enable REPIC to report on the carbon footprint of the WEEE which we finance the collection and recycling of, and to assist us longer-term in reviewing our carbon footprint. The outcomes of the research will be a report identifying the overall carbon savings associated with recycling WEEE and a carbon calculator tool to assist us going forward.

To enable this, we need detailed data from our transporters and treatment providers, to map the overall energy use and savings within the system. Further information about the research and how your data will be used is outlined below:

REPIC & Lancaster University carbon footprint research summary

This research, undertaken at Lancaster University, in partnership with REPIC, seeks to measure and reduce the carbon emissions of the collection and recycling of WEEE in the UK. To create a carbon emission calculator, data on WEEE collection and treatment activities will be collected from REPIC and its partners and collated, quantified and analysed in relation to carbon benefits and impacts. This will form the basis for a report outlining the overall carbon benefits of WEEE recycling. The system mapping will subsequently provide input for an optimisation model or tool.

A confidentiality agreement between the researcher and REPIC ensures that any information created, received, held, or transmitted is handled confidentially. Any published work will only include aggregated data that cannot be used to identify individual data sources, unless express permission has been given.

Matthew Bond, the researcher, has devised a detailed survey to collect the relevant information. This is provided in the file(s) attached. We would like your permission to pass on your contact details to Matthew so that he can talk you through the information needs in more detail and clarify any concerns you may have regarding commercially sensitive information.

I recognise that the level of detail requested is not insignificant. This is a great opportunity to communicate and quantity the carbon savings our sector is making, and I do hope that we can have your support in assisting REPIC with this study.

Yours sincerely,

Graeme Milne
Strategic Business Development Director

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E — info@repic.co.uk
W — repic.co.uk

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