CLOSING THE CYCLES OF IRON, STEEL AND ALUMINIUM IN THE UK

ON RECYCLING RATES, SCRAP QUALITY AND COLLECTION OF DISPERSED SCRAP

by

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Abstract

The closure of anthropogenic substance and material cycles is a central theme in industrial metabolism and ecology. Its desirability is based on the analogy with biological nutrient cycles that are closed, as a requirement for their long-term sustainability. This thesis sets out to assess the level of closure of the UK iron, steel and aluminium cycles; i.e. three of the main structural 'nutrients' of the global industrial ecology. To investigate this a new time-dependent methodology for material flow analysis (MFA) has been developed. In sectors such as iron, steel and aluminium where the life-span of goods may be long and the life-spans differ between applications, it is vital to include a temporal dimension in the MFA; different products available as scrap entered use at quite different past times. In this analysis, residence time distribution theory, as developed in chemical engineering science, has been successfully adapted to simulate the delay of goods in use. The methodology has been applied to track the flows of iron, steel and aluminium through the UK economy. Historic information on the amounts of these metals going into different groups of goods, together with values for their estimated life-spans, have enabled modelling of the yearly release of iron/steel and aluminium scrap from the use phase in the form of end-of-life scrap.

The iron and steel MFA carried out in this work shows that for 2001, the estimated release of end-of-life scrap and prompt scrap significantly exceeds the documented amount of scrap that is consumed within the country or is exported. This indicates a loss of end-of-life scrap of around 30% (corresponding to three and a half million tonnes). For aluminium, the analysis also shows that for 2001, the estimated amount of released prompt and end-of-life scrap is higher than the documented amount of recovered scrap. There is a loss of end-of-life scrap of about 20% (corresponding to 160 thousand tonnes). For both metals, a level of closure was achieved in the MFAs; i.e. modelled amounts of metal emerging from use could be largely balanced with documented amounts of metal being recycled and sent to landfill. The analysis shows that using a distribution of the life-span (as opposed to a fixed life-span) when modelling the delay of goods in the use phase is more important when the input of goods into use shows a significant increase or decrease over time.

To achieve and maintain higher recycling rates of these metals it is vital to avoid build-up
of alloying and contaminating elements in the scrap cycle. A model for exploring potential contamination build-up in the metal cycle has been developed in this work, which builds on the MFA methodology, incorporating the temporal dimension. It examines consequences for the composition of the metal flows depending on different future scenarios. A case study of exploring potential build-up of tin in the iron and steel cycle between 2000 and 2020 was performed to demonstrate the model. Not surprisingly, both increasing recycling rates and decreasing scrap exports leads to increases in the concentration of tin in metal products. By separating the scrap before remelting and choosing more carefully what type of scrap goes to which production, build-up can be avoided. The methodology presented here should prove useful in further exploring potential contamination in metal products and developing strategies how to avoid it.

The MFA studies show there are still improvements to be made in recovering end-of-life iron/steel and aluminium scrap. Small products such as packaging stand out as a major challenge for these metals. Therefore, possible ways of collecting beverage cans were investigated in a case study of used aluminium beverage cans (UBCs). Two main issues explored included the questions: (1) Does transport intensity differ greatly between various types of collection systems, recovery rates and population density? and (2) How significant is the environmental impact of the collection stage compared to the whole life cycle of the can? Overall, the differences in environmental impacts between the collection systems (kerbside, can banks and deposit) are not considerable. Transport per collected unit increases with decreasing population density. However, in the context of the whole life-cycle of aluminium cans, the analysis of the systems shows that over a range of population density, the collection stage makes negligible contribution to environmental burdens. The savings in environmental impact of recovering and recycling the cans after use far outweigh the impacts of collecting them. This very much highlights the need for functional and easily accessible recovery infrastructures for aluminium cans in the UK.

Keywords:
Time-dependent material flow analysis, residence time distribution, industrial ecology, iron/steel, aluminium, contamination, scrap quality, collection of used beverage cans, life cycle approach
For Mum
Preface

This work was performed under the course of two projects: the first, *Integrated Chain Management of Structural Metals* involved the development of industrial ecologies for iron, steel and aluminium in the UK, and was funded by the Engineering and Physical Sciences Research Council (EPSRC); followed by *Iron, Steel and Aluminium in the UK: Material Flows and their Economic Dimensions*, a mass balance project covering the whole production chain of iron, steel and aluminium in the UK. This latter project was funded by Biffaward under the Landfill Tax Credit Scheme, with contribution from Corus Research Technology & Development and the European Aluminium Association. The financial support from these institutions are gratefully acknowledged.

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I will look back on my time in CES with a smile thanks to all the amazing PhD students and staff from all over the world, I have enjoyed getting to know all of you! I would in particular like to thank Marilyn and Tam for your friendship and support.

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Gothenburg 31 October 2004
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Introduction

This chapter describes the main issues for ensuring sustainable use of iron, steel and aluminium and outlines the research questions addressed in this thesis. The importance of recycling these metals is discussed and the usefulness of material flow analysis as a tool for better understanding current recycling practices is demonstrated. Contamination of the scrap and environmental impacts of collecting dispersed scrap are then addressed.

1.1 SUSTAINABLE USE OF MATERIALS

In these industrialised times, it is recognised that use of material and energy resources and associated generation of wastes and dispersed emissions from human activities are steadily increasing; see e.g. Jackson (1996). This pattern is unsustainable and there are growing concerns about the environmental impacts caused by these material and energy intensive activities.

The human economy can be portrayed as in figure 1.1 (Clift 1997). Here, we see the required material flows to satisfy human needs. Human needs are met mainly by agricultural (e.g. food) and industrial activities (e.g. fuel and clothes), and also directly by natural ecosystems (e.g. air). Looking at this figure, the environmental problems connected to human activities can be categorised into two very broad groups: relating to extraction of non-renewable resources and relating to outputs of dispersed waste and emissions. We continuously extract non-renewable
1.1 Sustainable use of materials

Figure 1.1: The human economy (Clift 1997).
1.2 Recycling of iron, steel and aluminium

resources (mineral rock, metal ore etc), some of which will ultimately run out or will only be available in very low concentrations and therefore too expensive to extract. This is a problem as our current society is very dependent on many of these resources. The second problem concerns what we emit back into the environment, and the impacts these emissions have. To give a few examples, we emit phosphorus and nitrogen into water systems which causes eutrophication, chlorofluorocarbons (CFCs) which deplete the ozone layer, and CO₂ which contributes to the greenhouse effect and climate change. Human society is affecting the natural environment in an unprecedented way; with unpredictable consequences.

One important strategy for reducing the extraction of non-renewable resources and emissions is to increase the use, and re-use of waste. This not only reduces the amount of material entering the waste stream, but also displaces the need for extracting primary resources, and thereby avoids generation of waste and emissions and energy requirements earlier in the supply chain. As long as the waste is not dispersed or irreversibly contaminated, it can in principle be re-used a number of times, which is an essential part of industrial ecology and metabolism, see figure 1.2 (Mellor et al. 2002). Industrial ecology aims for closed material cycles whereby waste is seen as a resource rather than a disposal problem. To close the material cycles, one must go beyond re-use and recycling, to include use and re-use of materials in a series of different applications as demonstrated in the figure. These successive applications will often have progressively lower performance specifications. As an example, tin cans can be recycled a number of times until the specifications for sheet used in packaging can no longer be met; the metal can then be used in reinforcement bars or other applications with lower product specifications than this sheet. A sequence of applications as in figure 1.2 is sometimes called a cascade of uses.

1.2 Recycling of iron, steel and aluminium

As mentioned, the environmental motivator for recycling is often the benefit of displacing the need for extraction of primary resources. Whether the benefits of recycling outweigh the resources needed can be assessed by comparing the benefits obtained with the energy and material inputs to recycling. For metals, the benefits often far outweigh the resources required for recycling. Moreover, metal is particularly suitable for recycling as, in theory, it can be recycled an
unlimited number of times without losing any of its properties. However, mixing with alloying elements and possible contamination still leads to a pattern of cascaded uses.

Production of iron, steel and aluminium puts a large burden on the environment. The production routes of iron, steel and aluminium and their associated environmental interventions are described in more detail in chapter 2. To name a few concerns, aluminium production contributes to land degradation during mining of the bauxite, and generates emissions of alkaline solids ('red mud') and fluorinated hydrocarbons (molecules with high global warming potential) and consumes significant amounts of energy. Apart from the energy requirement, iron and steel production also produces considerable emissions of CO$_2$, CO, NO$_x$ and SO$_2$ and substantial amounts of solid waste. In order to reduce the environmental impacts of steel and aluminium, we must rethink the way in which we produce and use these metals and identify a more sustainable way forward. The following principles, not specific to any particular industry, could serve as a starting point for this (Ayers 1993):

- no (anthropogenic) change in the climate;
- no net increase in the acidity of the environment, especially the fresh water lakes and rivers.
1.2 Recycling of iron, steel and aluminium

and forest soils;

- no net accumulation of toxic heavy metals, radioactive isotopes, or long-lived halogenated chemicals in soils or sediments;
- no net withdrawal of groundwater;
- no net loss of topsoil; and
- no further net loss of wetlands, old-growth forest, or biological diversity, among other biological resources.

These principles are quite specific but only bring up issues which are currently recognised concerns. In future, there might be other issues that are just as or more important to consider, but we are not yet aware of them. Although they are not timeless, these principles offer a good starting point and can advise industry on what they should be aiming for.

Referring back to the portrayal of the human economy (figure 1.1) we discussed the extraction of non-renewable resources and dispersed emissions and wastes as threats to our long-term sustainability. In terms of bauxite and iron they are plentiful in the earth's crust; 8 and 5% respectively (Wedepohl 1995), so it seems we are unlikely to run out of these resources in the foreseeable future. What is more pressing is the pollution and energy use associated with extraction and processing of these metals, and thereby the failure to comply with the above mentioned principles.

Bauxite and iron ore are not only amongst the most abundant metals in the earth's crust; aluminium and iron are also the two metals which society produces the most. Figure 1.3 shows this correlation between availability and use of metals in society (Andersson 2001). Today the world annual production figure of crude steel is 965 million tonnes (IISI 2004). World primary aluminium production has increased rapidly from 1 million tonnes per year at the end of the Second World War to nearly 22 million tonnes in 2003 (Roskill 1999; IAI 2004). This growing trend is forecast to continue for some time as aluminium is continuously breaking into new markets (King 1997).
1.2 Recycling of iron, steel and aluminium

These large production volumes of steel and aluminium result in extensive auxiliary energy and material fluxes for their processing. The environmental impacts due to iron, steel and aluminium production are well recognised and documented, as described in chapter 2. The environmental savings from recycling of these metals are confirmed by the Life Cycle Inventory (LCI) studies that have been conducted for steel (IISI 2000) and aluminium (Bousted 2000), investigating all production processes from 'cradle to gate'. To give a few examples, production of primary steel requires six times more coal and emits three times more CO₂ than producing steel from remelting of scrap (BUWAL 1996a). For aluminium, the difference is even more evident: the secondary route only requires a fraction of the energy consumption, ca 5%, compared to that of the primary smelting (Bousted 2000). The main differences in environmental burdens between the production routes are summarised in table 2.1 in chapter 2. Thus, there is an environmental incentive for creating industrial ecologies, or 'closing the cycle', for these metals and thereby maximising the potential for secondary production.

Figure 1.3: Metal abundance in the Earth’s crust and metal use in society in 1999 (Andersson 2001).
1.2 Recycling of iron, steel and aluminium

It is not possible to separate secondary production from primary production, as the metal has to come from primary production in the first instance, but what is vital is ensuring that the metal that has been produced from virgin resources is not lost further down the process chain. In order to close the material cycle for steel and aluminium it is thereby vital to make sure that as little scrap as possible is being lost from the economic system.

1.2.1 Scrap

Losses of metal can occur at each stage in the iron, steel and aluminium cycles, which is often defined using the three process groups: production, fabrication/manufacturing and use (Michaëlis & Jackson 2000). The metal wastes that correspond to these three process groups are called home scrap, prompt or new scrap, and end-of-life or old scrap respectively, see figure 1.4. Home scrap is produced at the production plants of the metals. This scrap is recycled internally at the production plant and has recycling rates close to 100%. Fabricators and manufacturers of goods (packaging, automotives etc.) generate prompt scrap during their cutting, drawing, extruding and machining operations. Typically, prompt scrap has known physical and chemical characteristics, low contamination, and uncomplicated reverse logistics back to the metal plants for reprocessing. For these reasons prompt scrap is characterised by very high recycling rates. Overall, loss rates from iron, steel and aluminium production, fabrication and manufacturing are very low, and the home and prompt scrap cycles are fairly tightly closed. Things are different, however, for the iron, steel and aluminium contained in products that have reached the end of their useful lives, so called end-of-life (EOL) scrap. It is here where the highest uncertainties for levels of recovery exist and where the highest loss rates in these metal cycles are to be expected.

1.2.2 Recycling directives

Efforts to increase the recovery and recycling of end-of-life goods have been made on a European level. In 1994 the EC launched its directive on packaging and packaging waste, which was the first example in Europe of extended producer responsibility (EC 1994). The directive dictates specific recycling targets that have to be met by member countries by 2001. These targets have
1.2 Recycling of iron, steel and aluminium

![Diagram showing the different process stages in metal production and the corresponding nomenclature of generated scrap.](image)

Figure 1.4: The different process stages in metal production and the corresponding nomenclature of generated scrap.

been fulfilled in all member countries and new targets to be achieved have been proposed by the Commission. Under the accord, member states would have to recycle at least 55% and at most 70% of their waste packaging by 2008. Individual material-specific targets for generated waste were set at 55% for paper and board, 60% for glass, 50% for metals and 20% for plastics (EC 2002). Other protocols from the Commission include the Directive on End-of-Life Vehicles (EC 2000), WEEE - Waste from Electrical and Electronic Equipment (EC 2003b) and RoHS - Restriction of the use of certain hazardous substances in electrical and electronic equipment (EC 2003a). The ELV directive aims at 95% reuse or recovery of end-of-life vehicles by 2015. The WEEE directive states that four kilos annually of electrical and electronic waste must be collected per inhabitant by the end of 2006 and that firms will have to meet recycling targets of between 50% and 75% of product weight depending on appliance type. Furthermore, the RoHS bans lead, mercury, cadmium, hexavalent chromium and the brominated flame retardants PBDE and PBB in manufacture of these products from July 2006.

Directives like these put pressure on governments and parties in the product chain to improve the recovery of end-of-life products. This pressure seems to have had some effect within some sectors. In the UK, the recovery of aluminium cans reached 42% in 2001, a huge improvement since 1989 when only 2% was recovered (Alupro 2003); this will be discussed further in chapter 5. However, it is very hard to find information on what the recovery rate of metal is for other sectors. Even if some sectors provide recovery or recycling rates, it is not always clear how these rates have been derived. The lack of information on how much steel and aluminium is actually recovered is due to the fact that it is very hard to measure how much steel and aluminium in end-
of-life goods is potentially available for recycling each year. Part of this dissertation addresses this particular problem, and attempts to provide guidance on how this can be tackled (chapter 3).

1.3 MATERIAL FLOW ANALYSIS

One possible way of analysing the flows of steel and aluminium scrap from end-of-life goods, is to compile data on historical flows of iron, steel and aluminium through the economic system. A material flow analysis (MFA) that allows for the delay of stocks of goods in the use phase could be used to estimate end-of-life scrap arisings.

MFA is a fast-growing research field with increasing policy relevance, as a means to explore the economy-environment relationship. In general terms, MFA refers to the analysis of the throughput of process chains comprising extraction or harvest, production, manufacturing, use, recycling and disposal of materials. It is based on accounts in physical units (usually mass) quantifying the inputs and outputs of those processes (Bringezu & Moriguchi 2002). Despite, or possibly because of, its popularity there are as yet no internationally agreed guidelines or accounting methodology for MFA; rather, various methodological approaches have been used. However, there is an international network called ConAccount which was established in 1996 to provide a platform for information exchange on MFA (ConAccount 2004).

Even though there are methodological differences in MFA studies, they are all based on the application of the mass balance principle, loosely formulated as ‘what goes in must come out’ (Kleijn et al. 2000). In the UK, the Mass balance suit of Biffaward projects has generated data on resource flows through the UK economy; to maximise the usefulness of the data a common framework has been developed which is based on the mass balance principle (Linstead & Ekins 2001). The work on material flows on iron, steel and aluminium in this thesis, described in more detail in chapter 3, is part of these Biffaward projects.

There are basically two different types of MFAs depending on the primary focus of the analysis. Most MFAs would claim to contribute to knowledge that is essential to develop the industrial ecology. However, different strategies have been pursued to achieve a sustainable industrial ecology. One strategy can be described as detoxification and is aimed primarily towards the mitigation of polluting elements to the environment; this corresponds to the first three principles
by Ayers (1993) stated earlier. Here, MFA is used to determine the main entrance routes to the environment, the processes associated with these emissions, and the stocks and flows within the industrial system; in aid of the search for effective reduction measures. This type of MFA, also called substance flow analysis (SFA), is often applied to toxic substances such as heavy metals but also to other elements such as nutrients and carbon. The other complementary strategy to attain an industrial ecology can be described as dematerialisation. Dematerialisation implies provision of services and value-added in the economy with reduced resource requirements, which can indirectly be linked to the principles stated by Ayers (1993) earlier. This strategy can imply the reduction of the throughput of the economy as a whole, comprising the use of primary and secondary (recycled) materials. But it may also imply the reduction of primary resources and waste and emissions related to the service, product or benefit provided. To aid this strategy, MFA is used to analyse the throughput of bulk materials (e.g. plastics, biomass or, in our case, iron/steel and aluminium) of a sector, region or nation. This type of MFA is sometimes used to derive indicators for sustainability, e.g. Direct Material Input (DMI) and Total Material Requirement (TMR).

It is common in MFAs to account for one or two years’ flows of the studied system; i.e. use a simple “current account” approach. However, in sectors like iron, steel and aluminium, where the goods life-spans can be significant and the life-spans differ between applications, it is vital to include a temporal dimension in the MFA; different products available as scrap entered use at quite different past times. Michaelis & Jackson (2000) have performed a time-dependent material, energy and exergy analysis of iron and steel in the UK, in which an estimate of the overall recovery rate for iron and steel end-of-life scrap of 48% was derived for the year 1994. However, in the analysis, all iron and steel entering use is treated as one flow: i.e. there is no disaggregation into which type of goods the metal is contained in. As a consequence, it was necessary to assume an average life-span for all goods. The end-of-life scrap arisings were estimated by assuming that all goods in use have an average life-span of 15 years, i.e. scrap arisings in a particular year was assumed to be equivalent to the demand 15 years ago. The diversity of goods that contain iron and steel means that they will have very different life-spans. In order to infer more reliable figures for scrap arisings, the effect of assuming specific life-spans
for each goods category should be investigated. For aluminium, no material flow analysis has been performed for the UK, but Melo (1999) has modelled aluminium scrap arisings in Germany. In his study different life-spans are employed for each category of goods. Also, a distribution of each life-span is applied. van Schaik et al. (2002) have modelled a closed loop recycling system of passenger vehicles, and also stress the importance of using a distribution when modelling the life-spans of vehicles. Melo concludes that using a distribution model gives more accurate scrap arisings figures than when applying a fixed life-span. This is not easily verified due to a lack of statistics in the study, but logically a distribution model is less sensitive to fluctuation in demand in a single year compared to using a fixed life-span procedure; this will be explored in chapter 3. In this analysis, we will employ a distribution of the life-spans to model scrap arisings, and also explore further possibilities of modelling scrap arisings, by relating the scrap arisings to the age distribution of stock in use.

A material flow analysis of iron, steel and aluminium in the UK that takes into account the delay in use incorporating distributions of the life-spans would identify how much end-of-life scrap is currently being recovered and also pinpoint from which goods potential losses occur. In this work, the theory of residence time distribution from chemical reaction engineering science will be employed in the MFA to account for the delay of goods in use. Residence time theory is fifty years old (Danckwerts 1953). However, van Schaik et al. (2002) and Melo (1999) did not link MFA to the established theory of residence time distribution. This link is made for the first time in this research.

1.4 Impurity build-up

As mentioned earlier, metal is a particularly suitable material for recycling as, in theory, it can be recycled an infinite number of times without being degraded. Compared to paper recycling for example, which degrades the cellulose mainly by shortening or embrittling the fibres, metal is not transformed in any way when it is recycled: there is no difference between pure metal produced from primary resources compared to remelted pure metal scrap. However, the metals that are used in society are a sophisticated variety of different metals melted together into alloys. Therefore, the properties and quality of remelted scrap will ultimately depend on the blend of
1.4 Impurity build-up

the scrap that is remelted and the chemical composition of this scrap. In reality, this results in a down-cycling of the metal as demonstrated in figure 1.2; when scrap is not ‘pure’ enough for a certain application, it is recycled and used in another application with lower performance specifications in a cascaded use pattern.

To increase the flexibility of use of recycled metal; i.e. avoid unnecessary down-cycling, it is important to avoid a build-up of alloying elements and surface contamination in the metal scrap. This becomes even more pressing when high recovery rates are achieved as less virgin material is then required and therefore less dilution occurs. In order to minimise the amount of scrap with high levels of trace elements, cross-contamination of different types of scrap needs to be avoided. In Sweden, a study has been performed investigating the theoretical effects of dividing aluminium scrap into different categories. The results indicate that a more detailed scrap classification system than that in use in Sweden today could increase the flexibility of use for the remelted aluminium (Holmberg et al. 2000).

For both iron/steel and aluminium there are several elements of concern that can contaminate the scrap, as described in the following sections.

1.4.1 Impurities in the steel scrap cycle

There are a number of elements that can pose a problem in steel making. The elements that report to the metal (copper, tin, molybdenum, arsenic, nickel, chromium and manganese) are problematic regarding the quality of the steel product, especially “top end” products, i.e. products with stringent specifications, such as sheet for can production. Tin is discussed further in chapter 4. The elements that report to dust (bismuth, tellurium, cadmium, lead, zinc, chromium and manganese) are problematic as they cause unwanted emissions from the production process. This corresponds to the principle stated earlier that aims for no accumulation of toxic elements in soils or sediments (Ayers 1993). In the UK, there were plans to ban the use of leaded steel in vehicles but this legislation was never passed. Sulphur and phosphorus are also undesirable in steel but they are removable, either in vacuum treatment or other refining operation (Aumonier 2000; Miller 2000). There is more information about refining processes in the next chapter.

Recycled steel cans can still be produced without the build-up of contaminants being a con-
1.4 Impurity build-up

cem as virgin steel is added to the melt. But the specification for sheet that is used for can production is extremely high and a closed-loop recycling for steel cans would mean that build-up of copper and tin would be a problem. Tin and copper causes problems with the surface quality called “hot shortness”, where the surface breaks up during hot rolling/forming. It is possible to compensate this effect by adding nickel to the melt, but only to a certain degree. Scrap with high copper and tin content therefore commonly goes into production of reinforcement bars (re-bars) (Aumonier 2000; Miller 2000).

Radioactivity is increasingly becoming a concern in the recycling of scrap. The most common source for radioactive scrap is hospitals, from steel used in x-ray equipment. There is also the build-up of natural radioactivity in pipes; petrochemicals contain some radioactive elements that can build-up in oil rigs and industrial plants. In such cases the scale is removed and the steel can be recycled. Oil rigs operated in the North Sea are usually quite low in radioactivity (Aumonier 2000; Miller 2000).

1.4.2 Impurities in the aluminium scrap cycle

The use of aluminium in society has increased rapidly since the 1950s. This has been possible by the development of a very large variety of specialised alloys, which, in turn, makes recycling difficult. Copper, magnesium, manganese, silicon and zinc are all major alloying elements in aluminium products. There are existing refining processes to separate the aluminium from its alloying elements. However, these processes are complicated, and therefore expensive, by the high oxygen affinity of aluminium; i.e. the aluminium oxidises more easily than the unwanted element (Viklund-White & Menad 1999). As a result, aluminium scrap with high alloying content is often used in applications with lower performance specifications, so called down-cycling.

An example of down-cycling for aluminium is that mixed aluminium scrap from old cars is today mostly used for producing highly alloyed cast, used e.g. in engine blocks, aluminium since the melt is not suitable for wrought alloys due to its content of mixed alloying elements (D’Astolfo et al. 1993; Hoyle 1995).
1.5 Collection of dispersed scrap

1.4.3 Ensuring high quality scrap

In light of the preceding sections, there is an incentive to sort the scrap according to its alloying composition so that the range of use of the remelted steel and aluminium becomes less limited. The Swedish study mentioned earlier (Holmberg, Johansson, & Karlsson 2000) explores how flexible different alloys are in being turned into other alloys depending on the scrap grading system used, but does not look at the actual proportions of different alloys in use in Sweden. In order to capture the real problems with alloyed scrap, the actual flows through society need to be taken into account. Modelling the flow of alloying elements and contaminants in steel and aluminium in the UK, on a material flow analysis basis, would provide a prerequisite for designing an appropriate scrap classification system for steel and aluminium scrap in the UK.

In chapter 4, a model is developed that can investigate how the composition of UK produced metals will vary with the overall recycling rate of the metals and also with the quantity of scrap exported from the country. More importantly, the consequences of using different scrap grading systems can be explored. The model is based on the methodology for analysing the flow of steel and aluminium in the UK, i.e. the material flow analysis (MFA) model described in chapter 3. The use of the model is demonstrated in a case study exploring consequences of the concentration of tin in the iron and steel cycle, depending on different future scenarios.

1.5 Collection of dispersed scrap

In the context of minimising the loss of steel and aluminium from the economic system in the UK, recovering widely dispersed products such as packaging stands out as a main challenge. Packaging suffers from low recovery rates in many European countries, including the UK. This is often due to a lack of incentive for consumers to return the used packaging, which is discussed further in chapter 5.

In order to recycle the metal, the scrap first needs to be collected; an operation that could be quite energy and resource demanding if the scrap is widely dispersed. It is often argued that the relationship between environmental load (expressed as specific energy required) per unit collected and the recycling rate is governed by a U-shaped curve (e.g. McLaren et al.
1.5 Collection of dispersed scrap

Figure 1.5: A possible nonlinearity in the collection energy, adapted from McLaren (2000); the figure is schematic, i.e. it does not show real values.

(2000) and Karlsson (1998)); see figure 1.5 which shows schematically the kind of nonlinearity in the collection energy (note the figure is not derived from an analysis but is a hypothetical graph). For low values of the recycling rate, the energy load for recovery may be high since the infrastructure costs are high per unit. For example, if there are trucks driving around to collect recyclable material, but at each collection point there is very little material to recover, the energy load per collected amount of material could be very high, whereas if more material is recovered, economies of scale reduce the environmental load as the recovery increases. However, at very high recycling rates, the need to collect more dispersed units may lead to an increase in energy intensity again, e.g. by extensive transportation. However, despite this argument frequently being put forward, the dependence of environmental burdens associated with collection on recycling rate has still not been confirmed conclusively in any study. This issue will be addressed in chapter 5.

Edwards & Schelling (1999) have performed a transport analysis of collection of glass packaging and found indeed that the fuel requirement was higher at very low and very high recycling rates. However, this study only looked at fuel requirement associated with collection from bring-sites and is specific for glass. The situation might be very different for another type of collection system and other materials. A similar study for metal scrap has not yet been performed.

In terms of aluminium and steel packaging, which are examples of end-of-life scrap that
Research questions

are very dispersed in society and suffer from low recycling rates, the most urgent concern is actually how to recover this scrap. Exploring potential recovery systems and also comparing their environmental load per collected amount of scrap is thereby vital. Comparing different collection systems and also balancing the environmental benefit of remelting the scrap against the environmental cost of collecting it is something that needs to be considered and should therefore be explored further. This is the subject of chapter 5.

1.6 Research questions

In light of the previous sections, this dissertation sets out to explore the following:

1. What are the main consuming sectors for iron, steel and aluminium in the UK? What are the recycling rates for end-of-life scrap in the UK? From which types of end-of-life goods can the largest improvements be made in terms of increasing the recovery of iron, steel and aluminium? What is an appropriate methodology for addressing these questions?

Exploring this set of questions will help to understand the potential for achieving efficient industrial ecologies for iron, steel and aluminium in the UK. It will also give guidance as to where the focus should be put for increasing the recovery of these metals. It is envisaged that the methodology developed will be useful for similar studies of other material groups used in society.

2. How can we analyse whether there will be a problem with build-up of contaminating and alloying elements if high recycling rates of iron, steel and aluminium are achieved and maintained in the UK? What methodology should be used to explore how different measures affect the composition of metals in the scrap cycle?

This model will be useful for examining possible future scenarios of potential contamination and also how build-up of contamination could be avoided by different measures, e.g. scrap sorting.
3. What is the environmental impact associated with recovery of dispersed scrap? Does the environmental impact vary significantly between different types of collection systems and different recycling rates? How significant is the recovery stage of dispersed scrap taken in the context of the whole life cycle of the metal goods?

Answering this third set of questions will provide better understanding of what type of collection systems should be used to collect widely dispersed scrap such as packaging. Improving our knowledge of the environmental load associated with the actual recovery of scrap will help in making rational decisions about metal recycling.

1.7 OUTLINE OF THESIS

To further highlight the importance of recycling, the next chapter outlines the main production routes of iron, steel and aluminium in the UK and also summarises the most important environmental issues associated with the production of these metals. Chapter 3 summarises the theory of residence time distribution from chemical reaction engineering science and explores possibilities for applying the theory in MFA. It describes the methodology of tracking the flow of these metals from the different consuming sectors in the UK through to end-use and either recovery or disposal. Detailed accounts of performing the MFA of iron/steel and aluminium respectively are also given in that chapter. The annual recycling rates of both metals are determined, and an analysis to estimate which goods sectors are contributing to the most significant losses of end-of-life scrap is performed.

The material flow model is extended to include the production process of the metal in chapter 4; here a case study of exploring tin build-up in the steel cycle is performed to demonstrate the model. In chapter 5, collection of dispersed scrap is examined by exploring a case study of collection of used aluminium beverage cans in the UK. Various collection systems in two demographically and geographically different boroughs in the UK are analysed in terms of required transport per collected amount of cans. The collection stage is compared to the whole life-cycle of the cans in terms of contributing to environmental burdens. Finally, chapter 6 summarises the main conclusions and gives recommendations for further work.
This chapter gives a general introduction to iron, steel and aluminium and outlines the main production routes of these metals in the UK. The most important environmental issues associated with the production of these metals are also highlighted, and at the end, the differences between primary and secondary production in terms of environmental impact are summarised.

2.1 IRON AND STEEL

Iron and steel play a vital part in modern life. Since the industrial revolution in the UK in the early nineteenth century, iron and steel production has grown steadily. The production of steel had been known to man long before the industrial revolution but it was around this time that it was made technically possible to produce it in large quantities economically. Previous use of steel was primarily military, for weapons and armour, but the larger scale economic production of steel with consistent and controllable composition opened up a range of new and more routine applications.

It could be said that steel is a superior variety of iron, the vital chemical property separating the two being their carbon content. Carbon makes the metal harder and the connection between carbon content and hardness can be reflected in the properties of pig iron (ca 2.5% C), steel (ca 0.1 - 2% C) and wrought iron (< 0.1% C); decreasing carbon content translates into decreasing
hardness. What makes steel so desirable is its versatility in terms of properties. By the right choice of carbon content, alloying elements and heat treatments it can be made so soft and ductile that it can be cold-drawn into complex shapes such as automotive bodies. It can also be made extremely tough, but not brittle, so that it can withstand enormous loads and shock without deforming or breaking (Kirk-Othmer 1997a).

The numerous different steel products can be divided into three main categories: carbon steels, alloy steels and stainless steels. Alloy steels contain one or more of the following elements in quantities above specific thresholds: silicon, manganese, chromium, nickel, boron or other alloy element apart from carbon, lead, nitrogen, phosphorus or sulphur. Stainless steel is an alloy steel that contains at least 10.5% chromium with less than 1.2% carbon and is about ten times more expensive than ordinary carbon steel (ISSB 2000).

Iron is the third most abundant metal in the earth’s crust with a proportion of about 5% and it is found as oxides, carbonates, sulphides and phosphates. As sulphur affects adversely the properties of iron and steel, it is predominantly the oxides that are mined. Hematite (Fe₂O₃), a red ore, is the most abundant of the oxides. Magnetite (Fe₃O₄) is black and, implicit from its name, magnetic (Kirk-Othmer 1997b).

2.2 PRODUCTION OF STEEL

This section is focused on steel making processes currently in use in the UK. Information about steel making processes has been gathered mainly from the open literature, including the Best Available Technique document for production of iron and steel published by the European Commission (2000a), Michaelis (1998) PhD thesis on the UK iron and steel sector, and also by personal communication with Corus RD&T (Miller 2000).

Two process routes dominate global steel manufacturing, although variations and combinations of the two exist. The integrated route, or blast furnace - basic oxygen furnace route (BF-BOF), uses iron ore and scrap as input of iron. The electric arc furnace route (EAF) uses scrap almost exclusively as its source of iron. In 2001, about 75% of UK produced crude steel came from integrated steelworks and 25% from electric arc furnaces (Dahlstrom et al. 2004).
2.2 Production of steel

2.2.1 Blast Furnace - Basic Oxygen Furnace route (BF - BOF)

Figure 2.1 shows an overview of the processes included in the BF - BOF route. The most significant raw material inputs in terms of mass and energy in this production route are iron ore, coal and limestone. The extraction of these raw materials will be covered first, followed by a description of the operations taking place in integrated plants. Besides these, there are other raw materials, descriptions of which are not included in this overview.

Extraction of iron ore

In the late 1960s about 40% of the ore consumed in UK pig iron production was mined in the UK. Since then mining in the UK steadily decreased until it finally stopped in 1992. Today all the ore is imported, from a number of countries. The largest shipments to the UK come from Australia, Canada, South Africa, Brazil and Venezuela (in decreasing order) (ISSB 2000).

The two main methods for the mining of iron ore are open cast mining and underground mining. Open cast mining is the most widespread method used when the ore lies close to the surface. It is conducted by removing the overburden followed by blasting out whole sections of the iron bearing rock. The rock is usually transported in trucks to the primary crushing mill. In terms of environmental impact, the open cast method is less energy intensive compared to underground mining. However, depending on the distance to the crushing mill, a lot of energy might be consumed for transportation. The main disadvantage of this method is the destruction of the habitat above the ore deposit; even if the area is restored, this form of mining still constitutes a major disruption to the affected ecosystem. Underground mining requires more energy and is normally only used when the ore deposit lies close to an iron producing area, so that saved transport costs can make up for the extra mining cost. Most of the underground mining sites are situated in Europe, and not in the areas that export ore to the UK.

The primary crusher reduces the size of the rocks to approximately 300 mm. Further size reduction is then performed by more crushing and grinding down to the appropriate size depending on what process step is to follow. The ore used in the UK is normally sintered before it is fed into the blast furnace. For sintering, high-grade ore fines are suitable, in a size range of less than six mm. The sintering process is outlined below, in the context of integrated steel-making.
2.2 Production of steel

Figure 2.1: Overview of Blast Furnace-Basic Oxygen Furnace (BF-BOF) steel making.
2.2 Production of steel

Extraction of coal
The coal used in iron and steel making in the UK is imported from all over the world (Brazil, Australia, China), as the remaining coal deposits in the UK are relatively expensive to mine and also contain high sulphur and chlorine levels. Coal mining has many similarities to iron mining. The main difference is that coal is found in highly concentrated seams between layers of normal rock, so that by selective mining the need for beneficiation can be minimised (Kirk-Othmer 1997c). After mining, the coal is normally mechanically treated in some way to reduce its size and to remove ash forming materials and fine-grained coal. It is the intermediate size of coal that is consumed in steel making.

Extraction of limestone
The most common method of limestone extraction is open-pit quarrying (Kirk-Othmer 1997d). As for open-cast mining of ores and coal, this involves stripping of the soil to reveal the limestone. Much of this overburden is used for building roads and quarry ramps. The stripping is followed by drilling and then blasting. Oversized boulders are usually reduced to manageable sizes by drop ball cranes. The stones are then transported to crushers where the desirable size is obtained. Most limestone (CaCO₃ + MgCO₃) used in UK steel making operations is mined in a Corus owned plant at Shap Fell in Cumbria.

Integrated plant operations
All four integrated steelworks in the UK are owned by CORUS, a company formed by a merger between British Steel and the Dutch firm Hoogovens. However, the blast furnaces at the works in Llanwern, Wales, have been closed since 2001, leaving only three operating integrated steelworks in the UK at present. These are located at Teeside, Scunthorpe and Port Talbot as presented in figure 2.2. The plants are all situated near harbours for easy access of shipments of iron ore and coal.

In the integrated route the iron ore is first agglomerated in the sintering process in order to improve the performance of the blast furnace. The process involves mixing the fine ore with
Figure 2.2: Location of integrated steelworks in the UK.
2.2 Production of steel

limestone, coal dust and water, driving off unwanted gases and producing a porous material suitable for the blast furnace.

The centre point of the integrated route is the blast furnace where the iron oxide is reduced to liquid iron (pig iron), according to formula (2.1).

$$\text{Fe}_2\text{O}_3 + 3 \text{CO} \rightarrow 2 \text{Fe} + 3 \text{CO}_2$$ (2.1)

The main reducing agents in the blast furnace are coke and powdered coal forming carbon monoxide, which reduces the iron oxides. Sometimes other reducing agents are added as well, such as natural gas and oil. The coke and coal also act partly as fuel in this process. Coke is the main input of the two and is most often produced at the site by carbonising coal in the coking process, which drives off gases that might contaminate the iron and to form a rigid, porous material.

The blast furnace is operated continuously and consumes about 60% of the overall direct energy input of the steelworks (European Commission 2000a). The furnace is charged at the top with alternate layers of coke and sinter. Limestone is added to assist in forming the slag which absorbs impurities. A hot air blast provides the necessary oxygen to form carbon monoxide (CO). As liquid iron and slag are produced, they are collected at the bottom of the furnace, from where they are tapped. The slag is sometimes treated and used to produce aggregates, granulates or pellets for road construction or cement production. The liquid iron is transported in torpedo vessels to the steel plant and might be subjected to desulphurisation before being fed into the basic oxygen furnace. The blast furnace gas is collected and treated and used around the steelworks for heating purposes or electricity production.

The operation of the basic oxygen furnace (BOF) is semi-continuous. A cycle consists of charging the furnace with molten pig iron and scrap, oxygen blowing, sampling and tapping. During this 30-40 minute cycle a number of additives are used to adapt the steel quality and to form the slag. A modern steelworks produces about 300 tonnes of steel per cycle. The purpose of the BOF is to reduce the carbon content in the liquid pig iron from around 4% down to less than 1%. The process also removes impurities and adjusts the content of desirable foreign elements. The main elements that are oxidised in the basic oxygen furnace are carbon, sulphur, phospho-
2.2 Production of steel

Iron, silicon and manganese. Oxidation of these elements also provides exothermic heat to the process, so that no additional heat input is required. Scrap or ore is added to work as a cooling agent. About 15% scrap is commonly used but it can vary between 10 and 30%. Variations of the specification of the steel being produced and the market price of scrap influence the scrap consumption in the BOF. Slag is formed during the process by adding lime and limestone. Slag control is intended to reduce the amount of undesirable elements in the steel, such as sulphur and phosphorus. Following the BOF operation, the molten steel is refined to improve its quality, a process normally referred to as secondary metallurgy. There are a number of different processes depending on the end product specification; a few examples are addition of alloys, mixing and homogenizing electromagnetically or by gas blowing, vacuum processing etc.

When the desired quality of the steel is achieved, the liquid is cast. Today the most commonly used method for this is continuous casting. A shift from ingot casting to continuous casting occurred in the 1980s and this greatly increased the efficiency of the casting operation. The metal is poured into a water-cooled vertical mould with the desired shape. The mould performs oscillating movements and air is removed to avoid the metal sticking to the mould. When the metal leaves the mould at the other end, a skin of solidified steel has formed and an array of rollers pinches and rolls the steel forward into a horizontal position. At this stage the steel is cut into slabs, blooms or billets (see figure 2.3) and eventually transported to the rolling mills where they are re-heated before rolling. The rolling operation is the second most energy demanding process after the blast furnace, consuming about 25% of the overall direct energy demand for the steelworks (European Commission 2000a). The high energy consumption is mainly due to the re-heating of the steel.

2.2.2 Electric arc furnace (EAF) route

Steel making via the electric arc furnace (EAF) route has declined in the UK over the past 20 years, but it still produces a substantial amount of steel. As mentioned previously, 25% of UK produced crude steel was produced via the EAF route in 2001. The number of furnaces was 21 in 1993, but has decreased since (ISSB 2000). The plants are not solely owned by Corus as in the case of the integrated plants, but are operated by a number of companies.
2.2 Production of steel

Figure 2.3: The steel is cast into blooms (cross-section greater than 230 cm\(^2\)), billets (cross-section less than 230 cm\(^2\)) and slabs (cross-section greater than 100 cm\(^2\), and width more than twice the thickness).
There are two main sorts of EAF routes in the UK. The 'high value' version is focused on producing top-end products such as high quality stainless and engineering steels; this process is relatively costly as the EAF is followed by purification processes (e.g. vacuum oxygen decarburisation or argon oxygen decarburisation) to satisfy the product specification. The 'basic' version simply melts down scrap without special purification, producing low value carbon steel such as reinforcement bars. This relatively limited product range, and a fear of high scrap prices, might be two of the reasons for the closure of EAFs in the UK. Even though the 'high value' EAF route has the capacity to produce a wide variety of steel products, it cannot compete with the integrated route in terms of production costs. Another reason is the high price of electricity in the UK, not favourable to steel making via the EAF route. The trend is quite the opposite in the rest of Europe, where EAF production has increased. Germany, France, Spain and Italy have all increased their proportion of making steel via EAF over the past 20 years, while their production via the integrated route has been kept constant or has decreased (Mackrell 1999).

Figure 2.4 shows an overview of the EAF route. The production of steel is performed by the melting of scrap in the furnace followed by ladle treatment, casting and finally rolling. The main inputs in this production process are scrap and electricity. Lime (CaO) or dolomite (CaMg(CO₃)₂) is used as a flux for the slag formation. As in the BOF, the slag is intended to collect undesired components from the steel. The furnace is operated in batches and is charged with baskets of scrap and lime or dolomite while the roof is swung away and the electrodes raised to their top position. There are also furnaces (so called shaft furnaces) where part of the scrap can be preheated by charging it through a vertical shaft integrated in the furnace roof.

The melting is initialised by boring down the electrodes into the scrap while applying low power. Once the arcs that are generated between the electrodes are shielded with scrap, the power is increased to complete the melting. Fuels, such as oil and natural gas, and oxygen are often injected into the furnace to assist the melting. Oxygen also has the purpose of decarburising the melt (removing any excess carbon) and removing undesired elements such as phosphorus, silicon, manganese and sulphur. Argon or other inert gases may also be added to generate bath agitation and maintain temperature control.

In plants without separate secondary metallurgy facilities, alloys and other additives might
be added into the furnace ladle, before or during tapping. The tapping is normally performed by releasing the molten steel through a bottom tapping system, minimising the carry over of slag into the ladle.

As in the integrated route, the secondary metallurgy operations vary, depending on the steel end product. For the carbon and low alloy steel, the refining may include some ladle furnace treatment for quality adjustment, e.g. addition of alloys, mixing etc. For high alloyed and stainless steel, the operation sequence is more complex and tailor-made to the specific end product. Treatments carried out include desulphurisation, degassing for elimination of dissolved gases such as nitrogen and hydrogen and also decarburisation in either VOD (Vacuum Oxygen Decarburisation) or AOD (Argon Oxygen Decarburisation).

When the desired composition of the steel is achieved, the molten steel is cast. Today, most steel is cast by continuous casting, but ingot casting is also applied for some grades and applications. After casting the steel sections are transferred to the rolling mills where the final shapes of
the steel products are formed.

2.2.3 Environmental burdens associated with production of steel

Figure 2.5 shows the main resource consumption and emissions released at an integrated plant. The figures are only indicative as they have been collected from a number of sources but they still give an idea of the main environmental burdens associated with integrated steelmaking. The overall direct average energy consumption at an integrated steelworks is around 19.2 GJ/tonne crude steel (UNEP 1997). The overview does not include the energy consumption and waste from extraction of raw materials, but only the operations at the plant. Apart from the energy requirement, there are also considerable emissions of CO₂, CO, NOₓ and SO₂ and also a substantial amount of solid waste generated. The converter gas from the BOF is very rich in carbon monoxide (CO) and can be recovered and used as an energy source. In many steel plants measures have been taken to capture and use this gas. The slag that is formed during the process can be used for construction purposes, or other uses, or be disposed of in landfill.

Figure 2.6 shows the main flows associated with EAF steelmaking. Again, the figures are indicative, but still provide a useful image of what the main environmental burdens are. Compared to the integrated route, far less energy is consumed and less emissions are released, even when the plant operations alone are considered. Regarding the integrated route, in addition to the burdens from the plant there are also the burdens associated with the extraction of iron ore and coal. The International Iron and Steel Institute (IISI) has conducted a life cycle inventory of 29 integrated plants and 15 electric arc furnaces located all around the world (IISI 2000). It is the most comprehensive and up-to-date data set on worldwide steel production. However, the data are only available on request from the IISI for practitioners of life cycle assessment studies. Still, we can see from the UNEP data in figures 2.5 and 2.6 that there are significant savings in environmental impact when producing steel from remelting of scrap compared to primary production. This is discussed further in section 2.5.
2.3 Aluminium

Aluminium is the most widely used non-ferrous metal. It was only discovered some 160 years ago and has been produced in industrial quantities for the last 100 years. To name a few of its properties, it is odourless, conducts electricity well and it forms a stable oxide surface that resists corrosion. No doubt the most valuable property is that even though high purity aluminium is soft, it can be alloyed into a high strength material with excellent strength-to-weight ratios making it attractive for use in applications where weight saving is important, e.g. transportation. There are two main groups of aluminium alloys: wrought alloys and casting alloys. There are internationally agreed classifications for wrought alloys and various domestic nomenclature schemes for the casting alloys.

Aluminium is the second most abundant metal in the earth’s crust (8%). The most common mining source is the rock bauxite. The term bauxite originates from the location of the deposit.
2.4 Production of aluminium

Figure 2.6: Main resources consumed and emissions released in EAF steelmaking. Adapted from UNEP (1997)

discovered in 1821 near the village of Les Baux in Provence, France. Bauxite is weathered rock consisting mainly of aluminium hydroxide (Al(OH)₃) but also small and variable amounts of silica, hematite, magnetite, titanium oxide and aluminium silicate clays (Kirk-Othmer 1997e).

2.4 PRODUCTION OF ALUMINIUM

This section describes aluminium production in the UK. The two routes are primary production, where alumina is used as the main raw material, and secondary production, where aluminium scrap is used as a source of aluminium. The information about the processes has been gathered mainly from Kirk-Othmer (1997e) encyclopedia of chemical technology and the Best Available Technique Document for Non Ferrous Industries (European Commission 2000b).
2.4 Production of aluminium

2.4.1 Production of primary aluminium

Figure 2.7 shows an overview of the production route for primary aluminium. The largest inputs in terms of mass and energy to the process are bauxite, coal (for the electrodes in the electrolysis) and electricity. There are also other inputs for which production routes are not included in this overview, such as sodium hydroxide, lime and cryolite ($Na_3AlF_6$). Bauxite mining and production of alumina, which take place outside the UK, will be described first, followed by primary smelting and the finishing operations.
2.4 Production of aluminium

**Mining of bauxite**

Today the largest bauxite resources are found in Australia, Africa, South America and the Caribbean, the major producers being Australia, Guinea, Brazil and Jamaica. The bauxite that finally ends up in the production of aluminium in the UK has come mainly from Jamaica over the past ten years, imported mostly in the form of alumina ($\text{Al}_2\text{O}_3$) (WBMS 2001).

The bauxite rock consists mainly of aluminium hydroxide ($\text{Al(OH)}_3$) but can also contain minor quantities of silica, hematite ($\text{Fe}_2\text{O}_3$) and titanium oxide ($\text{TiO}_2$). The mining method is determined by the hardness and texture of the ore, and also by the amount of overburden that has to be removed to reveal it. The bauxite found in Jamaica (called Jamaica type) is a very fine-grained gibbsitic bauxite ($\text{Al(OH)}_3$). This bauxite is a very economical ore to process because of its high solubility in the Bayer process.

The most common method for mining is open pit, as most bauxite deposits are very shallow. The overburden usually consists of loose soil and uncemented rock. Thus, most operations do not need any explosives to break up the overlying area. The overburden is removed by scrapers, draglines, front-end loaders or hydraulic excavators. The latter two are also used for extracting the bauxite. Trucks transport the ore to a central location termed "the pit", and belt conveyers are normally used to move the ore to the processing plant. Most of the equipment used for the mining operations is driven by diesel engines.

**Production of alumina - Bayer process**

Bauxite is converted into alumina ($\text{Al}_2\text{O}_3$) in the well-established Bayer process. First the bauxite is dissolved in caustic soda ($\text{NaOH}$):

\[
\text{Al}_2\text{O}_3 \cdot x\text{H}_2\text{O} + 2\text{NaOH} \rightarrow 2\text{NaAlO}_2 + (x+1)\text{H}_2\text{O} \tag{2.2}
\]

Slurry is produced which contains dissolved sodium aluminate and a mixture of metal oxides called red mud that is removed in thickeners. The red mud constitutes a significant waste stream from the process. The aluminate solution is cooled and seeded with alumina ($\text{Al}_2\text{O}_3$) to crystallise hydrated alumina, see reaction (2.3). This is basically the reverse of (2.2), except that the product's nature can be carefully controlled by plant conditions. The hydrated alumina
crystals are washed and then calcined into alumina (Al₂O₃) in rotary kilns or fluid bed calciners. The mechanism for this step is complex; during heating the trihydroxide undergoes a series of changes in composition and crystal structure. The alumina product (Al₂O₃) is a white powder consisting of aggregates ranging in size from 20 μm to about 200 μm.

\[ 2\text{NaAlO}_2 + 4\text{H}_2\text{O} \rightarrow \text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O} + 2\text{NaOH} \]  

(2.3)

Two tonnes of bauxite produce approximately one tonne of alumina (does not follow directly from the stoichiometry as bauxite also contains minor quantities of other materials apart from aluminium hydroxide), which in turn produces about 0.53 tonnes of aluminium (European Commission 2000b). It is most common that the Bayer process is carried out close to the mine site but there are plants in Europe where the alumina is produced at the aluminium smelter site. Some alumina was produced in the UK before 2001 but most was imported. Today, all alumina used in UK aluminium production is imported. The three main suppliers of alumina to the UK during the past ten years have been Jamaica, Spain and Germany.

**Primary smelting of aluminium - Hall-Hroult process**

There are three primary smelters in the UK as shown in figure 2.8. The Alcan smelter in Lynemouth and the Anglesey smelter owned by Rio Tinto and Kaiser Aluminium are the two largest with an annual production of about 140 000 tonnes of primary aluminium each. The production plant in Fort William is owned by Alcan and has a production of around 40 000 tonnes per year (Roskill 1999). This smaller operation is run on hydropower, while the one in Lynemouth has its own coal-fired power station. The Anglesey smelter operates on electricity from the national grid. There was a fourth plant in Scotland, at Kinlochleven, but it closed in 2000 and its hydropower supply is now being redirected to the plant in Fort William (Harris 2000).

In the primary production route, aluminium is produced by the electrolytic reduction of alumina:

\[ \text{Al}_2\text{O}_3 + 4\text{C} \rightarrow 4\text{Al} + 3\text{CO}_2 \]  

(2.4)

The process is very energy intensive, requiring between 53 and 61 GJ of electricity per tonne of
2.4 Production of aluminium

Figure 2.8: Location of primary aluminium smelters in the UK.
aluminium depending on process type (European Commission 2000b). The alumina is dissolved in a molten bath of mainly cryolite (Na$_3$AlF$_6$) at a temperature of approximately 900 °C. Fluoride fluxes are added to lower the operating temperature. AlF$_3$, the most common additive, also neutralises the NaOH which is present as an impurity in the alumina feed. The fluoride emissions increase from the bath as the excess of AlF$_3$ is increased. The electrolytic cell comprises a carbon cathode, insulated by refractory bricks inside a rectangular steel shell, and a carbon anode suspended from an electrically conductive anode beam. Liquid aluminium is deposited at the cathode at the bottom of the cell and oxygen combines with the carbon anode to form carbon dioxide. The anode is therefore consumed continuously during the process. The cathode is not consumed but deteriorates with time: it absorbs electrolyte, resulting in swelling and cracking, and needs to be replaced every five to eight years.

There are two types of anodes used in the electrolytic cells: Soderberg and prebaked anodes. The Soderberg anodes are made in situ from a paste of calcined petroleum coke and coal tar pitch, which is baked by the heat arising from the molten bath. As the anode is consumed, more paste descends through the anode shell, thus providing a continuous process that does not require the anodes to be changed. Prebaked anodes are also produced from a mixture of calcined petroleum coke and coal tar pitch, but are baked in a separate anode plant. The anodes are regularly lowered as they are consumed and are replaced before the rods, which support the baked anodes, are attacked by the molten bath. The consumption of anodes is 400-440 kg/tonne aluminium for prebaked anodes, compared to 500-580 kg paste/tonne aluminium for Soderberg anodes (European Commission 2000b).

Molten aluminium is periodically withdrawn from the cells into crucibles. The crucibles are transported to the casting plant and the aluminium emptied into heated holding furnaces. Alloying is performed in these crucibles and the temperature is controlled to suit downstream casting operations. Apart from adding alloying elements, the metal is also refined by removing impurities such as sodium, magnesium, calcium, oxide particles and hydrogen. This is done by injecting a gas into the molten metal. Argon or nitrogen is used to remove hydrogen and mixtures of chlorine and argon or nitrogen are used to remove metal impurities. Additions to refine the grade of the aluminium are also made. Titanium and titanium boride are the most common
additives for this purpose. Skimmings (also called dross) created on the surface by oxidation of the aluminium are raked off and recycled by remelting operators. The oxidation can be avoided by using sealed crucibles or using nitrogen or argon blanketing.

When the desired composition of the aluminium is achieved, the molten metal is cast. Slabs, T-bars and billets are cast in vertical direct chill casting machines that have movable holding tables at the bottom of the mould. The table is lowered as the ingots are formed. Another method is continuous casting which produces thin sheets, wire rod and other shapes.

2.4.2 Production of secondary aluminium

Figure 2.9 shows an overview of the processes included in the production of aluminium from recovered aluminium scrap. There are many smelting facilities in the UK, operated by several different companies. The two most significant recycling facilities for prompt and end-of-life scrap are the plants at Warrington (British Alcan) and Deeside (Deeside Aluminium) (Roskill 1999).

There is a range of different furnaces used to melt the scrap. The type of furnace to be used is determined by the size, oxide content and the degree of contamination of the scrap and also by its pre-treatment. However, a common feature for all the melting furnaces is that they require much less energy for melting the scrap than required in the electrolysis for producing primary aluminium. Depending on furnace type the energy consumption is in the range from 2 to 12 GJ per tonne of secondary aluminium (European Commission 2000b). Pre-treatments of the scrap include de-coating and de-oiling if necessary; this improves the melting rate and reduces the potential for emissions and generation of skimmings. Scrap is sometimes sorted into alloy groups in order to produce the desired alloy with minimum reprocessing. Induction furnaces are used to melt reasonably clean aluminium grades. Rotary or reverberatory furnaces are used for melting a wider variety of scrap. Some reverberatory furnaces include a sloping hearth in the metal feed area where items containing large pieces of iron can be placed. Aluminium, due to its lower melting point, is melted off the iron piece while the iron remains on the slope.
2.4 Production of aluminium

Figure 2.9: Overview of secondary aluminium production.

2.4.3 Environmental burdens associated with production of aluminium

The environmental impacts due to production of primary and secondary aluminium are relatively well known. The European Aluminium Association (EAA) has commissioned a study exploring the Ecological Profile of the European aluminium industry, which covers resource consumption, waste and emissions from primary and secondary aluminium production from 'cradle-to-gate' (Bousted 2000). Performed by an independent consultant, this study summarises data collected from a substantial number of aluminium production sites in Europe (and also data on resource extraction outside Europe) and contains the most reliable data set based on primary information. Also, global attention to the climate change issue encouraged by the International Kyoto Protocol, has influenced the International Aluminium Institute (IAI) to conduct a life cycle inventory of aluminium production (IPAI 2000). The study covers energy consumption and emissions of greenhouse gases from plants that produce 82% of the alumina and 89% of the primary aluminium that is produced world-wide.

The major environmental issues for primary aluminium are land degradation due to mining
of the bauxite, solid emissions from the alumina production (red mud) and the considerable energy consumption during the electrolysis. The emissions of fluorinated hydrocarbon from the electrolysis are also an important concern because of their high global warming potential.

Bauxite mining can lead to substantial soil degradation, deforestation and destruction of wildlife habitats. On average 0.75 tonnes of overburden is removed for every tonne of bauxite mined (Mistry et al. 2000). Usually the topsoil is separated from the overburden and used in the reclamation. The overburden is commonly stored in the open-pit once the mining operation is finished. Although reclamation of the land is normally performed, the success of such an effort is usually dependent on many factors, e.g. topography and drainage (Martens et al. 2000).

One of the most menacing wastes from primary aluminium production is the alkaline bauxite residue, also called red mud, generated in the Bayer process. Due to its content of caustic soda it requires careful handling. The current practice is to deposit the red mud on or near the site in specially designed, sealed ponds, where the excess fluid from the ponds can be returned to the process. However, at some locations the red mud is not stored at controlled disposal sites but simply dumped on land or even in the sea (Mistry et al. 2000).

The most notorious environmental issue associated with primary aluminium production is probably the vast energy consumption during the electrolysis. As mentioned earlier between 53 and 61 GJ/tonne aluminium is consumed in the smelting process. Many aluminium plants use electricity generated by hydroelectric power for this operation and thereby claim that it is a relatively environmentally friendly process. However, in Europe about 44% of the electrolysis energy is generated from hydropower (Bousted 2000), which is a substantial proportion but a significant amount still comes from non-renewables. Moreover, it can be argued that the hydroelectricity saved by decreasing the production of primary aluminium (e.g. by recycling) could be used to replace more polluting energy sources such as coal and oil.

During the electrolysis, perfluorocarbon gases (PFCs) in the form of tetra-fluoro methane ($CF_4$) and hexa-fluoro-ethane ($C_2F_6$) are emitted. These are formed due to a reaction between the cryolite and the anodes and cannot be removed from the gas stream. The aluminium industry emits 95% of the global emissions of PFCs. Extensive research is under way to reduce these emissions as they have very large global warming potentials (GWP factors for $CF_4$ and $C_2F_6$.
2.5 Summary of environmental burdens

Estimated by the Intergovernmental Panel on Climate Change are 6500 and 9200 respectively).

Production of secondary aluminium, i.e. remelting of aluminium scrap, does not have such serious environmental burdens. As mentioned earlier, the main environmental benefit from producing secondary aluminium as opposed to primary, is the significant saving of energy. There is a general consensus that the energy consumption is about 5% of that consumed in primary production, e.g. (European Commission 2000b) and EAA-LCI. Most of the emissions from the melting process originate from combustion of the fuel and also from the potential contamination of the scrap input (e.g. organic content).

2.5 SUMMARY OF ENVIRONMENTAL BURDENS

The previous sections have described the production routes of steel and aluminium production in the UK, and their environmental implications. To highlight the difference in environmental burdens between the primary and secondary route, table 2.1 summarises some of the main resources consumed and emissions released during the cradle-to-gate life cycles of both metals; i.e. from extraction of resources to production of finished metal. For steel, the data are taken from the BUWAL LCI database (BUWAL 1996a), and the aluminium data are taken from the European Aluminium Association’s environmental profile report (Bousted 2000); both data sets represent average data for production in Western Europe.

Bearing in mind that these figures are average data, and that some variations of the values exist depending on techniques and process conditions etc., the table still demonstrates significant differences between the production routes. For steel, six times as much coal is consumed and 3 times more emissions of CO\textsubscript{2} are released when producing steel from ore compared to remelting of scrap. Overall, the primary route generates far more emissions than the secondary.

For aluminium, the most evident difference is the electricity consumption; the secondary route only requires 2% (and about 5% of the total energy input) of that required in the primary smelting. Consequently, the energy related emissions are higher in the primary route too. There are also process emissions of PFCs in the primary smelting, which have very high global warming potential, and these do not occur in the remelting of scrap.

Even if the table only shows a selection of the total environmental burdens in the life cycle
### Table 2.1: Resource consumption and emissions per tonne of primary and secondary steel and aluminium, adapted from BUWAL (1996a) and Bousted (2000).

<table>
<thead>
<tr>
<th>Resource consumption/ emission</th>
<th>STEEL</th>
<th>ALUMINIUM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Primary</td>
<td>Secondary</td>
</tr>
<tr>
<td>Ore [kg]</td>
<td>2 400</td>
<td>—</td>
</tr>
<tr>
<td>Scrap [kg]</td>
<td>—</td>
<td>1 190</td>
</tr>
<tr>
<td>Limestone [kg]</td>
<td>283</td>
<td>—</td>
</tr>
<tr>
<td>Coal [kg]</td>
<td>1 190</td>
<td>181</td>
</tr>
<tr>
<td>Crude oil [kg]</td>
<td>87</td>
<td>23</td>
</tr>
<tr>
<td>Electricity [kWh]</td>
<td>94</td>
<td>108</td>
</tr>
<tr>
<td>Mineral waste [kg]</td>
<td>1 450</td>
<td>—</td>
</tr>
<tr>
<td>CO₂ [kg]</td>
<td>2 950</td>
<td>1 160</td>
</tr>
<tr>
<td>CO [kg]</td>
<td>19</td>
<td>5</td>
</tr>
<tr>
<td>SO₂ [kg]</td>
<td>6.2</td>
<td>2.9</td>
</tr>
<tr>
<td>CH₄ [kg]</td>
<td>10.8</td>
<td>2</td>
</tr>
<tr>
<td>PFCs [kg]</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Inventory of each metal, it gives a picture of the difference in impact of the two routes. Overall, for both metals, secondary production involves far less consumption of primary resources and releases of emissions and waste, providing a powerful environmental incentive to ensure that as little steel and aluminium scrap as possible is lost from the economic system.
Determining recycling rates of iron/steel and aluminium in the UK

As was pointed out in chapter 1, end-of-life scrap is the most problematic type of scrap in terms of recovery. There is no clear picture of the amounts of iron/steel and aluminium end-of-life scrap released in the UK and hence the recycling rates are also ill-defined. This chapter addresses end-of-life steel and aluminium scrap and focuses on the first research objective in the study, as outlined in the final section of chapter 1. The questions addressed are: what are the main sources for end-of-life scrap arisings in the UK, and how much of it is currently recovered? The methodology used to answer these questions is material flow analysis (MFA) with a temporal dimension, by applying parts of residence time distribution theory (used in chemical reaction engineering). This is a novel development in MFA methodology. The general methodology of the analysis is first described followed by a more detailed description of the system flows, data collection, results and sensitivity analysis for iron/steel and aluminium respectively. Finally, the results of the two studies are discussed.
3.1 Introduction

Chapter 1 discussed one of the central themes in industrial metabolism and ecology: the closure of anthropogenic substance and material cycles. Its desirability is based on the observation that the biological nutrient cycles are closed; this is necessary for their long-term sustainability (Ayers 1994; Graedel & Allenby 2003). With current worldwide production of around 965 million tonnes of crude steel and one million tonnes of aluminium per year (see section 1.2), steel and aluminium are two of the main ‘nutrients’ of the global industrial ecology. Nevertheless, the primary resources of iron and aluminium are far from nearing depletion. As mentioned in the first chapter, aluminium and iron are amongst the most abundant metals in the earth’s crust with an average crustal abundance of 8 and 5.8% respectively (Wedepohl 1995). However, as discussed in chapter 2, it is well established that secondary iron, steel and aluminium production from scrap requires much less energy and also produces significantly less problematic wastes and emissions. This creates a powerful environmental incentive to keep the losses in the iron, steel and aluminium cycles to an unavoidable minimum.

Losses can occur at each stage in the iron, steel and aluminium cycles, which is often modelled using the three process groups, production, fabrication/manufacturing and use (Michaelis & Jackson 2000). As described in chapter 1, the metal wastes that correspond to these three process groups are called home scrap, prompt or new scrap, and end-of-life or old scrap (see figure 3.1). Overall, loss rates from iron, steel, and aluminium production, and fabrication and manufacturing are very low, and therefore the home and prompt scrap cycles are fairly tightly closed. Things are different, however, for the iron, steel and aluminium contained in end-of-life products that have reached the end of their useful lives, so called end-of-life (EOL) scrap. It is here where the highest uncertainties for levels of recovery exist and where the highest loss rates in these metal cycles are to be expected.

The availability and quality of data on production and consumption tends to decrease as one moves downstream in a supply chain (Graedel et al. 2002). The Iron and Steel Statistics Bureau (ISSB) collects detailed information for the production of iron and steel in the UK, just as the Aluminium Federation (Alfed) collects data for UK aluminium production. Things are a lot more challenging for the fabrication/manufacturing of goods. Whereas there are only few iron,
steel and aluminium producers in the UK, there are thousands of fabricators and manufacturers. Some of their trade bodies and the Office of National Statistics (ONS) collect production and consumption data for the UK, but typically they do not meet the requirements of an in-depth material flow analysis. The range of goods that contain these metals is also simply too vast to be covered in this way. Material data on the millions of users of final goods is even harder to come by. UK government and industry-funded bodies like the Automotive Consortium on Recycling and Disposal (ACORD) and the Industry Council for Electronic Equipment Recycling (ICER) have only just begun to collect data on the use and disposal of final goods in the UK. This lack of data is the reason why the flow of end-of-life scrap from the use phase of final goods is the least known quantity in the iron, steel and aluminium cycles of the UK, or any other nation for that matter. However, from an industrial ecology perspective it is one of the most important flows. Hence, one of the main objectives of this work is to gain further knowledge about this flow of end-of-life scrap from the use phase.

3.2 Scope and system definition

The scope of this study is to quantify and analyse the generation and recycling rates of end-of-life iron/steel and aluminium scrap in the UK. The aim is also to determine from which types of goods the main losses of end-of-life scrap originate. Since scrap consumption and trade data do not discriminate between prompt and end-of-life scrap, the systems must also include production and consumption of prompt scrap. Home scrap can be excluded from the system since it is always recycled internally and therefore never leaves the producers’ premises.
3.3 Methodology

The material flow model contains only those parts of the UK iron/steel and aluminium cycles that are necessary to quantify the material flows into and out of the stock of iron/steel and aluminium scrap. The model therefore consists of the processes ‘fabrication / manufacturing’ and ‘use’, as highlighted in figure 3.2. The system boundary of the analysis is the geographical border of the UK. Generation of prompt and end-of-life scrap in the UK therefore comprises all prompt scrap produced by UK based fabricators and manufacturers and all end-of-life scrap contained in final goods that become obsolete within UK borders. Recycled scrap is all the prompt and end-of-life scrap that is consumed by domestic iron, steel and aluminium producers. If scrap, i.e. ‘pure’ scrap and not scrap that is contained in end-of-life goods, leaves the UK economic system through export, it is assumed that it will be recycled abroad and is counted as recovered rather than lost (since it is most unlikely to import scrap and then not re-use or recycle it).

3.3 Methodology

There are two fundamentally different methods to quantify the generation of end-of-life scrap, an empirical, survey-based one and a theoretical, model-based one (Birat et al. 2002). The empirical method attempts to directly measure or estimate the flow of end-of-life scrap arisings. Since industrial societies do not traditionally monitor waste flows very carefully, ‘directly’ has to be read as ‘as directly as possible’. The most direct way to do this is probably to analyse samples...
of waste to be landfilled or incinerated for their material composition. This has been done, for example, to assess the average amount of steel packaging contained in municipal waste (May 2000). Another possibility is to survey the agents that are in charge of waste disposal. This has been carried out for the construction sectors for the UK and France for steel (Ley et al. 2002; Birat et al. 2002) and is also the standard method for end-of-life vehicles (ACORD 2000). Due to their enormous volume, the handling of end-of-life waste from the construction and automotive sectors is relatively well organised, making this approach possible. A third avenue to pursue is to directly address the users of the final goods to establish their disposal practices; this has been done to estimate the amount of waste electric and electronic equipment that is generated every year by UK consumers (ICER 2000; Mayers et al. 2002). All these options are plagued with the usual problems of empirical statistical methods: e.g. is the size of the sample and its composition representative? Are the answers given in interviews and questionnaires reliable? While empirical methods prove useful for certain well-defined industrial sectors and some specific final goods, they are far less fitting for certain types of consumer goods and sectors that are not easily defined. To empirically assess the entire flow of end-of-life scrap contained in all consumer and producer goods disposed of by all private, corporate and governmental owners would therefore be a huge, if not unfeasible, task.

Which leaves us the second method to achieve our goal. The theoretical, model-based method is fairly established by now and seems to be the method of choice for most MFAs that are conducted on a national scale (Birat et al. 1999; Michaelis & Jackson 2000; Fenton 2001). These MFAs may differ in some details but their general modelling approach is always based on the application of the mass balance principle, loosely formulated as ‘what goes in must come out’ (Kleijn et al. 2000).

In this model, “iron and steel” refers to all iron and steel quantities, including all ferroalloys and other elements contained in the material, e.g. carbon (C), sulphur (S), manganese (Mn) and chromium (Cr). Likewise, “aluminium” means all quantities of aluminium, including all aluminium alloys and other elements contained in the material. The aim of the model is to determine the release of scrap from the use phase; it does not determine the size of the total stock of metal contained in goods in use, although this would be possible given a sufficiently long time
3.3 Methodology

Figure 3.3: Model for estimation of prompt and end-of-life (EOL) scrap.

The flowchart and equations for estimating the end-of-life scrap arisings are summarised in figure 3.4. Explanations for the abbreviations used in this flowchart are given in figure 3.5. The modelling has been performed in excel and Matlab. A description of the modelling procedure follows here.

In this time dependent model, the historical time-series data for the various flows of metal are condensed into vectors: input of metal products to UK fabrication and manufacturing, import and export of metal contained in goods, etc. Each element in each vector represents the flow in year \( j = 1, 2, \ldots, p \), for example:

\[
M = \begin{bmatrix}
m_1 \\
m_2 \\
\vdots \\
m_p
\end{bmatrix}
\]  

(3.1)

When in the model the flows are split into different sectors, \( i = 1, 2, \ldots, n \), the vectors are extended to matrices with dimensions corresponding to the number of years and number of sectors.

The model starts with the flows of domestic and imported iron, steel and aluminium industry products that enter UK fabrication and manufacturing, follows through the fabrication and manufacturing processes and through the product use until the metals emerge as end-of-life scrap at
To calculate the recycling rate in year $j$

1. Define and declare vectors and matrices
2. Read known data
3. $DNG_{ji} = SC_{ji} \times (1 - PRate) - NExp_{ji} + NImp_{ji}$
4. Start loop over goods categories $i = 1, 2, ..., n$
5. $E_{ki} = \text{Life-span distribution}$
6. Start loop of distribution $k = 1, 2, ..., n_{\text{dist}}$
7. $EOL_{ji} = \sum_k (DNG_{ki} \times E_{ki})$
8. $k < n_{\text{dist}}$?
   - Yes
   - $i < n$?
     - Yes
     - No
     - $k < n_{\text{dist}}$?
       - Yes
       - No
     - No
8. $\text{Scrap}_{ji} = \sum_i (EOL_{ji} + SC_{ji} \times PRate)$
9. $Rrate_{ji} = (UKrec_{ji} - SImp_{ji} + SExp_{ji}) / \text{Scrap}_{ji}$

Figure 3.4: Flowchart for calculating prompt and EOL scrap arisings.
3.3 Methodology

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n$</td>
<td>Number of categories of goods</td>
</tr>
<tr>
<td>$n_{\text{dur}}$</td>
<td>Number of years considered in life-span distribution</td>
</tr>
<tr>
<td>EOL</td>
<td>End-of-life scrap arisings from each goods category (matrix)</td>
</tr>
<tr>
<td>E</td>
<td>Life-span distribution for each category of new goods (matrix)</td>
</tr>
<tr>
<td>SC</td>
<td>Consumption of metal in UK manufacturing sectors (matrix)</td>
</tr>
<tr>
<td>DNG</td>
<td>Delivery of metal in new goods to UK use (matrix)</td>
</tr>
<tr>
<td>PRate</td>
<td>Prompt scrap rate for each manufacturing sector (vector)</td>
</tr>
<tr>
<td>NExp</td>
<td>Exports of metal in new goods (matrix)</td>
</tr>
<tr>
<td>NImp</td>
<td>Imports of metal in new goods (matrix)</td>
</tr>
<tr>
<td>Scrap</td>
<td>Total amount of end-of-life and prompt scrap arisings (vector)</td>
</tr>
<tr>
<td>RRate</td>
<td>UK recycling rate (vector)</td>
</tr>
<tr>
<td>SExp</td>
<td>Exports of scrap (vector)</td>
</tr>
<tr>
<td>Simp</td>
<td>Imports of scrap (vector)</td>
</tr>
<tr>
<td>UKrec</td>
<td>Scrap consumption in UK metal production (vector)</td>
</tr>
</tbody>
</table>

**Figure 3.5:** Abbreviations used in flowchart for calculating prompt and EOL scrap arisings.

The end of the use phase (see figure 3.3). All flows are given on a yearly basis, i.e. as tonnes per year. It has been assumed that the fabrication and manufacturing sectors that consume the iron/steel and aluminium, together with other materials, process the materials in the same year they receive them. In a model with a time discretisation of one year these processes therefore appear to be instantaneous. The flow of metal to UK manufacturing is matrix $SC_{j,t}$. The stocks of iron/steel and aluminium contained in new goods are fed by the outputs from the UK manufacturing sectors, which are calculated from the sectors’ consumption of iron, steel and aluminium products minus prompt scrap, and by imports of new goods. Prompt scrap is modelled by assuming that a certain percentage, based on data for the rate of generation (i.e. the prompt scrap rate), of the inflow to each manufacturing sector is turned into prompt scrap. The flows that leave this stock are exports and the new goods that enter the use phase in the UK. The stocks of new goods in the UK are assumed to be constant, which allows us to calculate the flows into the use phase once the inflows from manufacturing and the trade flows are known. Hence, the deliveries...
of new goods to use in the UK is equal to:

\[ DNG_{j,i} = SC_{j,i}(1 - Prate_i) - NExp_{j,i} + NImp_{j,i}. \]

(3.2)

where \( NExp_{j,i} \) and \( NImp_{j,i} \) are the exports and imports of metal contained in new goods, and \( Prate_i \) represents the prompt scrap rate of each sector.

Clearly, the use phase cannot be modelled as an instantaneous process and is therefore treated as a process and a stock: new goods enter the stock in use and remain there according to their residence time distribution (i.e. life-span distribution). This usage period gradually depreciates the goods until they leave the use phase to become end-of-life products. A model developed in this work and described in the next two sections, resulting in equation 3.3, is employed to calculate the time-dependent flow of scrap contained in end-of-life products emerging from the use phase, i.e. \( EOL_{j,i} \).

\[ EOL_{j,i} = \sum_k DNG_{j-k,i} E_k \]

(3.3)

where \( E_k \) is the life-span distribution of sector \( i \). The prompt scrap coming from fabrication and manufacturing and scrap imports are the other two inflows to the stock of scrap:

\[ Scrap_j = \sum_i (EOL_{j,i} + Prate_i SC_{j,i}). \]

(3.4)

Scrap from this UK stock is recycled domestically, exported for overseas recycling or lost from the economic system, typically to landfill. With enough information about these flows and the changes of the scrap stock it is possible to assess the level of closure of the UK iron/steel and aluminium cycles respectively, i.e. what the recycling rates are for these metals. In other words, it is possible to compare the amount of prompt and end-of-life scrap consumed in UK metal production and scrap exports with the arisings of UK prompt and end-of-life scrap. However, as some scrap used in UK metal production has not arisen in the UK, this has to be deducted from the total scrap flows, which gives the definition of recycling rate used in the study:

\[
\text{Yearly recycling rate} = \frac{\text{Consumption of prompt and EOL scrap in UK production} - \text{scrap imports} + \text{scrap exports}}{\text{Arisings of prompt and EOL scrap in the UK}}
\]

(3.5)
Nevertheless, one of the main difficulties in determining the recycling rate is associated with calculating the flows of end-of-life scrap out of the goods in use, mainly because different goods have different life-spans and will emerge as scrap at different times. To deal with this problem, this work has developed a modelling approach applying the theory of residence time distribution from chemical reaction engineering. Although a few MFA studies have used life-span distributions (see section 1.3), as far as the author of this work is aware, this is the first time the connection between this theory and MFA has been laid out explicitly. Making the connection to residence time theory explicit links MFA to a wider set of tools; for example, it provides an explicit relationship between the distribution of service lives and the age distribution of goods in use (equations 3.11 and 3.12). The essential elements of this theory are outlined here.

3.3.1 Summary of theory of residence time distributions

In the science of chemical engineering, the entire branch of chemical reaction engineering relies on the analysis of the distribution of the time spent in a confined volume, usually a chemical reactor, of material flowing through that volume. Formally, analysis of the distribution of life-spans of goods is exactly the same as analysis of the residence time of chemicals in a reactor. The seminal analysis is fifty years old (Danckwerts 1953) and the topic is now an integral part of degree programmes in chemical engineering and is covered in undergraduate texts (e.g. Levenspiel (1972)). Rather than develop an apparently new analytic approach, the theory and the conventional notation of residence time theory has been employed in this study. The development is set out, however, in MFA terms rather than in terms of chemical reaction theory.

Consider goods leaving their use phase at the end of their life-span. The fraction of the End-of-Life (EOL) goods which were in use for times from \( t \) to \( (t + dt) \) is

\[
\frac{Edt}{\int_0^\infty Edt} = 1
\]

The function \( E(t) \) is known as the residence time distribution, RTD. Necessarily

\[
\int_0^\infty Edt = 1
\]

The fraction of EOL goods which has been in use for time \( t_1 \) or less is

\[
\int_0^{t_1} Edt
\]
while the fraction which has been in use for more than time $t_1$ is

$$\int_{t_1}^{\infty} E \, dt = 1 - \int_0^{t_1} E \, dt$$

The form of the RTD function $E(t)$ describes the distribution of residence times amongst goods at their end of life. If all goods are in use for exactly the same time, then $E(t)$ takes the form of a delta function, i.e. a spike. In chemical reactor theory, this idealised case is usually termed plug flow, with all fluid elements moving together through the reactor. At the opposite extreme is the case where the goods currently in use have equal probability of being scrapped. In chemical reaction engineering, this case corresponds to ideal complete mixing in the reactor; in MFA it is sometimes, confusingly, termed a leaching model. The RTD function takes the form

$$E = 1 - \exp(-t/\bar{t})$$

where $\bar{t}$ is the mean life-span (or residence time in the case of a chemical reactor).

Real life-span distributions can be described by functions with a form in between a delta function and equation 3.6. The mean life-span is

$$\bar{t} = \int_0^{\infty} t E \, dt$$

and the variance of life-spans is

$$\sigma^2 = \int_0^{\infty} (t - \bar{t})^2 E \, dt = \int_0^{\infty} t^2 E \, dt - \bar{t}^2$$

Other functions describing product ages can be defined, and may be useful for other purposes. The $F$ function could be defined to describe the proportion of EOL goods which has been in use for time $t_1$ or less; it rises from zero to one. If the stock of goods in use is constant (or, in practice, if the variation in stock is small compared to the rate of goods entering use) then the $F$ and $E$ functions are related by

$$F(t_1) = \int_0^{t_1} E(t) \, dt$$

and

$$E(t) = \frac{dF}{dt}$$

Although not used in this study, these relationships could be applied to interpret observations of the life-spans of EOL goods. For example, if a new type of goods was introduced into use at
3.3 Methodology

t = 0 and information was available on the rising fraction of these goods in the end-of-life scrap arisings, i.e. the \( F \) function, then at any time \( t > 0 \) this fraction in the arisings is younger than age \( t \).

Danckwerts (1953) also defined the \( I \) function, which describes the distribution of ages of the material in a vessel; in MFA this represents the distribution of the ages of goods currently forming the stock-in-use. In other words, the fraction of goods currently in use having ages between \( t \) to \((t + dt)\) is

\[
Idt
\]

Whereas \( E \) may be termed the exit age distribution, \( I \) is the internal age distribution. Again for the case where the stock of goods in use can be taken as constant,

\[
I(t_1) = \frac{\int [I - F(t_1)]dt}{t}
\]  
(3.11)

\[
= [1 - \int_0^h E(t)dt]/t
\]  
(3.12)

The average age of goods in use, \( \bar{t}_i \), clearly differs in general from the average age of goods leaving use at their EOL. It is given by

\[
\bar{t}_i = \int_0^\infty tI(t)dt
\]  
(3.13)

or

\[
\bar{t}_i = \frac{1}{I} \int_0^\infty t[1 - F(t)]dt
\]  
(3.14)

Again, equations 3.11 to 3.14 have not been used in this work, but they could be useful in relating the age distribution of goods in use to EOL goods. As an example, an analysis of the ages of goods currently in use could provide more detailed information on the actual distribution of life-spans of goods, and vice versa.

Equations 3.6 to 3.14 refer to the case where the residence time distribution is described by continuous functions. In the present analysis, as in most MFA work, discrete time intervals are used, e.g. \( \Delta t \), where \( \Delta t \) is normally one year. Provided that \( \Delta t \) is sufficiently small compared with the mean life-span, \( \bar{t} \), it is usually adequate to approximate \( E_k \), i.e. the fraction of EOL goods which was in use for \( k \) time periods, as \( E(k\Delta t)\Delta t \). The discretised forms of the \( F \) and \( I \) functions,
3.3 Methodology

i.e. discretised forms of equations 3.9 and 3.11, are

\[ F_k = \sum_{j=1}^{k} E_j \]  
\[ I_k = \frac{1 - F_k}{t} \]

(3.15)  
(3.16)

where \( F_k \) describes the fraction of EOL goods which has been in use for \( k \) time periods or less and \( I_k \) is the internal age distribution at time \( k \). Similarly, the discretised forms of equations 3.7 and 3.8 give the mean and variance of service life:

\[ \bar{t} = \sum_{k=1}^{\infty} t_k \bar{E}_k = \Delta t \sum_{k=1}^{\infty} k \bar{E}_k \]  
\[ \sigma^2 = \sum_{k=1}^{\infty} (t_k - \bar{t})^2 \bar{E}_k = \sum_{k=1}^{\infty} k^2 \bar{E}_k - \bar{t}^2 = \Delta t^2 \sum_{k=1}^{\infty} k^2 E_k - \bar{t}^2 \]

(3.17)  
(3.18)

For the case where the number of units of products or mass of material in service can be taken as constant, it is a general result (Danckwerts 1953) that the mean service life, \( \bar{t} \), is given by the stock in use divided by the rate of entry into use of new products or material. For the discretised case, if the stock comprises mass \( M \), and the material flux into use is \( m \) per year, then the mean life service is simply \( M/m \) years. In other words, if the mass in use is known and it is constant, the average life-span of goods leaving use can be calculated.

3.3.2 Modelling end-of-life scrap arisings

Following on from the theory of residence time distribution, this section describes how the theory has been applied to this work. In the model, the goods in use are divided into a number of different sectors, see figure 3.3. Each sector is distinct from the others, so that goods flow through the sectors in parallel and emerge as end-of-life (EOL) scrap. Consider any sector, numbered \( i \). Of the goods which entered use at time \( t \), a fraction \( E_i(t) \) has service life from \( \tau \) to \( \tau + d\tau \) and therefore emerges as EOL scrap in the time interval from \( (t + \tau) \) to \( (t + \tau + d\tau) \). If the rate of entry of new goods \( i \) into use in this sector is \( DNG_i(t) \), then the rate of arisings of used goods as EOL scrap is

\[ EOL_i(t) = \int_{t_{min}}^{t_{max}} DNG_i(t - \tau) E_i(\tau) d\tau \]

(3.19)
3.3 Methodology

where $\tau_{\text{min}}$ and $\tau_{\text{max}}$ represent the minimum and maximum life-span of goods in the sector, and $E_i$ is the distribution of their residence times or life-spans. In general the residence time distributions, $E_i$, will differ between the different sectors. Summing over the $n$ distinct sectors, the total rate of EOL scrap arisings is

$$EOL(t) = \sum_{i=1}^{n} EOL_i(t) = \sum_{i=1}^{n} \left[ \int_{\tau_{\text{min}}}^{\tau_{\text{max}}} DNG_i(t-\tau)E_i(\tau)\,d\tau \right]$$

(3.20)

Time in this work is measured not as a continuous variable but as multiples of a fixed interval (one year); then the fraction of EOL goods, from sector $i$, which were in use for $k$ intervals (years in this work) is denoted $E_k$. In terms of the discretised inflow and distribution, equation 3.19 takes the form

$$EOL_{j,i} = \sum_k DNG_{j-k,i}E_{k,i}$$

(3.21)

where $EOL_{j,i}$ is the EOL scrap arisings from sector $i$ in year $j$ and $DNG_{j,i}$ is the flow of new goods from sector to use in year $j$. Summing over the sectors,

$$EOL_j = \sum_i EOL_{j,i} = \sum_i \left[ \sum_k DNG_{j-k,i}E_{k,i} \right]$$

(3.22)

This equation is used in this work to calculate the yearly arisings of end-of-life scrap in the UK and introduces a novel element in the MFA methodology. In this study, the residence time distribution itself is assumed to be constant over time. The modelling approach could however easily accommodate time dependent residence time distributions.

3.3.3 Life-span distributions

In this study three life-span distributions (residence time distributions) have been used for each goods category to estimate the release of end-of-life scrap to analyse the impact on the results. The distributions are:

- no distribution, i.e. a fixed number of years ("plug flow");
- a Weibull distribution; and
- a lognormal distribution.
3.3 Methodology

The Weibull and Lognormal distributions have been chosen as they are common in analyses to simulate products' life-spans. No distribution is also used, so that a comparison between the results can be made: do the scrap arisings differ greatly depending on whether a distribution has been used? However, due to lack of precise information on the actual distributions of the life-spans, we have used information on the average life-span for each goods category. Consequently, the Weibull and Lognormal distribution are used not as precise representation of real life-span distribution data, but rather to give a general representative distribution of the life-span figure that has been collected for each goods sector. It is more likely that products will have a life-span distribution rather than all having exactly the same life-span, so these distributions should be able to simulate this effect. This will be discussed further in the section presenting the results of modelling. The parameters that define the Weibull and Lognormal curves have been chosen so that the mean of each distribution is equal to the average life-span figure.

Weibull distribution

The Weibull distribution is widely used to simulate life-spans of products. It has great flexibility which means it can take many different shapes depending on the shape parameter $\beta$. The distribution used in this analysis is the two-parameter Weibull distribution, as two parameters are adequate to define the shape of the life-span curve. The probability density function (pdf), or RTD function, of this distribution is

$$E(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta}\right)^{\beta-1} \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right]$$  \hspace{1cm} (3.23)

where $t$ is the life-span ($t \geq 0$), $\eta$ is the scale parameter ($\eta > 0$) and $\beta$ is the shape parameter, or slope parameter, ($\beta > 0$) (Suhir 1997). The scale and shape parameters used in this analysis to produce the pdf for each goods sector are given in sections 3.4.1 and 3.5.1 for iron/steel and aluminium respectively. The parameters are chosen so that the shape of the curve accommodates the information available on average life-span and, for some goods categories, also minimum and maximum life-spans. In other words, the mean of the Weibull distribution equals the average life-span figure for each goods sector. The mean, $\bar{t}$, is calculated according to:
\[ \bar{r} = \eta \Gamma \left( 1 + \frac{1}{\beta} \right) \quad (3.24) \]

where

\[ \Gamma (\alpha) = \int_0^\infty x^{\alpha-1} \exp (-x) \, dx \quad (3.25) \]

is the gamma function which is tabulated in many statistical handbooks, e.g. Applied Probability for Engineers and Scientists (Suhir 1997). The variance of the distribution is given by:

\[ \sigma^2 = \eta^2 \left[ \Gamma \left( 1 + \frac{2}{\beta} \right) - \left( 1 + \frac{1}{\beta} \right) \right] \quad (3.26) \]

The standard deviation is simply the square root of the variance.

Log-normal distribution

A variable \( T \) is log-normally distributed if \( Y = \ln(T) \) is normally distributed with \( \ln(\cdot) \) denoting the natural logarithm. The log-normal distribution is commonly used for analysis of cycles-to-failure in fatigue, material strengths etc. The distribution used in this analysis is the two-parameter log-normal distribution. The pdf for this distribution is:

\[ E(t) = \frac{1}{t \alpha \sqrt{2\pi}} \exp \left[ -\frac{1}{2} \left( \frac{\ln(t) - \mu}{\alpha} \right)^2 \right] \quad (3.27) \]

where \( t \) is the life-span \( (t \geq 0) \), \( \mu \) is the scale parameter \( (\mu > 0) \) and \( \alpha \) is the shape parameter \( (\alpha > 0) \) (Mood et al. 1974). The scale and shape parameters used to produce the pdf for each goods sector in the analysis are given in sections 3.4.1 and 3.5.1 for iron/steel and aluminium respectively. Again, these parameters are chosen to generate a shape of the curve that reflects the information available on average life-span for each goods category, i.e the mean of the distribution corresponds to the average life-span. The mean is calculated according to:

\[ \bar{t} = \exp \left[ \ln(\mu) + \frac{\alpha^2}{2} \right] ; \quad (3.28) \]

and the variance is given by:
3.3 Methodology

![Graph showing life-span distributions for vehicles using Weibull and log-normal distributions.]

Figure 3.6: Pdf of the life-span for vehicles using Weibull ($\eta = 14.2$ and $\beta = 5$) and log-normal ($\mu = 12.75$ and $\alpha = 0.2$) distributions.

$$
\sigma^2 = \exp \left[ 2 \ln(\mu) + 2\sigma^2 \right] - \exp \left[ 2 \ln(\mu) + \alpha^2 \right].
$$

(3.29)

As an example, figure 3.6 shows the life-span distributions using Weibull and log-normal distributions for the goods category vehicles. The mean of each distribution is the same, $\bar{t} = 13$, but their standard deviations are slightly different, $\sigma_{\text{Weibull}} = 3.0$ and $\sigma_{\text{lognormal}} = 2.6$. Further information on life-spans for each goods category and corresponding references are given in section 3.4.1 and 3.5.1 for iron/steel and aluminium respectively.

This methodology is now applied to the material flow analysis of iron and steel, and then to aluminium.
3.4 Material flow analysis of iron and steel

The system model to calculate the flow of iron and steel prompt and end-of-life scrap is shown in figure 3.7. This section is dedicated to describing, in more detail, how the iron and steel scrap arisings have been modelled, the data availability, necessary assumptions and the results of the study.

3.4.1 Description of system flows and data collection

The main data source employed in this study is the Iron and Steel Statistics Bureau (ISSB) which collects data directly from all UK iron and steel producers and other relevant sources like the Office of National Statistics (ONS) and HM Customs and Excise, and from surveys, e.g. of UK stockholders. Data on trade of finished goods have been collected from HM Customs and Excise. All the collected data are available on the enclosed CD-rom. The information on iron and steel content of traded goods, prompt scrap rates and life-spans have been gathered from a number of sources. The system flows, data collection and necessary assumptions are described in more detail in the following subsections.
Material categories and process groups

In the analysis, iron and steel are categorised into the four following material groups:

1. iron and steel industry products which are used to produce final goods in the fabrication and manufacturing stage;
2. iron and steel contained in new goods;
3. prompt scrap which is generated at the fabrication and manufacturing stage;
4. end-of-life scrap which leaves the use phase.

The model encompasses two processes, see figure 3.2: (1) fabrication and manufacturing of goods and (2) use of final goods. In the first process, iron and steel products are transformed into goods, i.e. vehicles, buildings, cans etc. The iron and steel in new goods are then either delivered to use in the UK or exported. The input into use consists of the flow from UK manufacturing and imports. The use stage represents a stock of iron and steel, but it is also a process as use can change the characteristics of the metals, e.g. by corrosion or by changes to the shape of the product. The materials that enter use are iron and steel contained in new goods whereas the material that comes out is iron and steel scrap contained in goods that have reached the end of their service lives (end-of-life scrap).

Iron and steel industry products delivered to UK manufacturing sectors

The flow of iron and steel industry products into UK manufacturing industry is divided into nine different sectors. The deliveries of iron and steel originate from UK producers, UK stockholders and imports. Because the products come from these three different supplies it is difficult to generate data on the amount of iron and steel that enters each industry sector. The ISSB collects data on the total amount of iron and steel that enters the UK manufacturing industry, defined as ‘net home disposals’. The ISSB also has some detailed information on how much iron and steel enter each industry sector, but only for iron and steel products that are delivered directly from UK producers. For the imported iron and steel and deliveries from UK stockholders, no documentation on how much goes into each industry sector is available. However, the ISSB has
analysed the imports in terms of what type of iron and steel products they comprise and has also performed elaborate market surveys of the stockholders in order to determine how much iron and steel is delivered to each manufacturing sector in the UK covering deliveries from all three sources: UK producers, imports and stockholders. This dataset, compiled for the years 1975 to 2000, has not been used for MFA-type research before and constitutes the backbone of this analysis. The data divides the total deliveries into nine industry sectors. This is therefore the sector division employed throughout the analysis; table 3.1 gives the sector division. The data is only available up until 2000. The split in 2000 has been used to infer the figures for 2001 as only the total amount of ‘net home disposals’ was available for this year and not the division into the different sectors. For iron and steel that goes into construction, data compiled by the Steel Construction Institute (Ley et al. 2002) have been used. This data set covers the time period 1900 to 2000 and it has been employed in this study for the years 1900 to 1975. The construction data from 1955 to 1975 are derived from the ISSB (ISSB 2001). From 1900 to 1955 construction data have been estimated using literature, UK steel consumption data and the economic output of UK construction from 1900 to 1955.

The data discussed above excludes cast iron products produced in iron foundries. Unfortunately data on consumption of cast iron in different industry sectors are not available. In the analysis it has therefore been assumed that one million tonnes per year of foundry iron is used in UK fabricating and manufacturing (Hunt 2003). It has been assumed that 50% is used in production of pipes for water and gas supply etc., which is included in ‘Structural steelwork and building and civil engineering’, and that the remainder is split between ‘Mechanical engineering’ and ‘Boilers, drums and other vessels’. These assumptions have been verified by personal communication with the British Foundry Association (Donahue 2003). Table 3.1 gives the resulting market shares for deliveries of iron and steel industry products to UK manufacturing industry in 2000.

Depending on the manufacturing sector, a certain amount of prompt scrap is generated from cutting, drawing, extruding or other shaping of the metal to produce final goods. In the analysis we have multiplied the inflow of iron and steel products to each sector with specific rates to generate the flow of prompt scrap from the fabrication and manufacturing stage. A prompt scrap
3.4 Material flow analysis of iron and steel

Table 3.1: Market shares for iron and steel in 2000 and prompt scrap rates.

<table>
<thead>
<tr>
<th>Goods category</th>
<th>Market share [%]</th>
<th>Prompt scrap rate [% of sector input]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical engineering</td>
<td>17</td>
<td>10</td>
</tr>
<tr>
<td>Electrical engineering</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Shipbuilding</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Vehicles</td>
<td>17</td>
<td>10</td>
</tr>
<tr>
<td>Structural steelwork and building and civil engineering</td>
<td>26</td>
<td>5</td>
</tr>
<tr>
<td>Metal goods</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>Cans and metal boxes</td>
<td>4</td>
<td>17</td>
</tr>
<tr>
<td>Boilers, drums and other vessels</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Other industries</td>
<td>20</td>
<td>10</td>
</tr>
</tbody>
</table>

rate of 10\% (Aylen 2003) has been used for all sectors except construction and packaging for which prompt scrap rates of 5\% (EC, 2002) and 17\% (May 2000) have been used respectively. These rates have been assumed to be constant over the time period analysed. The prompt scrap rates and market shares of each sector are given in table 3.1. These data have been used as fixed values in the analysis, i.e. no statistical distribution has been applied.

Trade in final goods

To derive the import and export of iron and steel contained in final goods traded across the UK border, all the goods that contain iron and steel were selected, compiled into the nine subcategories of industry sectors and their total mass was multiplied by estimated average iron and steel content figures. Data for trade in final goods have been collected from HM Customs and Excise for the years: 1968, 1973, 1978, 1983, 1988, 1993, 1998 and 2000 (Customs & Excise 2000). The data have then been linearly interpolated to yield yearly values and aggregated into the nine industry sectors. The categories and their corresponding SITC (Standard Industry Trade
3.4 Material flow analysis of iron and steel

Classification) and grouping into the nine sectors are given in Appendix A. In order to estimate how much iron and steel the traded goods contain we have assumed a constant average iron and steel content for each of the nine categories by using steel efficiency coefficients produced by the International Iron and Steel Statistics Bureau (IISI 1996); these coefficients give the amount of steel that is required to produce one tonne of finished goods. It has been assumed that the coefficient multiplied by a factor (1 - prompt scrap rate for each sector) is equivalent to the steel content in the finished goods; table 3.2 gives the resulting steel content figures used in the analysis. The resulting flows of iron and steel in imported and exported goods can be seen in figure 3.8. These data have been used as fixed values in the analysis, i.e. no distribution has been applied.

**Iron and steel in goods going to use in the UK**

As described previously, the stock of iron and steel contained in new goods is fed by the outputs from the UK manufacturing sectors, which is calculated from their iron and steel consumption and prompt scrap rates, and by imports of goods containing iron and steel. The flows that leave this stock are exports and new goods that enter the use phase in the UK. The stock of new goods in the UK is assumed to be constant, which allows us to calculate the iron and steel flows into the
3.4 Material flow analysis of iron and steel

Table 3.2: Iron and steel content of traded goods

<table>
<thead>
<tr>
<th>Goods category</th>
<th>Iron and steel content [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical engineering</td>
<td>71</td>
</tr>
<tr>
<td>Electrical engineering</td>
<td>30</td>
</tr>
<tr>
<td>Shipbuilding</td>
<td>70</td>
</tr>
<tr>
<td>Vehicles</td>
<td>58</td>
</tr>
<tr>
<td>Structural steelwork and building and civil engineering</td>
<td>100</td>
</tr>
<tr>
<td>Metal goods</td>
<td>85</td>
</tr>
<tr>
<td>Cans and metal boxes</td>
<td>100</td>
</tr>
<tr>
<td>Boilers, drums and other vessels</td>
<td>100</td>
</tr>
<tr>
<td>Other industries</td>
<td>60</td>
</tr>
</tbody>
</table>

use phase; this flow is shown in figure 3.9 for 1975-2000. It is clear that 'Vehicles', 'Structural steelwork, building and civil engineering' and 'Other industries' are consistently the three largest uses for iron and steel in society over the past 25 years. Over this time period the total amount of iron and steel contained in goods going to use does not display a clear upward or downward trend but rather a cyclical behaviour around an average value of around 13 million tonnes per year. The decrease in the 1980s was due to the national steel-strike which lasted several months.

Life-spans of goods

In the use phase, there is a time delay before the goods are released as end-of-life scrap according to the life-span of the specific goods. In the model, we capture this by taking into account the flow of iron and steel entering use over the past 25 years, in the case of construction the past 100 years, and applying a residence time distribution, or life-span distribution, to the goods. In the analysis we have used two life-span distributions for each goods category to estimate the release
### Table 3.3: Life-span data used in the modelling of end-of-life scrap arisings.

<table>
<thead>
<tr>
<th>Goods category</th>
<th>Average life-span [years]</th>
<th>Min and max life-span [years]</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shipbuilding</td>
<td>60</td>
<td>-</td>
<td>Melo (1999)</td>
</tr>
<tr>
<td>Structural steelwork and building and civil engineering</td>
<td>60</td>
<td>20-100</td>
<td>Amato (1996, Howard et al. (1999), Graedel et al. (2002), van der Voet (2002)</td>
</tr>
<tr>
<td>Boilers, drums and other vessels</td>
<td>10</td>
<td>-</td>
<td>Michaelis (1998)</td>
</tr>
<tr>
<td>Other industries</td>
<td>25</td>
<td>-</td>
<td>Michaelis (1998)</td>
</tr>
</tbody>
</table>
Figure 3.9: Iron and steel in finished goods going into use in the UK between 1975 and 2000.

Table 3.4: Parameters used to generate the Weibull and lognormal distributions and the corresponding mean, \( \bar{T} \), and standard deviation, \( \sigma \), of each distribution; these distributions are used to model iron and steel scrap arisings.

<table>
<thead>
<tr>
<th>Goods category</th>
<th>Weibull</th>
<th>Lognormal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \eta )</td>
<td>( \beta )</td>
</tr>
<tr>
<td>Mechanical engineering</td>
<td>16.28</td>
<td>5</td>
</tr>
<tr>
<td>Electrical engineering</td>
<td>17.40</td>
<td>5</td>
</tr>
<tr>
<td>Shipbuilding</td>
<td>65.30</td>
<td>5</td>
</tr>
<tr>
<td>Vehicles</td>
<td>14.20</td>
<td>5</td>
</tr>
<tr>
<td>Structural steelwork and building and civil engineering</td>
<td>65.30</td>
<td>5</td>
</tr>
<tr>
<td>Metal goods</td>
<td>14.20</td>
<td>5</td>
</tr>
<tr>
<td>Cans and metal boxes</td>
<td>1.10</td>
<td>5</td>
</tr>
<tr>
<td>Boilers, drums and other vessels</td>
<td>10.90</td>
<td>5</td>
</tr>
<tr>
<td>Other industries</td>
<td>27.25</td>
<td>5</td>
</tr>
</tbody>
</table>
3.4 Material flow analysis of iron and steel of end-of-life scrap, as well as using a fixed number of years. The following distributions have 
been explored: (1) no distribution, i.e. a fixed number of years, (2) a Weibull distribution and 
(3) a lognormal distribution. The equations for the two distributions are given in section 3.3.3. 
The Weibull and lognormal distribution give a general distribution of the average life-span figure 
that has been collected for each goods sector, see table 3.3. In the case where minimum and 
maximum life-span values for a goods category have been available, a corresponding shape of 
the curve has been chosen to model this. Table 3.3 gives the information on life-spans that have 
been collected and used in the analysis. Table 3.4 gives the parameters used in the analysis to 
generate the Weibull and lognormal distributions for each goods category. The parameters have 
been chosen in an iterative process, so that the mean of each distribution equals the average life­ 
span figure for that category. The table also gives the mean, \( \bar{t} \), and standard deviation, \( \sigma \), of each 
distribution. The standard deviation is simply a measure of the spread of each distribution.

Recycling of prompt and end-of-life scrap

Data on how much scrap is recycled in UK iron and steel production as well as data on scrap im­ 
ports and exports are available from the ISSB (ISSB 2002). The data do not distinguish between 
prompt and end-of-life scrap, but give a total amount of scrap consumed in iron and steel making. 
However, these data do not take into account the scrap that is consumed in iron foundries, which 
is why these data have been collected from the British Metals Recycling Association, formerly 
known as the British Metals Federation (BMRA 2002). In order to derive the actual amount of 
scrap that is recycled from the UK generated prompt and end-of-life scrap, scrap imports are 
subtracted from the consumption of scrap in UK iron and steel production and scrap exports are 
then added, see equation 3.5 given earlier. It is thereby assumed that exported scrap will be re­ 
cycled abroad. Most UK scrap exports go to China and Russia which are expanding their steel 
production capacity drastically and are therefore in great need of scrap.

3.4.2 Results

One of the main aims of this study is to estimate the arisings of UK prompt and end-of-life scrap 
and compare it to the actual recycling of UK generated scrap in order to investigate the level of
3.4 Material flow analysis of iron and steel

Table 3.5: Inferred recycling rate for iron and steel in 2001 using the three life-span distributions.

<table>
<thead>
<tr>
<th>life-span distribution</th>
<th>No distribution</th>
<th>Weibull</th>
<th>Lognormal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated scrap arisings [million tonnes]</td>
<td>11.8</td>
<td>11.8</td>
<td>11.6</td>
</tr>
<tr>
<td>Actual recycled amount [million tonnes]</td>
<td>8.1</td>
<td>8.1</td>
<td>8.1</td>
</tr>
<tr>
<td>Inferred recycling rate [%]</td>
<td>68</td>
<td>68</td>
<td>70</td>
</tr>
</tbody>
</table>

closure of the iron and steel cycle in the UK. The derived prompt and end-of-life scrap arisings in 2001 using each of the three different distributions are shown in figure 3.10. The figure shows that there are very small differences between the modelled arisings using the three distributions. This is due to the fact that the inflow of iron and steel in the form of new goods into use has been relatively stable over the past 25 years; if there had been more significant upward or downward trends in this inflow, the distribution of life-spans would have been more critical. Figure 3.10 also shows the actual recycling of prompt and end-of-life scrap that has been generated within the UK (scrap consumption minus scrap imports plus scrap exports) in 2001. By comparing the modelled arisings with the actual recycling we can derive a recycling rate (defined in equation 3.5). This inferred recycling rate is given in table 3.5 for each distribution. It appears that the inferred amount of scrap available is about three and a half million tonnes more than the amount of scrap actually recycled this year. In other words, the inferred recycling rate in 2001 is 68-70%. The model thereby suggests that there is a large amount of scrap that is not being recovered and recycled at present.

Using statistics from Defra and the Environment Agency on how much waste was sent to landfill in 2000/2001 and information on how much of this waste is ferrous metal, it appears that industrial and commercial waste together with the municipal waste make up about two and a half million tonnes of ferrous metal going to landfill (see Appendix B for calculation and references). Bearing in mind this is based on estimated data, this amount would explain a significant part of
3.4 Material flow analysis of iron and steel

Figure 3.10: Modelled arisings of prompt and end-of-life scrap using three different life-span distributions compared to actual recycling of scrap in the UK.

...the three and a half million tonnes of iron and steel scrap that is not being recovered at present. The remaining scrap not accounted for must simply still be in society, e.g. in the form of old buildings and abandoned cars etc.

Sensitivity analysis of the inferred recycling rate

The end-of-life scrap arisings estimated in this model are affected by the key parameters average expected life-spans, prompt scrap rates and iron and steel contents of traded goods. In order to understand the reliability of the inferred recycling rate, an investigation has been carried out on how changing these parameters influences the predicted amounts of released scrap and thereby the inferred recycling rate.

Estimates of the iron and steel content are only applied to traded goods in the model and changing these parameters radically does not have a significant effect on the amount of released...
scrap. The reason for the low impact of changing the iron and steel content is that imports and exports of goods have been largely similar in quantity and growth rate over the last 30 years, so that they largely balance each other out.

Halving all life-spans gives an increase in released end-of-life scrap in 2001 and thereby reduces the inferred recovery rate, see table 3.6. When using a Weibull distribution for inferring the end-of-life scrap arisings this results in a reduction in the recovery rate to 63% from the original 71%. Because the data cover the time period 1975 to 2000, it has not been possible to analyse what the effect would be of increasing the life-spans by 50%. Again using the Weibull distribution, changing all prompt scrap rates to for example 40% also reduces the inferred recycling rate to 63%. Decreasing all prompt scrap rates to zero, and again using the Weibull distribution, increases the recovery rate to 74% from the original 68%. Combining a reduction of the life-spans by 50% and increasing all prompt scrap rates to 40% yields an inferred recovery rate of 58%. All these changes in life-spans and prompt scrap rates result in an inferred recycling rate of 58 to 74% and do not fall far from the inferred recovery rate using the original life-spans and prompt scrap rates (68 to 70%). This therefore confirms that the results are reliable and robust, under the assumptions made.

Table 3.6: Effect on inferred recycling rate (using a Weibull distribution) of changing prompt scrap rates and life-spans.

<table>
<thead>
<tr>
<th>Change of parameters</th>
<th>Inferred recycling rate [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decrease prompt scrap rates to 0%</td>
<td>74</td>
</tr>
<tr>
<td>Increase prompt scrap rates to 40%</td>
<td>63</td>
</tr>
<tr>
<td>Decrease life-spans by 50%</td>
<td>63</td>
</tr>
<tr>
<td>Increase prompt scrap to 40% and decrease life-spans by 50%</td>
<td>58</td>
</tr>
</tbody>
</table>
Recycling scenarios for each sector

Recycling rates have also been explored further by distinguishing between the different use sectors. The total arisings of prompt and end-of-life scrap arisings in the UK are estimated using the model outlined in figure 3.7. By applying recycling rates to each of the modelled outflows of end-of-life scrap arisings and comparing the sum of the resulting flows to the actual recycling of scrap in the UK, the results can be validated. However, recycling rates for each goods sector are not readily available; if recycling rates are available it is not always clear how they have been derived (which is one of the main reasons for performing this study in the first place). Nevertheless, possible recycling scenarios have been created using the available information.

A recycling rate of 89% was obtained from Defra for 'metal products in industrial and commercial sector in the UK', and this rate was assumed for 'mechanical engineering' and 'other industries'. For 'constructional steelworks etc.', 'vehicles' and 'cans and metal boxes', information from independent studies to determine their recycling rates has been obtained from various sources, see table 3.7. It has been assumed that 'Boilers, drums and other vessels.' has the same recycling rate as 'cans and metal boxes', as they are similar in components. Information on recycling rates for the remaining sectors has not been found, and rates for these have been chosen to obtain a total scrap recycling to match the documented overall scrap recycling in 2001; these recycling rates are given in table 3.8.

The scenarios are shown in table 3.8. In scenario 1, the rate 0% is chosen for all sectors other than those in table 3.7. This generates a little less than the amount of scrap that was recycled in 2001: 8.01 million tonnes compared to 8.06 million tonnes. It is likely that some scrap is recycled from electrical engineering and metal goods (ships are no longer scrapped in the UK, but sailed abroad to be scrapped at foreign dockyards; recycled scrap from ships in the UK is therefore negligible), so in scenarios 2 and 3 these sectors have recycling rates of 10 and 20%. The recycling rates of mechanical engineering goods and other industries have then been reduced slightly to obtain a recycled amount equivalent to that in 2001. Providing the literature recycling rates are defined according to equation 3.5 and that they are realistic, the model suggests the largest scrap losses originate from the goods categories 'metal goods' and 'electrical and mechanical engineering', which together make up more than 50% of the
3.4 Material flow analysis of iron and steel

<table>
<thead>
<tr>
<th>Goods category</th>
<th>Recycling rate [%]</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical engineering</td>
<td>89</td>
<td>Defra (2003a)</td>
</tr>
<tr>
<td>Vehicles</td>
<td>87</td>
<td>ACORD (2000)</td>
</tr>
<tr>
<td>Structural steelwork and building and civil engineering</td>
<td>85</td>
<td>Ley et al. (2002)</td>
</tr>
<tr>
<td>Cans and metal boxes</td>
<td>37</td>
<td>May (2000)</td>
</tr>
<tr>
<td>Boilers, drums and other vessels</td>
<td>37</td>
<td>May (2000)</td>
</tr>
<tr>
<td>Other industries</td>
<td>89</td>
<td>Defra (2003a)</td>
</tr>
<tr>
<td>Prompt scrap</td>
<td>100</td>
<td>Hunt (2003)</td>
</tr>
</tbody>
</table>

potential three and a half million tonnes currently not being recycled. These would be products like domestic appliances, hand tools, cutlery, metal furniture etc; products which might be very dispersed in society and therefore difficult to recover for recycling.

3.4.3 Overall overview of UK iron and steel flows in 2001

The work described in the previous sections is part of a larger study in which all iron and steel flows through the UK were mapped out. As included in the Mass Balance suit of Biffaward projects, coordinated by the Sustainable Economy Programme of the Forum for the Future, the aim of this work was to provide a reliable set of time series data on the flows of iron/steel and aluminium as they pass through the UK economy. To enhance the policy relevance of these flows, a parallel value chain analysis was also performed; to map the value chain corresponding to these material flows, and to examine how these values relate to resource productivity and recovery. This project is published in the report “Iron, steel and aluminium in the UK: Material flows and their economic dimensions” (Dahlstrom et al. 2004). The following text summarises the material flows of iron and steel in the UK in 2001. To put the scrap arisings into context,
Table 3.8: Scenarios of different recycling rates for the different sectors in 2001 used in the model to generate the amount of recovered scrap that match the documented recovery of scrap in 2001: 8.06 million tonnes.

<table>
<thead>
<tr>
<th>Goods category</th>
<th>2001 scrap arisings [million tonnes]</th>
<th>Recycling rates scenario 1 [%]</th>
<th>Recycling rates scenario 2 [%]</th>
<th>Recycling rates scenario 3 [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical engineering</td>
<td>1989</td>
<td>89</td>
<td>85</td>
<td>78</td>
</tr>
<tr>
<td>Electrical engineering</td>
<td>621</td>
<td>0</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Shipbuilding</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Vehicles</td>
<td>2331</td>
<td>87</td>
<td>87</td>
<td>87</td>
</tr>
<tr>
<td>Structural steelwork and building and civil engineering</td>
<td>1038</td>
<td>85</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>Metal goods</td>
<td>1497</td>
<td>0</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>Cans and metal boxes</td>
<td>801</td>
<td>37</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td>Boilers, drums and other vessels</td>
<td>536</td>
<td>37</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td>Other industries</td>
<td>1636</td>
<td>89</td>
<td>84</td>
<td>79</td>
</tr>
<tr>
<td>Prompt scrap</td>
<td>1383</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Inferred amount of recycled scrap [million tonnes]</td>
<td>8.01</td>
<td>8.06</td>
<td>8.06</td>
<td>8.06</td>
</tr>
</tbody>
</table>
3.4 Material flow analysis of iron and steel

Figure 3.11: System overview of UK iron and steel flows in 2001 (Dahlstrom et al. 2004).
3.4 Material flow analysis of iron and steel

Figure 3.11 shows an overview of all the flows of iron and steel in the UK for 2001.

All iron ore used in iron and steel production in 2001 was imported, as there is no longer any mining of iron ore in the UK. Most of the pig iron used in production is produced domestically; only a very small part is imported. In 2001, about 75% of UK-produced crude steel came from integrated steelworks (BF/BOFs) and 25% from electric arc furnaces (EAFs). Further down the chain we can see that almost half of the iron and steel products produced in the UK is exported and that imports of iron and steel products are just as high as the exports. This implies that a large part of the domestically produced iron and steel products is different from those required by UK goods manufacturers and fabricators, or that it is financially more attractive for UK iron and steel producers to export and goods manufacturers to import iron and steel products.

About 15 million tonnes of iron and steel products were delivered to UK goods manufacturers and fabricators in 2001. Most of this iron and steel went into building and construction followed by other industries, mechanical engineering and vehicles. These four sectors currently consume 80% of the total deliveries of iron and steel products in the UK. Just less than 10% of the total iron and steel deliveries to UK manufacturers was turned into prompt scrap and recycled back into the system. Out of the iron and steel in goods produced in the UK, about 40% was exported, and the rest was delivered to use in the UK. There is a substantial amount of iron and steel in goods imported to the UK; in 2001 more than 7 million tonnes of iron and steel in goods were imported. The fact that more goods are imported than exported from the UK is consistent with the general trend that the UK is moving from being a manufacturing country to being a service economy that imports a large part of its material needs. However, this could not be verified just by looking at the flows of one metal, as all materials used in society would need to be taken into account.

About 10 million tonnes of end-of-life scrap were released in 2001. Together with available prompt scrap arisings, this makes up more than 11 million tonnes, of which 4.8 million tonnes were exported and recycled abroad whereas 3.2 million tonnes were recovered and recycled domestically. A further two and a half million tonnes ended up in landfill. The recovery of iron and steel scrap arising in the UK thereby seem to be working relatively well in that about 70% of the scrap arisings is being recovered and recycled (although not domestically). However, the
flow diagram suggests there is still room for improving recovery and recycling practices of iron and steel in the UK.

### 3.4.4 Discussion

The analysis carried out in this work shows that for 2001, the estimated amount of released prompt and end-of-life scrap significantly exceeds the documented amount of scrap that is consumed within the country or is exported. This indicates either a loss of end-of-life iron and steel scrap of around 30% to landfill or that there is an undocumented accumulation of iron and steel within the economy. Sensitivity analysis of the MFA model has shown that the end-of-life scrap arisings are affected by what life-spans are used in the model. Still, even quite dramatic changes to the life-spans produces estimates for end-of-life scrap arisings that are in the same order of magnitude as the estimates based on the original information on life-spans. This is due to the fact that the yearly iron and steel input to use in the UK has been relatively stable over the past decades.

Possible scenarios of recycling for each sector have been modelled, using literature recycling rates when available. Recovery in the major sectors construction and vehicles is reported as working well with fairly high recycling rates of around 85% (Ley et al. 2002; ACORD 2000) and the model does not contradict this. The scenarios suggest that a significant part of the potential scrap loss originates from products like domestic appliances, hand tools, metal furniture and other products that are included in the goods categories metal goods, electrical and mechanical engineering. This result highlights the need for further material flow analyses of these specific sectors. Furthermore, current legislation that concerns metals is mostly focused on increasing recovery from packaging, vehicles and electronic waste (see section 1.2.2). Our results indicate that the focus is appropriate but that general metal goods, such as furniture, non-electric tools, kitchen articles etc, needs further drivers for recovery.

The modelling suggests that the recovery of iron and steel in the UK at end-of-life is relatively high and the sector is on the right road to sustainability. The central theme of industrial ecology but also one of the aims of sustainable development is to reach a ‘closed loop’ for material cycles. This currently appears unlikely for the UK iron and steel cycle due to the inability of the country
3.4 Material flow analysis of iron and steel

to consume its own end-of-life scrap arisings, resulting in high scrap exports. Even though all of these scrap exports are likely to be recycled overseas, it could still be considered a loss not to use this valuable resource domestically.
3.5 Material flow analysis of aluminium

Figure 3.12: Modelling methodology for estimating aluminium prompt and end-of-life scrap arisings (note: 'trade' means across the UK border).

3.5 MATERIAL FLOW ANALYSIS OF ALUMINIUM

The system model used to calculate the flow of aluminium prompt and end-of-life scrap is shown in figure 3.12. This section is dedicated to describing, in more detail, how the aluminium scrap arisings have been modelled, the data availability, necessary assumptions and the results of the study.

3.5.1 Description of system flows and data collection

The main data source used in this study is information provided by the Aluminium federation (Alfed) which collects data directly from all UK aluminium producers. The European Aluminium Association (EAA) has also supplied data. Data on trade of finished goods have been collected from HM Customs and Excise. All the collected data used in the analysis are available on the enclosed CD-rom. The information on aluminium content of traded goods, prompt scrap rates and life-spans have been gathered from a number of sources. The system flows, data collection and necessary assumptions are described in more detail in the following subsections.
Aluminium industry products delivered to UK manufacturing sectors

Deliveries of aluminium to UK manufacturers and fabricators of goods originate from UK producers, UK stockholders and imports. About 70% of the UK aluminium product market is handled by stockholders, making it difficult to generate data on the amount of aluminium that enters each industry sector. The information available from the EAA gives data on deliveries to UK manufacturers and traders, dividing the deliveries into six different sectors. However, close inspection of the data shows that it describes small deliveries, too small even to support the export of aluminium in new goods. There are a number of reasons why these data are too low, primarily because some manufacturers of goods have their own foundries and this aluminium input will not show in the EAA data set. Another reason is that trade classification codes have changed over time, which have resulted in aluminium being categorised in the ‘wrong’ group so that this data set may be distorted.

Alfed also has statistics on the use of aluminium products by the downstream manufacturing sectors in a slightly different reporting format. The data are provided as dispatches of aluminium castings, extrusions and rolled products from UK producers, and import and export of these products. Alfed also has information on the proportion of each type of product that is delivered to each industry sector; this information is however only available for 2001.

The delivery of aluminium products to the downstream sectors has been inferred by adding up the dispatches and imports and subtracting the exports of the three categories; and then multiplying each product category by the proportion entering each industry sector. The proportion is given for each type of aluminium product: one split for extrusions, rolled products and castings respectively, see table 3.9. Data on dispatches of extrusions, rolled products and castings are available for 1978 to 2001, while the import and export data are available for the years 1981 to 2001. The proportions divide the deliveries into six categories: transport, construction, engineering, packaging, consumer durables and other. It is assumed the Alfed proportions are constant over the time period studied. In order to model construction scrap arisings, the data provided by the EAA have been used for the years 1958 to 1977. Also, for packaging, data from the Aluminium Packaging Recycling Organisation (Alupro 2003) have been used for the years 1999, 2000 and 2001 to provide a more accurate figure for this specific sector. The Alupro figures
Table 3.9: Breakdown of deliveries of castings, extrusions and rolled products to UK manufacturing industry.

<table>
<thead>
<tr>
<th>Goods category</th>
<th>Castings [%]</th>
<th>Extrusions [%]</th>
<th>Rolled [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td>75</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td>Building and construction</td>
<td>7</td>
<td>54</td>
<td>20</td>
</tr>
<tr>
<td>Engineering</td>
<td>14</td>
<td>14</td>
<td>12</td>
</tr>
<tr>
<td>Packaging</td>
<td>—</td>
<td>—</td>
<td>41</td>
</tr>
<tr>
<td>Consumer durables</td>
<td>—</td>
<td>—</td>
<td>4</td>
</tr>
<tr>
<td>Other</td>
<td>4</td>
<td>19</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 3.10: Market shares for aluminium in 2001 and prompt scrap rates.

<table>
<thead>
<tr>
<th>Goods category</th>
<th>Market share [%]</th>
<th>Prompt scrap rate [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td>21</td>
<td>20</td>
</tr>
<tr>
<td>Building and construction</td>
<td>30</td>
<td>5</td>
</tr>
<tr>
<td>Engineering</td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>Packaging</td>
<td>21</td>
<td>10</td>
</tr>
<tr>
<td>Consumer durables</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>Other</td>
<td>6</td>
<td>5</td>
</tr>
</tbody>
</table>

are broadly consistent with estimates for the amount of aluminium entering packaging generated using the Alfed data. Table 3.10 shows the resulting market shares for deliveries of aluminium to UK manufacturing in 2001.

Depending on the manufacturing sector, a certain amount of prompt scrap is generated from cutting, drawing, extruding or other shaping of the metal to produce final goods. In the analysis, the inflow of aluminium products to each sector have been multiplied with specific rates (see
3.5 Material flow analysis of aluminium

Table 3.11: Average aluminium content in traded goods.

<table>
<thead>
<tr>
<th>Goods category</th>
<th>Aluminium content [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td>10</td>
</tr>
<tr>
<td>Building and construction</td>
<td>90</td>
</tr>
<tr>
<td>Engineering</td>
<td>5</td>
</tr>
<tr>
<td>Packaging</td>
<td>100</td>
</tr>
<tr>
<td>Consumer durables</td>
<td>20</td>
</tr>
<tr>
<td>Other</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 3.10), to generate the flow of prompt scrap from the fabrication and manufacturing stage. A prompt scrap rate of 5% has been used for all sectors apart from transport and packaging for which prompt scrap rates of 20% and 10% have been used respectively. All information on prompt scrap rates has been gathered from Alfed. These rates have been assumed to be constant over the time period analysed.

Trade in final goods

To derive the import and export of aluminium contained in traded final goods we selected all the goods that contain aluminium, compiled them into the six sub-categories of industry sectors and multiplied their total mass by the estimated average aluminium content. Data for trade in final goods have been collected from HM Customs and Excise for the years: 1968, 1973, 1978, 1983, 1988, 1993, 1998 and 2000 (Customs & Excise 2000) and then linearly interpolated to yield yearly values for the six industry sectors. Details of the categories and their corresponding SITC (Standard Industry Trade Classification) are given in appendix A. In order to estimate how much aluminium the traded goods contain, a constant average aluminium content for each category has been assumed using information provided by Alfed. Table 3.11 gives the aluminium content figures used in the analysis. The resulting flow of aluminium in imported and exported goods can be seen in figure 3.13.
3.5 Material flow analysis of aluminium

Figure 3.13: Aluminium in imported and exported goods between 1968 and 2001.

Aluminium in goods going to use in the UK

The stock of aluminium contained in new goods is fed by the outputs from the UK manufacturing sectors, which is calculated from their aluminium consumption and prompt scrap rates, and by imports of goods containing aluminium. The flows that leave this stock are exports and new goods that enter the use phase in the UK. The stock of new goods in the UK is assumed to be constant, which allows us to calculate the aluminium flows into the use phase; this flow is shown in figure 3.14 for 1978-2001. Transport, construction and packaging have consistently been the largest consumers of aluminium in the past 23 years. As opposed to iron and steel, the input of aluminium has increased dramatically over this time period, as aluminium is continuously breaking into new markets.

Life-spans of goods

As in the iron and steel analysis, three life-span distributions for each goods category have been used to yield the release of end-of-life scrap: (1) no distribution, i.e. a fixed number of years, (2) a Weibull distribution and (3) a lognormal distribution. However, due to lack of scientific information on the actual distributions of the life-spans, information on the average life-span figures for each goods category has been used. Consequently, the Weibull and lognormal distribution give a general distribution of the average life-span figure that have been collected for
3.5 Material flow analysis of aluminium

![Material flow analysis of aluminium](image)

Figure 3.14: Aluminium in finished goods going into use in the UK between 1978 and 2001.

Each goods sector. In the case where minimum and maximum life-span values for a goods sector have been available, a corresponding shape of the curve has been chosen to accommodate this. Section 3.4.1 gives more information on the life-span modelling. Table 3.12 gives the data on life-spans that have been collected and used in the analysis. Table 3.13 gives the parameters used to generate the Weibull and lognormal distributions for each goods category. In the same table, the mean, $\bar{t}$, and standard deviation, $\sigma$, of each distribution are also given. The mean values of the Weibull and lognormal distribution of each goods sector are the same; corresponding to the collected information on average life-span of goods in the sector.

Recycling of prompt and end-of-life scrap

The world bureau of Metal Statistics (WBMS) has data on scrap consumption in secondary smelters in the UK provided by Alfed in the 1970s. However, this information was regarded as confidential after 1982 and has not been available in the statistics since. However, Alfed has compiled a detailed study of scrap consumption in secondary smelters and refineries for the year 2001 only and this data set has been used in the analysis.

Customs & Excise gathers data on aluminium scrap imports and exports, which are available from the WBMS.
Table 3.12: Life-span data used in the modelling of aluminium end-of-life scrap arisings.

<table>
<thead>
<tr>
<th>Goods category</th>
<th>Average life-span [years]</th>
<th>Min and max life-span [years]</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Packaging</td>
<td>1</td>
<td>-</td>
<td>Alfed (2003)</td>
</tr>
<tr>
<td>Consumer durables</td>
<td>7</td>
<td>5-8</td>
<td>Alfed (2003)</td>
</tr>
<tr>
<td>Other</td>
<td>10</td>
<td>0-10</td>
<td>Alfed (2003)</td>
</tr>
</tbody>
</table>
3.5 Material flow analysis of aluminium

Table 3.13: Parameters used to generate the Weibull and lognormal distributions and the corresponding mean, \( \bar{t} \), and standard deviation, \( \sigma \), of each distribution; these distributions are used to model aluminium scrap arisings.

<table>
<thead>
<tr>
<th>Goods category</th>
<th>Weibull</th>
<th>Lognormal</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \eta )</td>
<td>( \beta )</td>
</tr>
<tr>
<td>Transport</td>
<td>14.20</td>
<td>5</td>
</tr>
<tr>
<td>Building and construction</td>
<td>38.10</td>
<td>5</td>
</tr>
<tr>
<td>Engineering</td>
<td>18.50</td>
<td>5</td>
</tr>
<tr>
<td>Packaging</td>
<td>1.10</td>
<td>5</td>
</tr>
<tr>
<td>Consumer durables</td>
<td>7.60</td>
<td>5</td>
</tr>
<tr>
<td>Other</td>
<td>10.90</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 3.14: Inferred recycling rate for aluminium in 2001 using the three life-span distributions.

<table>
<thead>
<tr>
<th>Life-span distribution</th>
<th>No distribution</th>
<th>Weibull</th>
<th>Log-normal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated scrap arisings [tonnes]</td>
<td>852</td>
<td>652</td>
<td>711</td>
</tr>
<tr>
<td>Actual recycled amount [tonnes]</td>
<td>546</td>
<td>198</td>
<td>546</td>
</tr>
<tr>
<td>Inferred recycling rate [%]</td>
<td>64</td>
<td>77</td>
<td>77</td>
</tr>
</tbody>
</table>

3.5.2 Results

The delay of goods in the use phase has been modelled using three different life-span distributions: (1) no distribution (i.e. a fixed number of years), (2) a Weibull distribution and (3) a lognormal distribution. The resulting arisings in 2001 using each distribution are given in Table 3.14. The table also gives the actual recovery in 2001 and the inferred recycling rate using equation 3.5.
3.5 Material flow analysis of aluminium

There is a difference of about 140 thousand tonnes between the modelled arisings of EOL scrap using no distribution and when using a Weibull or lognormal distribution. Looking at the total inflow of aluminium in goods to use in the UK in figure 3.14, there are quite significant fluctuations and a clear increase over the past 20 years, mainly in buildings, transport and packaging. This demonstrates the importance of modelling the delay of goods in use when the quantity of the material entering use varies significantly over time. Arguably, using a distribution of the life-span is more representative of reality. There is little difference between the Weibull and lognormal distributions as they have similar shapes of the curve and they share the same mean, $\bar{t}$.

Even allowing for the distribution of service lives, the results indicate there are about 160 thousand tonnes of aluminium that are not being recovered at present. This aluminium could either be accumulating in use or be lost to landfill. Using statistics from Defra and the Environment Agency on how much waste was sent to landfill in 2000/2001 and information on how much of this waste is nonferrous metal, it appears that industrial and commercial waste together with the municipal waste make up about 200 thousand tonnes of aluminium going to landfill. The calculation and references for this estimation are given in Appendix B.

Sensitivity analysis of the inferred recycling rate

The parameters that may affect the modelled amount of scrap arisings, and thereby the inferred recycling rate, are the aluminium content in traded goods, the life-spans and the prompt scrap rates. These parameters have been changed in order to explore the robustness of the inferred recycling rate.

Table 3.15 shows how changing the aluminium content of traded goods affects the inferred recycling rate. The aluminium content for packaging has not been changed as there are no data reported on trade in packaging; data on trade of packaging are included in trade of packaged goods, e.g. juices, food etc, but the type of packaging used is not specified in these goods categories. Even small decreases and increases to the aluminium content, see table 3.15, change the recycling rate from the original 77% to 83 and 60% respectively.

Table 3.16 shows the effect on inferred recycling rates of changes of prompt scrap rates and life-span data of goods. Quite dramatic increases and decreases in the prompt scrap rates changes
3.5 Material flow analysis of aluminium

Table 3.15: Effect of changing the aluminium content in traded goods on the inferred recycling rate (using lognormal distribution).

<table>
<thead>
<tr>
<th></th>
<th>Original Al content [%]</th>
<th>Decreasing Al content to [%]</th>
<th>Increasing Al content to [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td>10</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>Construction</td>
<td>90</td>
<td>70</td>
<td>100</td>
</tr>
<tr>
<td>Engineering</td>
<td>5</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Packaging</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Consumer durables</td>
<td>20</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>Other</td>
<td>10</td>
<td>5</td>
<td>50</td>
</tr>
<tr>
<td>Inferred recycling rate</td>
<td>77</td>
<td>83</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 3.16: Effect of changing life-spans and prompt scrap rates on the inferred recycling rate (using a lognormal distribution).

<table>
<thead>
<tr>
<th>Change of parameter</th>
<th>Inferred recycling rate [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase all prompt scrap rates to 40%</td>
<td>62</td>
</tr>
<tr>
<td>Decrease all prompt scrap rates to 2%</td>
<td>75</td>
</tr>
<tr>
<td>Double life-spans of packaging and consumer durables and and increase remaining to 20 years (construction unchanged)</td>
<td>82</td>
</tr>
<tr>
<td>Half all life-spans</td>
<td>64</td>
</tr>
</tbody>
</table>
the recycling rates, but to a limited extent. Life-span data have been increased quite significantly (as much as possible considering the limitations of the time-series available), resulting in an increase of the recycling rate. This is due to the growing trend of aluminium entering use over the years (see figure 3.14); the longer the life-span, the further back in time did the aluminium enter use, resulting in less aluminium being released as scrap in 2001 so that the inferred recycling rate is higher. Similarly, decreasing the assumed life-spans leads to a higher inferred scrap release in 2001 and thereby a lower recycling rate.

Overall, the model is relatively sensitive to changes to the parameters outlined above. However, even quite dramatic change to the parameters still produce a recycling rate in the order of 60 to 83%, which is not greatly different from the initial recycling rate of 77% using the original parameters. In conclusion, the inferred recycling rate has to be treated with caution, but it still indicates that a large amount of aluminium is currently not being recovered and that there is room for improving the recovery practices of end-of-life aluminium scrap.

**Recycling scenarios for each sector**

Recycling rates have also been explored further by distinguishing between the different use sectors. The arisings of prompt and end-of-life scrap in the UK are estimated using the model outlined in figure 3.12. By applying recycling rates to each of the modelled outflows of end-of-life scrap arisings and comparing the sum of the resulting flows to the actual recycling of scrap in the UK, the results can be validated. However, recycling rates for each goods sector are not readily available; furthermore, if recycling rates are available it is not always clear how they have been derived. Alupro (2003) reports the overall recycling rate of aluminium packaging in the UK to be 34% and has statistics that support this. For all the other sectors Alfed (2003) has provided us with estimated recycling rates. Possible recycling scenarios using this information have been created, shown in table 3.17. In scenario 1 the recycling rates provided by Alfed and Alupro are multiplied with the modelled arisings (modelled with the lognormal distribution); the resulting amount of recycled scrap is a little less than the reported amount of recycled scrap: 519 thousand compared to 546 thousand tonnes. This indicates that either the modelled arisings are a little too high or that the estimated recycling rates are slightly too low. Still, the recycled amounts of scrap
3.5 Material flow analysis of aluminium

Table 3.17: Two scenarios of different recycling rates for the different goods categories in 2001.

<table>
<thead>
<tr>
<th>Goods category</th>
<th>2001 scrap arisings [tonnes]</th>
<th>Literature recycling rates scenario 1 [%]</th>
<th>Recycling rates scenario 2 [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td>234 490</td>
<td>95</td>
<td>97</td>
</tr>
<tr>
<td>Construction</td>
<td>35 620</td>
<td>98</td>
<td>98</td>
</tr>
<tr>
<td>Engineering</td>
<td>95 370</td>
<td>75</td>
<td>90</td>
</tr>
<tr>
<td>Packaging</td>
<td>152 270</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td>Consumer durables</td>
<td>89 040</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>Other</td>
<td>20 810</td>
<td>50</td>
<td>60</td>
</tr>
<tr>
<td>Prompt scrap</td>
<td>80 778</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Inferred amount of recycled scrap [tonnes]</td>
<td></td>
<td>518 756</td>
<td>546 656</td>
</tr>
<tr>
<td>Actual 2001 scrap recycling</td>
<td></td>
<td>546 198</td>
<td>546 198</td>
</tr>
</tbody>
</table>

are in the same range which indicates that the model produces reasonable results. In the second scenario, the recycling rates are increased slightly so that the modelled amount of recycled scrap is equal to the reported amount of recycled scrap: 546 thousand tonnes.

In both scenarios, it is evident that the largest losses of aluminium originate from end-of-life engineering goods, packaging and consumer durables. The industry is well aware of the loss of aluminium from used beverage cans (UBCs), which is why it launched a national aluminium can recycling scheme in 1989. The recycling rate has since risen from only 2% in 1989 to 42% in 2001 (Alupro 2003).
3.5 Material flow analysis of aluminium

3.5.3 Overall overview of UK aluminium flows in 2001

To put the scrap arisings into context, figure 3.15 shows an overview of all the flows of aluminium in the UK for the year 2001. As described earlier, the work in this chapter has been fed into a larger study in which all aluminium flows through the UK were mapped out (Dahlstrom et al. (2004)). However, it is clear from figure 3.15 that the flows within the aluminium system do not balance; this is particularly evident in the flows of refined and remelted aluminium, where the discrepancies are too large to be explained by stock change. No such problem arose in the case of iron and steel. In part at least, the discrepancies must result from the fact that the data for aluminium do not come from a single source. Fortunately, this has no effect on the conclusions in this thesis, as data used to determine the aluminium recycling rate (deliveries of semis and castings to UK manufacturing and scrap consumption in UK production) have been taken from one single source (Alfed). The following text summarises the flows of aluminium through the UK in 2001, subject to these unresolved inconsistencies.

All alumina used in primary aluminium production in 2001 was imported, as there is no longer any alumina production in the UK since 2000. There was however still a small quantity of bauxite imported. In 2001, about 340 000 tonnes of primary aluminium and 830 000 tonnes of remelted aluminium was produced in the UK. Further down the chain we can see that one third of the aluminium semis and castings produced in the UK is exported and that imports of aluminium semis and castings products are about double that of exports. The reason why the inputs and outputs of UK aluminium production in the flowchart (from primary smelting and refining/remelting to deliveries of semis and castings) do not balance, is partly due to that the data on all the flows are not available from one single source, but have been taken from different sources, and partly as there might be some stock changes at the production plants. This, however, does not affect the work in this thesis, as data used to determine the aluminium recycling rate (deliveries of semis and castings to UK manufacturing and scrap consumption in UK production) have been taken from one single source (Alfed).

About 9 thousand tonnes of aluminium semis and castings were delivered to UK goods manufacturers and fabricators in 2001. Most of this aluminium went into construction followed by the transport and packaging sectors. These three sectors currently consume more than 70% of
3.5 Material flow analysis of aluminium

the total deliveries of aluminium semis and castings in the UK. Just less than 10% of the total aluminium deliveries to UK manufacturers was turned into prompt scrap and recycled back into the system. There is a substantial amount of aluminium in goods imported into and exported from the UK. In 2001 more than 800 000 tonnes of aluminium in goods were exported from the UK and almost 1 million tonnes of aluminium in goods were imported. This massive trade in goods containing aluminium is the result of an increasing trend over the last ten years, as can be seen in figure 3.13.

About 630 thousand tonnes of end-of-life scrap were released in 2001. Together with available prompt scrap arisings this makes up just over 700 thousand tonnes. 200 thousand tonnes of scrap were exported and recycled abroad and 340 thousand tonnes were recovered and recycled domestically. An estimated further 200 thousand tonnes ended up in landfill. The recovery of aluminium scrap arisings in the UK thereby seems to be working relatively well in that more than 75% of the scrap arisings is being recovered and recycled. However, there is still room for improving recovery and recycling practices of aluminium in the UK.

3.5.4 Discussion

The analysis shows that for 2001, the estimated amount of released prompt and end-of-life scrap exceeds the documented amount of scrap that is consumed within the country or is exported. This indicates either a loss of end-of-life scrap of 160 thousand tonnes to landfill or that there is an undocumented accumulation of aluminium within the economy. This result corresponds relatively well with information on how much aluminium is contained in waste sent to landfill (ca 200 000 tonnes) so that it appears to be a real "leakage" from the economy.

Sensitivity analysis of the MFA model has shown that the predicted end-of-life scrap arisings are affected by the aluminium content of traded goods and life-spans used in the model. Still, even quite dramatic changes to the life-spans produce results that are relatively close to the results produced using the original data. The reason why life-span data affect the end-of-life scrap arisings is the fact that the input of aluminium to use in the UK has increased significantly over the past two decades. This means longer life-spans will produce less end-of-life scrap than shorter ones, as the goods entered use further back in time. Another implication of the dramatic
3.5 Material flow analysis of aluminium

Figure 3.15: System overview of UK aluminium flows in 2001 (Dahlstrom et al. 2004).
increase of aluminium used in the UK is that the modelled end-of-life scrap arisings will depend on whether a distribution of life-spans has been used in the model. Using a distribution of the life-span will represent reality closer, as it is unlikely that all aluminium in a particular type of goods that entered use in a particular year, will become end-of-life scrap a fixed number of years later; rather, the aluminium will become end-of-life scrap over a distribution of years. This very much highlights the need for more detailed information on the distribution of life-spans for different types of goods containing aluminium.

The analysis shows that most aluminium entering use in the UK is contained in goods from the sectors transport, construction and packaging and this pattern is evident for the time-series studied (i.e. 1978-2001). Possible scenarios of recycling for each sector have been modelled, using information on recycling rates from the industry. The scenarios suggest that a significant part of the potential scrap loss originates from products in the categories packaging and consumer durables. This result indicates the need for further material flow analyses of these specific sectors. The industry is well aware of the limited recovery of aluminium packaging and launched a national campaign to boost recovery of used aluminium beverage cans in 1989. The recycling has since increased from 2% to 42%, but could be improved further. As packaging is one of the major consumers of aluminium, it is an important sector to focus on.

End-of-life scrap arisings of aluminium will increase in the coming years, due to the growth of aluminium entering use. Just by looking at the aluminium entering use in the goods categories ‘transport’, ‘construction’ and ‘other’ (i.e. goods with life-spans of 10 years or longer), we see there are drastic increases in the last 20 years. This means there will be at least 700 000 tonnes of end-of-life scrap arisings by 2010. This is an increase of almost 100 000 tonnes compared to the arisings in 2001. A large part of the recovered aluminium scrap is currently recycled domestically, but large volumes of scrap are exported. The industry reports there is enough capacity to deal with increasing scrap arisings in the UK in the future as most of the secondary capacity currently still is not fully utilised. The massive export of scrap is simply due to trade being more profitable.
3.6 CONCLUSIONS

A new time series MFA methodology has been developed and applied in this analysis to track the flows of iron, steel and aluminium through use in the UK. In sectors like iron, steel and aluminium, where the goods life-spans can be significant and the life-spans differ between applications, it is vital to include a temporal dimension in the MFA as different products available as scrap entered use at quite different past times. In this analysis, residence time distribution theory from chemical engineering science has successfully been applied to simulate the delay of goods in use. It is demonstrated that this methodology proves useful when dealing with materials that are contained in products with significant life-spans. It is well recognised that successful application of the methodology depends largely on data availability. For both metals, difficulties in acquiring the necessary data were experienced, but guidance from experts in the industries and their respective trade organisations helped in clearing most of the data gaps. A level of closure was achieved in the analyses, in that metal emerging from use could be largely balanced with metal being recycled (domestically or abroad) and metal sent to landfill.

The analysis has shown that using a distribution of the life-span when modelling the delay of goods in the use phase is more important when the input of goods into use shows a significant increase or decrease over time. In the case of iron and steel in the UK, the inputs into use of iron and steel containing products have been fairly stable over the past 25 years, so the modelled overall recycling rate was not significantly affected by the modelling approach used (i.e. using a distribution of service lives or not). However, in the case of aluminium, there has been a dramatic increase of aluminium input to society over the past two decades, so here it proved more important to model the end-of-life scrap arisings using a realistic distribution of service lives. This highlights the need for more detailed information on distribution of life-spans of different types of goods, in particular when analysing material in goods with significant life-spans and that have large fluctuations in demand over time.

Around 15 million tonnes of iron and steel products were delivered to UK goods manufacturers and fabricators in 2001 from both domestic and foreign producers. Most of this iron and steel went into building and construction (26%), followed by other industries (20%), mechanical engineering (17%) and vehicles (17%) in 2001. These four sectors currently consume 80%
3.6 Conclusions

of the total deliveries of iron and steel products in the UK and have done so over the last 30 years. Similarly, the majority of iron and steel contained in goods going to use in the UK are goods from these sectors. The analysis shows that for 2001, the estimated release of end-of-life scrap and prompt scrap significantly exceeds the documented amount of scrap that is consumed within the country or is exported. This indicates either a loss of end-of-life scrap of around 30% (corresponds to about three and a half million tonnes) or that there is an undocumented accumulation of iron and steel within the economy. Possible scenarios of recycling for each sector have been modelled, using literature recycling rates when available. Recovery in the major sectors, construction and vehicles, is reported as working well with fairly high recycling rates of around 85% (Ley et al., 2002; ACORD, 2001) and our model does not contradict this. The scenarios suggest that a significant part of the potential scrap loss originates from products like domestic appliances, hand tools, metal furniture and other products that are included in goods categorised as metal goods, electrical and mechanical engineering. This result highlights the need for further material flow analyses of these specific sectors.

For aluminium, the analysis shows that most aluminium entering use is contained in goods from the sectors transport, construction and packaging and this pattern is evident for the time-series studied (i.e. 1978 to 2001). The analysis shows that for 2001, the estimated amount of released prompt and end-of-life scrap exceeds the documented amount of scrap that is consumed within the country or is exported. This indicates either a loss of end-of-life scrap of around 160 thousand tonnes or that there is an undocumented accumulation of aluminium within the economy. This result corresponds reasonably well with information on how much aluminium is contained in waste sent to landfill (ca 200 000 tonnes). Recycling scenarios of each sector suggest a significant part of the potential scrap loss originates from products in the categories packaging and consumer durables.

It is recognised that several parameters in the model can affect the inferred recycling rates; for example metal content in traded goods and life-spans might change. Sensitivity analysis of these parameters shows that indeed the inferred recycling rates changes, but quite dramatic changes to the parameters still produce recycling rates that are not far from the original estimates. However, for future studies it is recommended to obtain further information on life-spans and material
3.6 Conclusions

composition in goods and how these have changed over time, in order to acquire even more reliable results.

There is a "leakage" of both iron/steel and aluminium occurring currently in the UK and it would be interesting to find out more on how these losses come about. How much iron is lost in corrosion, how many dumped cars are there in society etc? Would it be possible to "mine" landfill sites for old discarded metal goods? This also represents a further need for research.

Finally, use of the kind of model developed in this chapter could prove a vital instrument in formulating comprehensive recycling policies. By identifying potential leakage problems and highlighting product groups that contribute to the largest material losses, this gives valuable direction on where the focus should be put to increase the recovery. Furthermore, the model can also be used to predict future scrap arisings, in particular for product groups with long life-spans, which can facilitate metal production capacity planning and policy developments.
Model for exploring potential build-up of contamination in metal scrap cycle

As described in chapter 1, it is important to avoid build-up of alloying and contaminating elements in the metal cycle if high recycling rates of steel and aluminium (or any other metal) are to be achieved and maintained. In this chapter, a model is developed that can investigate how the composition of UK produced metals will vary with the overall recycling rate of the metals, and also the dependence on the levels of scrap exports. The use of the model is demonstrated by a case study exploring potential contamination by tin in the iron and steel cycle. The model is based on the methodology for analysing the flow of steel and aluminium in the UK, i.e. the material flow analysis (MFA) model described in chapter 3.

4.1 INTRODUCTION AND SCOPE

One of the main benefits of metals is that pure metal can be recycled an infinite number of times without losing any of its properties. In chapter 2 we discussed the significant savings in environmental interventions that can be made when producing steel and aluminium from scrap compared to primary resources. Not only are the environmental savings large when metals are recycled; more importantly, multiple recycling is feasible. Compared to paper recycling for ex-
ample, which degrades the cellulose mainly by shortening or embrittlement the fibres, metal is not transformed in any way when it is recycled: there is no difference between pure metal produced from primary resources compared to remelted pure metal scrap. However, the metals that are used in society are a sophisticated variety of different metals melted together into alloys. Therefore, the properties and quality of remelted scrap will ultimately depend on the blend of the scrap that is remelted and the chemical composition of this scrap. Another potential source of contamination is mixing with components containing other materials, during the manufacture or use of goods containing different materials. An example of the former is copper cables used in cars; when the cars are scrapped these may contaminate the scrap if they are not taken out before shredding. Examples of contamination during use are paint in metal containers and radioactivity in metal hospital equipment. So in fact, even though it is possible to recycle metal infinitely if it is pure, contamination introduces constraints on recycling.

This study focuses on developing a general model that can be applied to investigate the concentration of a particular element in the metal cycle. Different scenarios will be explored looking at a single element in order to demonstrate the model. The modelling methodology can, however, accommodate several elements at the same time.

The aim of the study is to explore a possible way of determining the change in composition of the metal produced, depending on the recycling rate of each category of prompt and end-of-life scrap and also the amount of scrap that is traded across the UK border. Since a reliable and complete data set was obtained for the iron and steel MFA, the study will analyse the composition of the iron and steel flows in a case study. The composition is examined while the recycling rate and scrap export change over time. Tin has been selected as an example of a potentially problematic element in the iron and steel cycle.

4.2 Modelling methodology

The methodology for exploring the composition of the metal cycle is based on the material flow model described in chapter 3. Figure 4.1 shows the model used in the analysis. The difference between this model and the MFA model is that the contamination model includes one more production step: the production of metal in the UK, along with trade of metal industry products.
4.2 Modelling methodology

Also, as each metal product will have separate specifications for concentrations of alloying elements and acceptable levels of contamination, UK metal production is split into the production of \( i = 1, 2, \ldots, p \) metal products (rods, sheets, castings etc.), rather than aggregating all into one process. This disaggregation into the specific metal products is maintained throughout the model, whereas in the MFA model there is no distinction of type of metal product. The final, and most important difference is that this model incorporates information about the amount of an alloying or contaminating element contained in the metal. The model does not take into account loss of material through incomplete scrap separation, downcycling to lower grade and incomplete metallurgical recovery in the remelting of scrap; these are all very important aspects in recycling of metals. In this simplified model, however, these aspects have been omitted, but when more data are available in future, they are aspects that should be included.

The aim of the model is to calculate the concentration of element A in each of the metal products on a year-on-year basis. The concentration is calculated after the metal production stage, as highlighted in figure 4.1. The flowchart and equations for calculating the concentration of a contaminating element in the produced metal is summarised in figure 4.2. Explanations for the abbreviations used in this flowchart are given in figure 4.3. The modelling is performed in Matlab. A description of the modelling procedure follows here. More specific details, such as which data were used in the analysis will be explained in the next section describing the case study.

In this time-dependent model, there is a matrix for the bulk metal flow and a parallel matrix for each element that is to be analysed. The metal matrix, \( M \), represents the total mass of all metal quantities, including all alloys and other elements (one of which is the element to be investigated). The \( A \) matrix represents the quantity of the element of concern for contamination. Each row in the matrix represents the flows in year \( j = 1, 2, \ldots, q \); i.e. all flows are given on a yearly basis, as tonnes per year (just as in the MFA model). As the flows move through the system, these matrices change names and sometimes dimensions; this is described in the following text. The \( A \) matrix always has the same name as the \( M \) matrix but with an 'A' first; see figure 4.2.

As in the MFA model in chapter 3, the ovals represent stocks of material and the rectangles
4.2 Modelling methodology

Figure 4.1: Material flow model used for analysing the composition of the metal flow.
4.2 Modelling methodology

Figure 4.2: Flowchart for calculating concentration of contamination in the metal products.
Figure 4.3: Explanation of abbreviations used in flowchart for calculating concentration of contamination in the metal cycle.
represent processes (see figure 4.1). All stocks in the model are assumed to be constant apart from the stock of goods in use. For a well-defined stock of material, the flows out of the stock can then be calculated if we know how much of the specified material flows into it and vice versa. The model starts with UK production of \( p \) metal products, which consumes both virgin input (e.g. iron ore) and prompt and end-of-life scrap (generation and consumption of home scrap is excluded from the system, for the reasons set out in developing the MFA). So here, the flows which make up the columns of the \( M \) and the \( A \) matrices are categorised into \( p \) different metal products, see matrix \( \text{Prod}_{ij} \): 

\[
\text{Prod}_{ij} = \begin{bmatrix}
\text{prod}_{i1} & \text{prod}_{i2} & \cdots & \text{prod}_{ip} \\
\text{prod}_{i2} & \text{prod}_{i3} & \cdots & \text{prod}_{ip} \\
\vdots & \vdots & \ddots & \vdots \\
\text{prod}_{ip} & \text{prod}_{i1} & \cdots & \text{prod}_{ip}
\end{bmatrix}
\]  

(4.1)

which represents the bulk metal flows. Accordingly, this matrix has dimensions corresponding to the number of metal products, \( p \), and number of years, \( q \), in the analysis. The production matrix \( \text{Prod}_{ij} \) is the input to the model, i.e. it is populated with data specified at the outset. Alloying elements and metal coating are also added to the metal production. Apart from the intentional addition of elements, some might also be added through the scrap charge which potentially contains contaminating and/or alloying elements. It is assumed that prompt and end-of-life scrap generated in one year is used in metal production the following year. This is based on the fact that scrap is collected by scrap dealers and retained until the market favours selling it, so that the scrap may be stored for a period of time before being remelted. In the example developed in this chapter, a delay in the scrap flows of one year has been chosen, but the methodology allows for any number of years or a distribution of years to be used. When using a delay of one year, the amount of element A in the metal product \( i \) in year \( j \), \( \text{AProd}_{ij} \), is as follows:

\[
\text{AProd}_{ij} = \text{APromptin}_{ij-1} + \text{AEOLin}_{ij-1} + \text{Aload}_{ij}
\]  

(4.2)

where \( \text{APromptin}_{ij-1} \) and \( \text{AEOLin}_{ij-1} \) are the amount of prompt and end-of-life scrap released, recovered and aggregated into \( p \) categories in the previous year with imports and exports.
4.2 Modelling methodology

of scrap taken into account (see equations 4.24 and 4.26). $A_{load}$ is the amount of element $A$ added to the production of metal product $i$ in year $j$. All these matrices have dimensions according to the number of metal products, $p$, and number of years analysed, $q$, in the analysis.

The metal products are then either exported or delivered to UK manufacture of goods together with imported metal products. Accordingly, the deliveries of metal industry products to UK goods manufacture and the amounts of $A$ in these products are:

$$DMIP_{i,j} = Prod_{i,j} - Exp_{i,j} + Imp_{i,j}$$

$$ADMIP_{i,j} = AProd_{i,j} - AExp_{i,j} + AImp_{i,j}$$

where $Exp_{i,j}$ and $Imp_{i,j}$ are exports and imports of metal products and $AExp_{i,j}$ and $AImp_{i,j}$ are the corresponding amounts of contamination contained in these traded products. The products are delivered to $n$ different sectors; see figure 4.1. So here, the matrices are extended to matrices with dimensions corresponding to the number of sectors, $n$, number of years, $q$, and number of metal products, $p$. In other words, at this stage the matrices represents the amount of metal product $i$ consumed in goods sector $k$ in year $j$:

The matrices $SC_{k,i,j}$ and $ASC_{k,i,j}$ are constructed according to:

$$SC_{k,i,j} = Split_{k,i} \cdot DMIP_{i,j}$$

$$ASC_{k,i,j} = Split_{k,i} \cdot ADMIP_{i,j}$$
4.2 Modelling methodology

where $SC_{k,j,t}$ is the consumption of each metal product $l$, in each goods sector $k$, in year $j$. $Split_{k,i}$ is the operator for allocating each metal product to the sectors with dimensions according to the number of sectors and number of metal products; i.e. the $Split_{k,i}$ matrix contains the fraction of each metal product that goes to each sector.

At the manufacturing stage, more potentially contaminating elements might be added, e.g. copper cables in vehicles, paint on packaging etc. This addition is defined as $Al_{oad2_{k,j,t}}$ and is a further matrix with dimensions according to number of sectors, years and metal products in the analysis. So the ultimate amount of element $A$ in the manufactured goods is calculated as:

$$ASC_{Out_{k,j,t}} = ASC_{k,j,t} + Al_{oad2_{k,j,t}}$$  \hspace{1cm} (4.8)

When the goods are produced, some metal will be turned into prompt scrap through cutting and shaping of the metal products. This prompt scrap is generated according to:

$$Prompt_{k,j,t} = Prate_{k,j} \cdot SC_{k,j,t}$$  \hspace{1cm} (4.9)

$$APrompt_{k,j,t} = Prate_{k,j} \cdot ASC_{Out_{k,j,t}}$$  \hspace{1cm} (4.10)

We assume that the fabrication and manufacturing sectors that consume the metal, together with other materials, process the materials in the same year they receive them and that the new goods are exported or delivered to UK use in this same year. In a model with a time discretisation of one year, these processes therefore appear to be instantaneous. The deliveries of new goods to use in the UK are as follows:

$$DNG_{k,j,t} = SC_{k,j,t} - Prompt_{k,j,t} - NExp_{k,j,t} + NImp_{k,j,t}$$  \hspace{1cm} (4.11)

$$ADNG_{k,j,t} = ASC_{Out_{k,j,t}} - APrompt_{k,j,t} - ANExp_{k,j,t} + ANImp_{k,j,t}$$  \hspace{1cm} (4.12)

where $NExp_{k,j,t}$ and $NImp_{k,j,t}$ are the exports and imports of metal contained in traded goods, and $ANExp_{k,j,t}$ and $ANImp_{k,j,t}$ represent the amounts of element $A$ contained in the metal of the traded goods. The goods are followed through the use phase until the metals emerge as end-of-life scrap at the end of the use phase.
4.2 Modelling methodology

The time delay in the use phase for each goods category is modelled in the same way as in chapter 3. In accordance with equation 3.21 in chapter 3, the end-of-life scrap arisings are given by:

\[ E_{OL_{k,j,i}} = \sum_{m=1}^{r} D_{NG_{k,j,i+1-m,i}} \cdot E_{k,m} \]  
\[ A_{EOL_{k,j,i}} = \sum_{m=1}^{r} A_{DNG_{k,j,i+1-m,i}} \cdot E_{k,m} \]

where \( E_{OL_{k,j,i}} \) and \( A_{EOL_{k,j,i}} \) are the amounts of end-of-life scrap arisings and amounts of element A in the arisings respectively. The matrices contain information about the composition of the scrap, i.e. what type of metal products it consists of and from which goods category it originates. The matrices \( D_{NG_{k,j,i}} \) and \( A_{DNG_{k,j,i}} \), are the amounts of metal and element A in the goods delivered to use, and \( E_{k,m} \) follows from the distribution of service lives of each of the goods categories \( k \) (see chapter 3). The parameter \( m = 1, 2, \ldots, r \) represents the number of past years taken into account when calculating the end-of-life scrap arisings. As an example, the last 50 years of input of metal into use might be taken into account. This would require the matrices \( D_{MIP_{k,j,i}} \) and \( A_{DMP_{k,j,i}} \) to contain historic input data (i.e. given data) reaching back 50 years. The residence time distribution of each category will then give the arisings from each sector in a particular year.

Some of the prompt and end-of-life scrap arisings are recovered according to the prompt scrap recycling rates, \( \text{Prompt}_{recrate_{k,j,i}} \), and recycling rates of each sector, \( EOL_{recrate_{k,j,i}} \):

\[ E_{OLr_{k,j,i}} = E_{OL_{recrate_{k,j,i}}} \cdot E_{OL_{k,j,i}} \]  
\[ A_{EOLr_{k,j,i}} = A_{EOL_{recrate_{k,j,i}}} \cdot A_{EOL_{k,j,i}} \]  
\[ \text{Promptr}_{k,j,i} = \text{Prompt}_{recrate_{k,j,i}} \cdot \text{Promptr}_{k,j,i} \]  
\[ A_{Promptr}_{k,j,i} = A_{Prompt}_{recrate_{k,j,i}} \cdot A_{Promptr}_{k,j,i} \]

The recovered scrap is aggregated and then either exported for recycling abroad or recycled domestically together with imported scrap. The matrix of the aggregated scrap is constructed according to:
4.2 Modelling methodology

\begin{align*}
\text{EOL}_\text{agg}_{i,j} &= \sum_{l=1}^{p} \sum_{i=1}^{n} \sum_{k=1}^{n} \text{Eagg}_{i,k,l} \cdot \text{EOL}_{k,j,l} \\
\text{AEOL}_\text{agg}_{i,j} &= \sum_{l=1}^{p} \sum_{i=1}^{n} \sum_{k=1}^{n} \text{Eagg}_{i,k,l} \cdot \text{AEOL}_{k,j,l} \\
\text{Prompt}_\text{agg}_{i,j} &= \sum_{l=1}^{p} \sum_{i=1}^{n} \sum_{k=1}^{n} \text{Pagg}_{i,k,l} \cdot \text{Prompt}_{k,j,l} \\
\text{APrompt}_\text{agg}_{i,j} &= \sum_{l=1}^{p} \sum_{i=1}^{n} \sum_{k=1}^{n} \text{Pagg}_{i,k,l} \cdot \text{APrompt}_{k,j,l}
\end{align*}

This aggregation means that the 3-dimensional \( \text{EOL}_{k,j,l} \), \( \text{AEOL}_{k,j,l} \), \( \text{Prompt}_{k,j,l} \) and \( \text{APrompt}_{k,j,l} \) matrices are reduced to matrices with dimensions according to the number of metal products and years. In other words, the aggregation groups the scrap into \( p \) number of categories. In this way different ways of aggregating the scrap can be modelled in the system, i.e. choosing variations of which type of scrap (e.g. old cast iron scrap, uncoated sheet scrap etc.) goes into production to which metal product. Here, we have chosen to aggregate the scrap into \( p \) different categories, but the methodology can accommodate any chosen number of categories to represent different scrap sorting scenarios. Some of the scrap is exported and some will be imported, according to:

\begin{align*}
\text{EOL}_\text{in}_{i,j} &= \text{EOL}_\text{agg}_{i,j} - \text{EOL}_\text{exp}_{i,j} + \text{EOL}_\text{imp}_{i,j} \\
\text{AEOL}_\text{in}_{i,j} &= \text{AEOL}_\text{agg}_{i,j} - \text{AEOL}_\text{exp}_{i,j} + \text{AEOL}_\text{imp}_{i,j} \\
\text{Prompt}_\text{in}_{i,j} &= \text{Prompt}_\text{agg}_{i,j} - \text{Prompt}_\text{exp}_{i,j} + \text{Prompt}_\text{imp}_{i,j} \\
\text{APrompt}_\text{in}_{i,j} &= \text{APrompt}_\text{agg}_{i,j} - \text{APrompt}_\text{exp}_{i,j} + \text{APrompt}_\text{imp}_{i,j}
\end{align*}

where \( \text{EOL}_\text{in}_{i,j} \), \( \text{Prompt}_\text{in}_{i,j} \), \( \text{AEOL}_\text{in}_{i,j} \) and \( \text{APrompt}_\text{in}_{i,j} \) are the amounts of end-of-life and prompt scrap used in UK metal production and the corresponding amounts of element A contained in this scrap. As described earlier, prompt and end-of-life scrap released in one year is used in UK metal production the following year (see equation 4.2). Finally, from the annual production of metal products and the amount of A contained in the metal products (from equation 4.2), we calculate the concentration of element A. The concentration is defined as:

\[ \text{Conc. of A in metal product } i [\%] = \frac{\text{AProd}_{i,j}}{\text{Prod}_{i,j}} \times 100. \]
This methodology is now applied to a case study of exploring potential build-up of tin in the iron and steel cycle in the UK.

### 4.3 Case study - tin

Tin is never added intentionally as an alloying agent in steel making, only as a protective and/or decorative coating, e.g. when producing tinplate for packaging. Even small amounts of tin are harmful to the ductility and sheet formability of steel. With a low melting point (232° C) and a high boiling point (2750° C), its presence in the steel will mean that liquid pools of tin form at the surface during hot working operations and this leads to a problem known as 'hot-shortness', where the surface breaks up during hot rolling/forming. Tin is also one of the tramp elements (with phosphorus and arsenic) known to make steels susceptible to temper embrittlement, especially when chromium, nickel or manganese are also present. For these reasons, efforts should be made to keep tin from entering the steel (Deele et al. 1981). However, tin does have metallurgical uses in cast iron: it is a pearlite stabiliser and therefore increases strength and hardness.

Tin is not often associated with the iron ore entering the blast furnace. A more serious problem is the carryover of tin in the scrap charge. Tinplate is the most common source. Some tin may also be contained in galvanizing spelters (commercial crude smelted zinc), where it is used to control spangle appearance. All such tin is retained in the melt throughout the steelmaking process, with the result that the build-up of residual tin levels was a matter of serious concern for a number of years. However, the heavier tin coatings once produced by hot dip tinning have virtually disappeared since the replacement of this process by electrolytic tinning. Nevertheless, steels for critical applications should still be made from selected scrap and other known low-tin raw materials.

#### 4.3.1 Scenario description

The scenarios considered here explore consequences for the concentration of tin in UK produced iron and steel products over the next twenty years: year 2000 to 2020. The scenarios portray possible future developments of recycling rates and trade of scrap. It is explored how the con-
centrations vary when recycling rates of prompt and end-of-life scrap increase, and scrap exports from the UK decrease. The implication of an alternative procedure for separating the scrap before remelting is also explored.

The annual metal production of each metal product is given as input data to the model, so this information is defined for each year (2000 to 2020) at the outset. Four scenarios are explored:

- **Scenario 1**
  
  This scenario explores the consequences for the tin concentration if the situation in the UK is essentially unchanged over the next 20 years, with the recycling rates of end-of-life and prompt scrap kept constant at their current level and the high levels of scrap exports allowed to continue. In scenario 1 therefore, the end-of-life scrap recycling rates for each goods category are maintained at their 2001 values over the whole time period (2000-2020); this means keeping an annual overall recycling rate of 72%. The prompt scrap recycling rates are also kept at their current level: 100%. Today, about 4 million tonnes of scrap are exported from the UK every year; in this scenario, scrap exports are therefore kept level at 4 million tonnes per year from 2000 to 2020. In terms of selecting which type of scrap goes to which metal production, no special consideration is made; all different types of scrap are mixed together before remelting. Currently in the UK, scrap is categorised according the 'UK scrap specifications' before remelting, so some consideration is taken when choosing which scrap goes into which metal product. However, the grading system does not specify accepted levels of alloying content in the scrap (only for tin and copper in 2 out of 29 categories); this is described further below.

- **Scenario 2**
  
  This scenario explores the change in concentration of tin if recycling rates of end-of-life scrap increase in the UK. With the pressure the UK is facing in terms of increasing its recycling, it is reasonable to expect that recycling rates of iron and steel will increase in the future. In the scenario, the end-of-life overall recycling rate increases from 72% in 2000 to 90% in 2010 and stays at this level until 2020 (i.e. each individual sector is assumed to increase the recycling rate from the known level in 2001 to 90% in 2010). Scrap export is kept constant at 4 million tonnes per year from 2000 to 2020, as in scenario 1. Here too,
all different types of scrap are mixed together before remelting.

- **Scenario 3**
  Currently, there are large quantities of scrap exported from the UK each year. UK production plants, on the other hand, still produce about the same amount of metal products each year, with small fluctuations. To make up for the 'lost' resource (scrap that is exported), a significant amount of virgin iron ore is required in UK production. Instead of exporting large amounts of scrap, the scrap could be used in UK production and thereby reduce the amount of virgin input needed. It might be argued that this will only increase the environmental impacts of iron and steel production globally, as the replaced iron ore will be used in integrated steel plants elsewhere in the world where pollution prevention is not so controlled as it is in the UK. Still, in future, all parties in the worldwide iron and steel industry must eventually comply with environmental regulations so it will be irrelevant where the virgin metal is produced. If the UK can handle all of domestically generated scrap this would also reduce the transport, and associated environmental impacts, of exporting the scrap to distant places like China and Russia.

In this scenario therefore, the end-of-life recycling rates increase as in scenario 2, and at the same time scrap exports are reduced. Scrap exports decrease from 4 million tonnes per year in 2000 to zero in 2010 where they remain until 2020. All different types of scrap are mixed together before remelting, as in scenarios 1 and 2.

- **Scenario 4**
  With increased recycling rates and decreased scrap exports, the system has become quite 'closed', and one would expect there to be increases in the concentrations of tin in the metal products. 'Can these be avoided by choosing more carefully which type of scrap goes into production of which metal product?', is then the natural question. In this fourth scenario, the end-of-life recycling rates increase and the scrap export decreases as in scenario 3, but the scrap is aggregated differently. Here, the scrap is separated into its original metal product components before remelting, i.e. cast iron scrap goes to production of cast iron, uncoated sheet scrap goes to production of uncoated sheet and so on.
There are some common features in the scenarios. In all scenarios scrap imports are assumed to be negligible; historically, imports of scrap have been in the order of 100,000 tonnes per year (Dahlstrom et al. 2004), which is very low compared to the 4 million tonnes that are exported. We therefore assume that this trend of low imports will continue for the years concerned by the analysis and disregard scrap imports.

The scrap aggregation is the same in the first three scenarios but different in the fourth. In the UK currently, the scrap grading system used is called “UK Specifications” and has been agreed by the British Foundry Association, the British Iron and Steel Producers Association and the British Metals Federation. The specifications came into force on January 1, 1995. There are altogether 29 groups roughly divided into new scrap (prompt scrap) and old scrap (end-of-life scrap); see table 4.1. The grading system is relatively broad and does not specify the alloying and contamination level in each type of scrap. It has therefore not been possible to use this grading system in the model. In the first three scenarios, all different types of scrap are mixed together before being remelted in the production of new metal products. This means equal proportions of all different types of scrap (old cast iron, old sheet etc) have gone into the production of all metal products. In the fourth scenario however, the scrap is disaggregated to its original old metal products and each old metal product scrap goes into production of the corresponding metal product.

Also, in all scenarios, tin is added intentionally only to two of the metal products: cast iron and tin coated sheet. The use of these metals (i.e. what type of goods they are contained in), are shown in figure 4.4.

More detailed information about the scenarios is given in the next section.

4.3.2 System description, data sources and assumptions

Production of metal products

Table 4.2 lists the 12 iron and steel metal products produced in the UK and their production volumes used in the analysis. This production flow is the input into the model. In this case study we disregard trade of metal products. Historically there have been large quantities of both import and export of metal products (see Dahlstrom et al. 2004), but on average the imports balance out
Table 4.1: UK scrap grading system - “UK Specifications”.

<table>
<thead>
<tr>
<th>No</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>OA</td>
<td>Plate and structural (old structural)</td>
</tr>
<tr>
<td>1</td>
<td>Old steel</td>
</tr>
<tr>
<td>2</td>
<td>Old steel</td>
</tr>
<tr>
<td>3A</td>
<td>Fragmentised</td>
</tr>
<tr>
<td></td>
<td>(old, &lt; 150 mm, clean, no tin cans, &lt; 0.03 % Sn, &lt; 0.20 % Cu, 1 tonnes/m³)</td>
</tr>
<tr>
<td>3B</td>
<td>Fragmentised</td>
</tr>
<tr>
<td></td>
<td>(old, &lt; 200 mm, clean, no tin cans, &lt; 0.03 % Sn, &lt; 0.25 % Cu, 0.8 tonnes/m³)</td>
</tr>
<tr>
<td>3C</td>
<td>Fragmentised</td>
</tr>
<tr>
<td></td>
<td>(old, clean, no tin cans, 0.6 tonnes/m³)</td>
</tr>
<tr>
<td>4A</td>
<td>New production compressed steel sheet</td>
</tr>
<tr>
<td></td>
<td>(less than 3 mm thick, not tinned, coated, galvanised, enamelled or harmful)</td>
</tr>
<tr>
<td>4C</td>
<td>New production compressed steel sheet</td>
</tr>
<tr>
<td></td>
<td>(less than 3 mm thick, in bales, may include some coated material)</td>
</tr>
<tr>
<td>4E</td>
<td>New production compressed steel bales</td>
</tr>
<tr>
<td>4F</td>
<td>New production steel strip and/or wire bobbins</td>
</tr>
<tr>
<td>4G</td>
<td>New production compressed detinned steel sheet</td>
</tr>
<tr>
<td></td>
<td>(less than 0.25 mm thick, in bales)</td>
</tr>
<tr>
<td>5A</td>
<td>Compressed old light steel</td>
</tr>
<tr>
<td>5B</td>
<td>Pressed and sheared old light steel</td>
</tr>
<tr>
<td>5C</td>
<td>Loose light steel</td>
</tr>
<tr>
<td>6A</td>
<td>Incinerator bales, compressed steel bales</td>
</tr>
<tr>
<td>6B</td>
<td>Loose incinerated</td>
</tr>
<tr>
<td>7A</td>
<td>Heavy carbon steel turnings</td>
</tr>
<tr>
<td>7B</td>
<td>Heavy carbon steel turnings</td>
</tr>
<tr>
<td>8A</td>
<td>New loose light steel cuttings</td>
</tr>
<tr>
<td>8B</td>
<td>Loose light steel cuttings</td>
</tr>
<tr>
<td></td>
<td>(suitable for pressing, may include some coated material)</td>
</tr>
</tbody>
</table>
Table 4.1: (continued).

<table>
<thead>
<tr>
<th>No</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>9A</td>
<td>Heavy cast iron (&gt; 13 mm)</td>
</tr>
<tr>
<td>9B</td>
<td>Cylinder block</td>
</tr>
<tr>
<td></td>
<td>(old low phosphorus iron, from dismantling of vehicles)</td>
</tr>
<tr>
<td>9C</td>
<td>Oil free new production or burnt cylinder block</td>
</tr>
<tr>
<td></td>
<td>(low phosphorus iron)</td>
</tr>
<tr>
<td>10</td>
<td>Light cast iron</td>
</tr>
<tr>
<td>11A</td>
<td>Clean cast iron or malleable iron borings and drillings</td>
</tr>
<tr>
<td>11B</td>
<td>Briquetted cast iron borings</td>
</tr>
<tr>
<td>12A</td>
<td>New production heavy steel</td>
</tr>
<tr>
<td>12C</td>
<td>New production heavy steel</td>
</tr>
<tr>
<td>12D</td>
<td>New production shovellable steel</td>
</tr>
</tbody>
</table>

the exports. Thus, it is assumed the import and export contain about the same amount of tin, so that trade can be disregarded. Unfortunately, information about trade of metal products is not available at the level of detail giving metal compositions. Due to lack of precise information, we assume that differences between the compositions of imported and exported metal products is negligible. This assumption is discussed later in the final section. Therefore, in this study, all UK metal products can be modelled as being delivered to UK manufacturing sectors, i.e. none is exported.

The ISSB has data on the amount of each metal product that is delivered to each manufacturing sector (Hunt 2003). The data are categorised into 12 metal products and 9 manufacturing sectors. Accordingly, this is the split we use in the analysis. Unfortunately, the most recent year for which this information is available is 1989; in subsequent years, only the total delivery to each sector is available. In the analysis, we assume the split in 1989 to be valid for the time period we study; i.e. we use this split for each year between 2000 and 2020. Needless to say, there are no data for future years, and using this information from 1989 at least gives us an indication
Table 4.2: Categories of metal products and annual UK production level used in the study (see text for how this has been derived).

<table>
<thead>
<tr>
<th>Metal product</th>
<th>UK annual production [Thousand tonnes]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid steel for castings</td>
<td>140</td>
</tr>
<tr>
<td>Ingots for tubes</td>
<td>1540</td>
</tr>
<tr>
<td>Heavy sections</td>
<td>1540</td>
</tr>
<tr>
<td>Merchant bars</td>
<td>2100</td>
</tr>
<tr>
<td>Wire rod</td>
<td>1120</td>
</tr>
<tr>
<td>Hot rolled narrow strip</td>
<td>980</td>
</tr>
<tr>
<td>Plate (Coil and lengths)</td>
<td>1540</td>
</tr>
<tr>
<td>Uncoated sheet</td>
<td>1820</td>
</tr>
<tr>
<td>Coated sheet other than zinc coated</td>
<td>1260</td>
</tr>
<tr>
<td>Zinc coated sheet</td>
<td>840</td>
</tr>
<tr>
<td>Cast iron</td>
<td>840</td>
</tr>
<tr>
<td>Forgings</td>
<td>280</td>
</tr>
</tbody>
</table>

of which types of metal products go into which types of goods. We have assumed that the total production of metal products in the UK remains at 14 million tonnes per year between 2000 and 2020, this is the production level in 2000. Using the split from the ISSB for 1989 we get the production of each metal product used in the analysis, as given in Table 4.2.

Tin added to production

As noted above, tin is only added to two of the metal products: 'Cast iron' and 'Coated sheet other than zinc coated'. Tin is added to cast iron so that the resulting concentration in the finished metal product equals 1%. It is thereby assumed in the study that the specification for cast iron
A concentration of 1% of tin. When taking into account how much tin is added to the production of cast iron via the scrap, tin is only added to the extent needed to bring the concentration up to 1%. If the concentration in the cast iron is already higher than 1% because of the scrap charge, no tin is added. Accordingly, if

$$\frac{\text{APRin}_{ij-1} + \text{AEOLin}_{ij-1}}{\text{Prod}_{ij}} < \text{Aspec}_{ij}$$

(4.28)

where \(\text{Aspec}_{ij}\) is the maximum allowed concentration of element A in metal product \(i\), then

$$\text{Load}_{ij} = \frac{\text{Aspec}_{ij} \cdot \text{Prod}_{ij}}{100} - \frac{\text{APRin}_{ij-1} - \text{AEOLin}_{ij-1}}{\text{Prod}_{ij}}$$

(4.29)

It is assumed that all the coated sheet is tincoated to a level of 0.4% tin; this is based on the average tin content in tinplate being 0.4%. However, unlike cast iron, tin is always added to this metal product independent of the tin concentration in the sheet, as in this case it is added as a coating and not an alloying element. In other words,

$$\text{Load}_{\text{coated sheet},ij} = 0.004 \cdot \text{Prod}_{\text{coated sheet},ij}$$

(4.30)

Deliveries to UK manufacturing

Figure 4.4 shows the deliveries of each metal product to each of the nine UK manufacturing industries. This is based on the information from ISSB in 1989 (see the first section in 4.3.2). Prompt scrap arises from each manufacturing sector according to the appropriate prompt scrap rate. The prompt scrap rates are assumed to be constant over the time period studied and are given in Table 3.1 in chapter 3.

Deliveries of new goods to use

The goods produced in the UK are all assumed to be delivered to use in the UK, i.e. trade in new goods is disregarded. This is similar to the assumption made earlier that all metal products produced in the UK are delivered to UK manufacturing sectors. As in the case of metal products, there have been large imports and exports of new goods over the past 30 years, but on average they balance each other. Again, due to lack of quantitative information about the composition
of metal contained in traded goods, we assume the imports and exports contain about the same amount of tin so that the net effect can be disregarded. This assumption will be reviewed again in the discussion at the end. The goods stay in use until they reach the end of their service lives. The life-span distribution used in the model to simulate the delay in use for each category of goods is a Weibull distribution. As there was no great difference between the different distributions used when modelling of end-of-life scrap arisings in the iron and steel MFA, the Weibull distribution is used in this study. Data for the average life-spans of different categories of goods are given in table 3.3 in chapter 3. In order to model end-of-life scrap arisings for the years 2000 to 2020, data on deliveries of metal in new goods entering use prior to 2000 need to be provided. This data set is the same as was used in the material flow analysis study of iron and steel, see section 3.4.1. In other words, the matrix $D_{NG}^{k,j,t}$ in equation 4.11, deliveries of metal in new goods to UK use, contains information on the amount of iron and steel going into UK use for years prior to 2000; the data reach back to 1975 for all categories apart from 'Construction' which reaches back to 1900. Naturally, the iron and steel in these goods will contain some level of tin; this information is contained in the matrix $AD_{NG}^{k,j,t}$ in equation 4.12. We have assumed that for years prior to 2000, the steel from the packaging sector going into use consists solely of tinplate.

Figure 4.4: Deliveries of metal products to UK manufacturing sectors in thousand tonnes in 1989 (Hunt 2003).
and that the goods categories ‘Mechanical engineering’, ‘Construction’ and ‘Boilers, drums and other vessels’ contain amounts of cast iron corresponding to the deliveries of cast iron to these sectors in 1989 (ISSB data set): 8%, 12% and 30% respectively. We assume that the cast iron contains 1% of tin and that the tinplate has 0.4% of tin as a coating layer.

Recovery of scrap

In the analysis we assume that 100% of the prompt scrap is recovered and recycled in the UK. The end-of-life scrap is recovered according to the recycling rate of each goods sector (see chapter 3. In scenario 1 we assume the EOL recycling rates of 2001 to remain constant until 2020. These recycling rates are given in the righthand column in table 3.8 in chapter 3; the average recycling rate of all these goods categories equals 72%. In scenarios 2, 3 and 4 we assume that the recycling rates for all the goods categories increase linearly from their level in 2001 to 90% in 2010 and remain at this level until 2020.

Scrap aggregation and trade of scrap

In all scenarios, the amount of scrap that is allocated to each metal production is proportional to the production volume of each metal product, i.e. the largest metal product in terms of production mass consumes the most scrap and so on. However, the composition of the scrap is different in the four scenarios. In scenarios 1, 2 and 3 the scrap consumed is a mix of all the different types of scrap; it goes into all the metal products independent of how much tin the scrap contains. So in these scenarios, the total amount of scrap consumed in each metal product depends on the production volume of the product and the composition of the scrap is the same.

In scenario 4 however, the composition of the scrap is also taken into account when allocating the scrap. The scrap from the different goods categories (prompt and EOL scrap) consists of different types of old metal products. Here, the scrap is disaggregated into these metal products and each old metal product goes to the production of that metal product.

In scenarios 1 and 2 scrap exports equal 4 million tonnes per year until 2020. In scenarios 3 and 4 we reduce the export of scrap linearly so that in 2010 it is equal to zero and remains at this level until 2020. The scrap export is deducted from the 9 scrap categories with the largest
4.3 Case study - tin

4.3.3 Results

The results have been generated in Matlab; the code is given in Appendix C.

Scenario 1

Figure 4.5 shows the average concentration of tin in all the metal products in scenario 1, along with the other scenarios. Scenario 1 represents the build-up of the concentration of tin if the end-of-life scrap recycling rates and scrap export are kept constant at the same level as in 2001. There is no significant increase of tin over the years despite there being quite high overall recycling rates in the system: 72% on average for EOL scrap and 100% for prompt scrap. This is because, although a lot of the scrap is recovered, almost half is exported and is not used in UK production. This means quite large amounts of virgin input are still required in UK production, which dilutes the tin. Figure 4.6 shows the individual concentrations of each metal product in the same scenario.
4.3 Case study - tin

Figure 4.6: Concentration in each metal product between 2000 and 2020 in Scenario 1: constant EOL recycling rate of 70% and an annual scrap export of 4 million tonnes.
(note the different scaling of the axes in the three figures). Again, there are only slight increases in the concentrations of all 12 products apart from ‘Cast iron’ which remains at 1%. The reason why cast iron and coated sheet are different is that here tin is not only added via the scrap charge but also added intentionally in the production. The tin level in ‘Cast iron’ is constant as the tin in the scrap charge to this product is not enough to result in a concentration of 1% in the finished product, external tin is therefore intentionally added. Note that the concentration of tin in ‘Coated sheet’ includes the mass of the coating layer of tin.

So evidently, without taking any special care when allocating the different types of scrap to each metal product, and having reasonably high recycling rates in the system, there is no significant build-up of tin in the system. In this scenario, the problems seems literally to be exported from the country.

Scenario 2

Figure 4.5 also shows the tin concentration build-up for scenario 2, in which the scrap export is still kept constant at 4 million tonnes/year, but the average EOL recycling rate increases from 72% in 2000 to 90% in 2010 and stays constant until 2020. Here, there is an increase from ca 0.12% in 2000 to around 0.15% in 2020. It is not surprising that the concentration increases with increasing recycling rates, as less and less virgin material will be used in UK iron and steel production, i.e. less dilution occurs.

Figure 4.7 shows the individual concentrations of each metal product in scenario 2. Here too, there is an increase in all products except ‘Cast iron’ which, as in scenario 1, remains level at 1%. However, the tin scrap charge increases in this product, as for the others, meaning that less and less intentionally added tin is needed each year. In other words, as the concentration of tin in the scrap used in production of cast iron has increased, less external tin is added to this product.

Scenario 3

In scenario 3 (see Figure 4.5), the iron and steel cycle becomes even more ‘closed’ over time with both increasing recycling rates and decreasing scrap exports. In this scenario the scrap export decreases linearly from 4 million tonnes/year in 2000 to none at all in 2010 and the
4.3 Case study - tin

Figure 4.7: Concentration in each metal product between 2000 and 2020 in Scenario 2: increasing EOL recycling rate and an annual scrap export of 4 million tonnes.
Figure 4.8: Concentration in each metal product between 2000 and 2020 in Scenario 3: increasing EOL recycling rates and decreasing scrap export.
4.3 Case study - tin

Figure 4.9: Concentration in each metal product between 2000 and 2020 in Scenario 4: increasing EOL recycling rates and decreasing scrap export and disaggregation of the scrap before remelting.

following years. Here, the average tin concentration of all products increases further from 0.12% in 2000 to around 0.19% in 2020. If we look at the individual metal products in Figure 4.8, the same dramatic increases are evident in all products except 'Cast iron'. The reason why the concentration in the ten products with the lowest concentrations merge at 2010 is that all scrap export has ceased in this year. As described earlier, the amount of scrap allocated to each scrap category is proportional to the production volume of the corresponding metal product; because all scrap is identically mixed in the first three scenarios, all products will have proportional amounts of element A in the scrap charge when exports cease.

At these high increases in the concentrations, there will be problems in several of the metal products, particularly 'Uncoated sheet' which requires very low levels of tin to enable rolling etc. Bearing in mind that the concentration in the actual sheet (without the coating) is only around 0.1% in 2020, this is still too high for this particular product. However, the concentrations are still far away from 1%, meaning that production of 'Cast iron' still requires some addition of tin to the production.
Scenario 4

In scenario 4, the scrap recycling rates and export are the same as in scenario 3, but the scrap is disaggregated into its metal product components before being remelted and returned to the metal production from which it came. The resulting average concentration in all the metal products is seen in Figure 4.5. It is clear that the development of the concentration is lower than in scenario 3, which is due to there being less tin added to the system. In scenario 3, more external tin is added to the production of ‘Cast iron’ as not so much cast iron scrap is used in the production of cast iron; in scenario 4, however, smaller amounts of external tin are added to production of ‘Cast iron’ as more tin comes from the old cast iron scrap charge.

However, if we look at the individual concentrations of each metal product (figure 4.9), the picture looks different. Here, the concentration in cast iron is the same as before, but for all other products the development in concentration build-up has changed from that in scenario 3. As coated sheet is the product that contains the most tin after cast iron, feeding back all scrapped coated sheet into the production of coated sheet will lead to a dramatic increase in the concentration of tin in this product. Before, all the remaining products experienced an increase of the tin concentration. Now, with scrap disaggregation, all build-up in these metal products has ceased. This would mean that it is beneficial to disaggregate the scrap as much as possible before using it in the production. In the case of coated sheet, it seems necessary to use virgin material to produce the sheet and use the sheet scrap in production of a metal product that is less sensitive to tin build-up, for example cast iron. Alternatively, the tin coating might be separated from the sheet before remelting.

4.4 DISCUSSION AND CONCLUSIONS

This study has focused on developing a general methodology for examining the concentration of one or more particular elements in metal cycles in the UK. It is not a model that attempts to forecast future trends but rather to examine consequences for the composition of the metal product flows depending on different future scenarios. The model, however, allows different scenarios to be examined and if more realistic data can be obtained in the future, the model could
be useful in predicting the build-up of contamination of different elements. It could also be used for other metals than steel. The application of the model has been illustrated here by a case study, examining potential build-up of tin for different scenarios between 2000 and 2020 in the iron and steel cycle. The different scenarios examined are: constant recycling rates and scrap export over time, increased recycling rates and decreased scrap export over time. Two ways of aggregating the scrap before remelting were also examined: (1) mixing all the scrap together regardless of tin content; and (2) separating the scrap into its original metal product components (wire, sheet, cast iron etc.) and recycling it in a ‘closed loop’ recycling pattern.

When the recycling rates and scrap export are kept constant over time at the 2001 level, no build-up occurs in the system; as so much scrap is exported, there is a substantial input of virgin material which dilutes the recycled tin and so avoids contamination problems. However, this pattern is not sustainable in the long-term as legislation will force recycling rates to increase. Furthermore, the expanding steel countries such as China and Russia, will eventually start generating their own end-of-life scrap, and will become more self-sufficient in terms of scrap supply; this might influence the scrap prices and make UK scrap exports less economical in future. Not surprisingly, both increasing the recycling rates and decreasing the scrap export lead to increases in the concentration of tin in the metal products. If the scrap is separated before remelting and control is maintained over the type of scrap recycled into different products, build-up can be avoided in most products. However, this means it must be feasible to disaggregate the end-of-life goods into their original metal products, which will be difficult in some cases and perhaps also expensive. Still, if relatively ‘closed’ recycling systems are to be achieved and maintained, for example maintaining the EOL recycling rate at 90% and using minimal input of virgin ore in the metal production, such separation procedures will be essential. Otherwise there will be a deterioration in the scrap quality and ultimately the quality of the metal products will be affected.

In the scenarios studied here, we have disregarded trade of metal products and goods containing metal. However, this could easily be incorporated in the study, using forecast values for trade and estimated levels of tin content in this trade; the effects of different trade values could then be analysed. This is therefore not a shortcoming of the model as such, but a choice that was made in designing the case study scenarios. We chose to investigate changes to the recycling rates,
4.4 Discussion and conclusions

scrap exports and scrap aggregation; by avoiding too many variables in the system, the effects of changing these three variables can be seen more clearly.

To facilitate disaggregation of different types of scrap, it would be beneficial to have a marking system which would make it easy to identify the alloy composition of the product. If such a system were put into force today, the effect would be delayed several years as some of these products will emerge as scrap in future years. Still, this only reinforces the importance of implementing a marking system as soon as possible in order to enable the segregation of scrap which will be necessary in future if higher recycling rates are achieved.

There are a vast number of alloying elements used in iron, steel and aluminium production, and it is quite difficult to acquire information on alloy consumption and specifications of each different metal product produced in the UK. This means that the type of modelling explained in this chapter can become very data intensive and thereby it can be a major challenge to obtain the necessary information. In order to gain a more complete picture of possible future build-up scenarios, more alloying elements and other possible contaminants need to be explored, especially as some elements only cause concern in conjunction with other elements. This task is outside the timeframe of this project but the methodology presented here should be useful in further exploring potential contamination and how it can be avoided. If sustainable use of metal is to be achieved, information on metal product composition and goods composition must become more available in the future.
Recovery of dispersed scrap

As discussed in chapter 1, in the context of minimising the loss of iron, steel and aluminium from the economic system in the UK, recovering widely dispersed products such as packaging stands out. This chapter is focused specifically at packaging. In order to recycle used packaging, the scrap first needs to be collected, an operation that can be quite energy intensive if the scrap is very dispersed. This chapter explores whether the environmental impacts vary notably between different collection systems and also how significant these collection stages are in the context of the whole life cycle of the metal. As a case study, collection of used aluminium beverage cans (UBCs) has been investigated in two local authority areas in the UK with significantly different characteristics. The transport requirements for these two systems have been modelled for different recovery rates. By comparing the cost of collection to the value of the recovered cans, the economic incentive for collecting cans has been analysed. In the same way, the environmental cost of collection has been compared to the environmental benefit of recycling the used cans.

5.1 INTRODUCTION AND SCOPE

The UK is the largest consumer per capita of beverage cans in Europe (see figure 5.1). About 75% of the cans consumed in the UK are of aluminium, the remainder consisting of steel cans (Griffin 2001). In actual numbers, 5.3 billion aluminium cans were sold in the UK in 2000, corresponding
to roughly 78,000 tonnes of cans (Alupro 2003). The total consumption of aluminium in the UK is around 950,000 tonnes a year (see figure 3.14); thus beverage cans make up a significant part of this consumption.

The aluminium manufacturers claim that aluminium is a suitable material for packaging in a more sustainable society, despite the fact that producing aluminium from primary resources requires significant amounts of energy. This message is based on the fact that it is technically possible to recycle aluminium an infinite number of times, without decreasing the quality of the metal. This holds true provided that a build-up of contaminants and alloying elements is avoided, as was demonstrated in chapter 4. They also argue that because aluminium is highly valuable, aluminium scrap is rarely lost from the economy. However, aluminium packaging, due to its often dissipative use, is still lost to a great extent, as discussed in chapter 3. As already mentioned, only 2% of used aluminium beverage cans (UBCs) were collected and recycled in 1989. This led to the launch of a national aluminium can recycling scheme in the same year. Recovery and recycling has since increased dramatically and in 2001 the rate was 42% (Alupro 2003). However, in the face of rising environmental concerns, action needs to be taken to increase this rate further if beverage cans are to be part of a more sustainable use of aluminium in the UK.

As discussed in chapter 1, in 1994 the EC launched its directive on packaging and packaging

![Figure 5.1: Yearly consumption of cans (steel and aluminium) per capita (BCME, 2001).](image-url)
waste, which was the first example in Europe of extended producer responsibility (EC 1994). The directive mandates certain recycling targets that have to be met by member countries by 2001. The target set for the recovery of packaging in total is 50% as a minimum and 65% as a maximum, and at least 15% by weight of each packaging material has to be recycled. The maximum target was set at 65% to discourage that large quantities of waste are recovered and exported. The recycling targets have been fulfilled in all member countries and new targets to be achieved by 2006 have been proposed by the Commission. The new proposal features a minimum recycling target of 60% for all packaging in parallel with differentiated targets for specific packaging materials: 60% for glass, 55% for paper and cardboard, 50% for metals and 20% for plastics (EC 2002). In terms of aluminium packaging, the current recycling rate in the UK is 34%. Therefore, it is imperative we find strategies to further increase the recovery of aluminium packaging in the UK.

One way of increasing the recovery is to provide an economic incentive for consumers to return their cans to their local retailer, by applying a deposit on the cans. Deposit systems on aluminium cans are operated in Sweden, Norway and Finland; in all these countries the recovery rate for aluminium cans is above 80%, as seen in figure 5.2. Denmark has long had a ban on beverage cans, but this was lifted in January 2002 on the condition that a deposit was imposed on the cans. Germany and Switzerland have managed to maintain very high recovery rates without a deposit; in Switzerland, consumers pay a small levy on each can which finances a comprehensive network of easily accessible collection points and in Germany households are encouraged to separate their waste by being charged for waste that is not separated. French-Brooks (1999) has performed a survey in London which revealed a certain degree of support for the introduction of a deposit system amongst the buying public. Even though this might not be true for the whole country, it shows that some people would accept paying a deposit on drink containers. The study also found that the technology needed for such a system is already available and is ready to be successfully applied.

As shown in chapter 2, the savings in process energy from producing cans from recycled aluminium (secondary aluminium) instead of virgin resources (primary aluminium) are vast. The energy requirement for producing primary aluminium is in the order of 50 MJ/kg, whereas
5.1 Introduction and scope

The environmental incentive to make sure that as many aluminium cans as possible are recovered and re-melted is therefore obvious. However, in order to re-melt the used cans, they must first be collected, an operation that can be quite energy intensive depending on how dispersed the scrap is.

The aim of this study is to analyse the transport requirement of different collection systems for used cans, in order to understand how significant the environmental impacts are of the collection stage, compared to the whole life cycle of the aluminium can (see figure 5.3) in terms of environmental impacts. The study will explore the variation in transport intensity of different types of collection structures for aluminium cans. Furthermore, the economic cost of collection will be compared to the economic value of the collected cans.

As a case study, collection of used aluminium beverage cans (UBCs) is investigated in two local authority areas in the UK with significantly different characteristics. The two boroughs are the London Borough of Tower Hamlets (TH; population: 186700, area: 19.7 km²) and the Borough of Waverley in Surrey (W; population: 115800, area: 344 km²)(National-Statistics 2001). UBCs are selected in this study, as the consumption of UBCs is high in the UK, and there is a need to improve collection systems for this particular type of packaging. The transport
requirements for these two systems are modelled for different recovery rates. By comparing the cost of collection to the value of the recovered cans, the economic incentive for collecting cans can be analysed. In the same way, the environmental cost of collection can be compared to the environmental benefit of recycling the used cans.

5.2 Methodology

First, information about the current systems for collecting UBCs in the selected boroughs is gathered. Information on other alternative collection systems that have been successful is also collected. The deposit system in Sweden is selected as complete information on this system is available and its feasibility in terms of technical issues seems well established.

In the scenarios, the transport requirements of the current collection systems at the current recovery rates in each borough are calculated, and used as the basis for calculating the requirements at higher recovery rates. The transport requirements of using the deposit system at different recovery rates are also calculated. The transport calculations for the current systems are based on information gathered from the contractors performing the collection (e.g. number and location of bring sites etc.) and also on personal experience of going with the collection trucks to see how it is done first hand (e.g. estimating the distance between collection point in the kerbside schemes). In the deposit scenarios, information on the geographic location of retailers in each borough are collected and used in the calculation of transport requirements. Detailed information of the scenarios explored and how the transport requirements are calculated is found in section

![Figure 5.3: Life cycle of aluminium cans.](image)
5.4 and appendices D and E.

In the study the transport distances associated with the collection of cans have been calculated with the help of the logistics software package (Optrak 1999) using digital maps of the areas. Optrak optimises the route that should be taken in order to minimise the transport distance for a particular collection. The main parameters that define each collection round are: number and location of collection points, amount that is to be collected at each point, depot location and the truck capacity.

The transport requirement considered in the case studies is that of the collection of cans from bring sites and retailers to a depot, and also from kerbsides to a depot. Any potential transport of the cans to the bring sites and retailers is thereby not included. In the case of collection from retailers, this is realistic, as consumers would combine the return of UBCs with doing their shopping.

In the scenarios where shared collection occurs, only a portion of the transport need is allocated to the aluminium cans, according to the load composition of the truck by mass.

The environmental burdens of each collection system are derived by attaching environmental data to the transport requirements; this is done by using the life cycle assessment (LCA) software package SimaPro (SimaPro 1999). The life cycles are studied for each different collection scenario. SimaPro is also used to obtain the environmental burdens from the entire life cycle of the aluminium cans (see Figure 5.3). Data for production of primary aluminium and remelting of used cans are taken from average data for Western European aluminium production in the SimaPro database (BUWAL 1996b), the same data that is referred to in chapter 2.

The economic cost of collection is estimated by attaching cost figures to the transport requirements. The cost data are taken from the Freight Transport Association (FTA 1998), which has cost estimates per kilometer for different types of vehicles. The cost of each collection scenario is then compared to the economic value of the collected cans.

5.3 Description of collection systems

There are several ways in which cans can be recovered after use. Three main methods for recovery in Europe are: deposit systems, kerbside systems and bring site systems, all of which are
5.3 Description of collection systems

described below. Both the kerbside and bring schemes are operated in the UK today, whereas the deposit system has so far not been applied to cans (although it has been used for reusable bottles in the past). In the two areas investigated in this study, a combination of the bring site and kerbside scheme is operated. In order to obtain higher recovery rates for cans, it is vital to make it as convenient as possible for consumers to return their cans. Therefore, in the scenarios of higher recovery, only kerbside collection and collection using a deposit system have been investigated, because these are considered to be more convenient and motivating for consumers to return their used cans.

5.3.1 Deposit system

In the subsequent case studies the deposit scenarios are based on the system used in Sweden. A detailed description of the Swedish deposit system for collection of aluminium cans is given below.

Aluminium has been the only material used for the manufacture of beverage cans in Sweden since the beginning of the 1980s. The issue of collection of aluminium cans was raised in 1984 by the Swedish parliament. They ruled that at least 75% of all beer and soft drink cans made out of aluminium should be recycled by the end of 1985. This target has since been revised to 90%. The government did not decide how the collection system should work but gave industry the responsibility to design its own system, provided that the recycling target could be fulfilled. This resulted in the packaging industry, breweries and retailers collaborating to develop the deposit system that is still in operation in Sweden today. The system is organised by the company AB Svenska Returpack, in short Returpack, which is responsible for the administration and co-ordination of the system. The recycling operation is conducted according to the terms of a special government licence, subject to Swedish law. This license was issued to Returpack, which is owned jointly by the breweries (49%), packaging industry (Rexam 49%) and the retail trade (2%). Returpack is a non-profit company and any profit made is spent on campaigns for increasing the recovery of cans and PET bottles. Returpack is divided into two limited companies with their own separate finances; one is responsible for the recycling system of aluminium cans and the other for recyclable PET bottles. There are also deposit systems for refillable PET bot-
5.3 Description of collection systems

Figure 5.4: The Swedish deposit system - from can manufacturer to consumer.

ties and refillable glass bottles; these are however managed by the Swedish breweries association (Returpack 1997).

All breweries that can or bottle drinks in Sweden are part of the recycling system and have agreements with Returpack. Figures 5.4 and 5.5 show how the flow of the can is connected with a reverse flow of the deposit fee. Figure 5.4 shows that the can manufacturer pays a deposit to Returpack for every can that is produced. Importers also have to pay a deposit and an import fee on imported cans. If the importer is a brewery, the import fee is reimbursed by Returpack. In the next step, the can manufacturer receives a deposit from the breweries when the can is sold. The brewery receives a deposit when it sells the packaged drink to the retailer and the retailer then adds the deposit onto the price when the consumer buys the drink.

The consumers get their deposit back when they return the used can to any retailer that has facilities for collection. Most retailers operate automatic reverse vending machines, but there are still some places that receive the cans manually from the consumer. There are approximately 5000 shops with reverse vending machines in the country, providing reverse vending opportunities for a population of approximately 9 million people. It is the breweries’ responsibility to collect the returned cans from the shops and to pay the deposit fee to the shops. The retailers are also given a fee for every can that they receive to help finance their cost of handling the returned cans. The retailers themselves make the investment to buy a reverse vending machine which can
5.3 Description of collection systems

Figure 5.5: The Swedish deposit system - from consumer back to can manufacturer.

Cost up to as much as 200 000 SEK (ca £12 500). The payback period for the machine therefore depends on the flow of returned cans through the shop. However, some small retailers can receive subsidies from Returpack for buying a reverse vending machine. One could say that it is the breweries and the large shops with a high throughput of cans that make a profit from this system. Smaller shops might lose out if their throughput of cans is low, as this results in a very long payback period for the reverse vending machine. However, it is normally a service consumers expect, which is why a lot of shops still have them (plus the subsidies from Returpack).

As a means to keep track of the cans, Returpack makes use of the barcodes on the cans, also known as EAN codes. The breweries and importers therefore have to report all their products’ EAN codes to Returpack. The reverse vending machines in the shops are updated with these codes every week via the machine supplier. Thereby, the consumer only gets reimbursed for packaging which has the correct EAN codes. Cans that have been imported by the consumer, and thereby are included in the collection scheme, will not be recognised by the machine and the consumer will not receive money for them. The same goes for crushed or dirty cans on which the machine cannot read the EAN code. By keeping track of the cans in this way, Returpack receives a basis on which to calculate the deposit and handling fees they have to pay to the retailers and breweries for cans that have been collected.

When the breweries have collected the cans from the retailer, the cans are transported to
5.3 Description of collection systems

![Balance of revenues and costs for cans at Returpack]

**Figure 5.6: Revenues and costs at Returpack (Funke, 2001).**

an aluminium smelter (cost of transportation paid by Returpack) where they are sold and the earnings go to Returpack. Previously, most of the used cans were smelted in Finspång, Sweden. Since 1995, however, due to the strong British pound, about 90% of the cans are transported to England and are smelted at Alcan’s UK plant in Warrington as the scrap can be sold at a higher price here. About 12 000 tonnes per year of used beverage cans from Sweden are smelted at Warrington (Funke 2001). Ironically, by studying the cost and the revenues of Returpack in figure 5.6, it can be noted that Returpack makes a larger profit if the rate of returned cans is low. This is because Returpack is paid a deposit for every can that is sold to the breweries but they only have to reimburse for cans that are collected and returned to the retailer so that, for every can that is not returned, Returpack saves money on not having to repay the deposit for that can. This seems controversial, as Returpack’s main aim is to strive for a recycling rate of more than 90% for aluminium cans (by Swedish law). But as Returpack is not meant to make a profit, all profits made when the recycling rate is low are spent on campaigns for increasing the rate; if this is effective, the profit will decrease and presumably the campaigns will become less intense.

The recycling rate of aluminium cans in Sweden was above 90% for about five years until 1997 when it started to drop. The recycling rate in 2000 was 86%. The Swedish government therefore wants to double the current deposit of 0,50 SEK a can to 1 SEK in an attempt to
increase the incentive for consumers to return their beverage cans. To put this in relative terms, the average cost of a 33 cl beverage drink can is about 6 SEK, so the deposit share of the price would then still be less than 16%. But an increase of the deposit might only increase the recovery temporarily and not have any long-term effect. The main reason why the recovery has decreased in recent years is due to a change in consumption patterns (Funke 2001). People's habit of eating and drinking on their way to somewhere has increased considerably, and this trend makes it more difficult for people to return the packaging to the retailer. If, for instance, they have a drink in their car, they probably do not want to store a collection of used cans in the vehicle nor do they want to stop at a retailer to return the single item of packaging. They will therefore throw the can into a bin for mixed waste, or leave it somewhere where it might not be picked up. Returpack hopes to fight the trend of decreasing recovery with advertising campaigns. Another idea might be to introduce bins for cans at strategic points where a lot of people pass, as is the common practice in Germany for example; in this way the consumer would not be reimbursed for the deposit, but the can could still be collected and brought back into the system.

5.3.2 Kerbside system

In the kerbside system, collection occurs at the households. Each household included in the scheme is given a specific container into which they put recyclable waste that has been separated out from their household waste. Depending on which scheme, one or several materials are collected. Figures 5.7 and 5.8 show the trucks that are used for kerbside collection in Tower Hamlets and Waverley respectively.

5.3.3 Bring site system

In a bring site scheme, consumers deposit their recyclable waste in “banks” provided at convenient locations, e.g. at the supermarket. The responsibility thereby lies with the consumer to take their waste to these sites, rather than having it collected at the household as in the kerbside scheme.
5.3 Description of collection systems

Figure 5.7: Multi-compartment truck used for kerbside collection of cans, glass, cardboard, paper and textiles in Tower Hamlets.

Figure 5.8: Split bodied vehicle used for kerbside collection of cans and paper in Waverley.
5.4 Case studies

The following section demonstrates in two case studies the environmental and economic implications of different collection schemes.

5.4 Case studies

The two areas chosen for the study are the London Borough of Tower Hamlets (TH; population: 186,700, area: 19.7 km²) and the Borough of Waverley in Surrey (W; population: 115,800, area: 344 km²) (National Statistics, 2001). These two boroughs are quite different in population density, housing structure and socio-economic profile. In Waverley there are mainly detached houses, whereas Tower Hamlets has some semi-detached houses but also a great number of blocks of flats. Situated in the central part of London, Tower Hamlets has a much higher population density than Waverley.

The total amount of Used Beverage Cans (UBC) available for collection in each area has been approximated straightforwardly by multiplying the average annual consumption of aluminium cans in the UK of 1.30 kg per capita (Alupro, 2003), by the respective population in that area. However, the UBC generation in TH is assumed to be 20% higher than the UK average, mainly because of the fast-food oriented lifestyle exercised in the cities, but also due to London tourism; i.e. the consumption in Tower Hamlets is assumed to be 1.56 kg per capita.

The depot locations used in the TH and W scenarios are the same as are used in the current collection of cans in the two areas.

In summary, the transport requirements for the following scenarios are analysed:

- Current collection system in Tower Hamlets: collection from kerbsides and can banks – at today’s recovery rate of 3% and also at higher recovery: 30, 50, 70, 90%;
- Deposit system in Tower Hamlets: collection from retailers – at 30, 50, 70, 90% recovery;
- Current collection system in Waverley: collection from kerbsides and can banks – at today’s recovery rate of 19% and also at higher recovery: 30, 50, 70, 90%; and
- Deposit system in Waverley: collection from retailers - at 30, 50, 70, 90% recovery.
5.4 Case studies

5.4.1 Current collection systems

Cans are currently collected in both boroughs by kerbside and bring site collection; see Table 5.1. More detailed information on these parameters, as well as transport calculations, can be found in Appendices D and E.

The transport requirements of the current collection system (kerbside and bring site collection) in the two areas, have been modelled at today's recovery rates: 3% for TH and 19% for W, respectively. Compared to the national recovery rate of 42% these rates are quite low. However, they only take into account collection by the local authorities and not any other collection initiatives, for example 'cash-for-cans' schemes.

5.4.2 Scenarios of higher recovery

Two different ways of increasing the recovery of cans have been investigated: (i) increasing the collection from kerbsides to cover all households in the areas; and (ii) providing an economic incentive for people to return their cans by implementing a deposit system.

Note that the overall assumption for exploring a deposit system for cans is that deposits are imposed on not only aluminium cans but also steel cans, PET bottles and glass bottles, so that any distortion of the packaging market is avoided (in line with EU legislation). However, it is only the collection of aluminium cans that is investigated in the present study.

Increased kerbside collection

The transport needs for higher recovery rates of cans in TH and W using the current structure have been calculated. The transport needs have been modelled for 30, 50, 70 and 90% recovery.

It has been assumed that the increase in recovery will be achieved by increase in kerbside collection, i.e. increase in the number of households that participate in the scheme. As the kerbside scheme increases, the can banks will decrease in importance as consumers are unlikely to go to the can bank if they have a service provided at home for collecting their recyclables.

Parameters used in calculating the transport requirements are found in Table 5.2. Further information on these parameters and the transport calculations are found in appendices D and E.
Table 5.1: Parameters for current kerbside and bring site collection (Sekibo, 2001; Moore, 2002; Buchan, 2002; Lamport, 2002).

<table>
<thead>
<tr>
<th></th>
<th>Tower Hamlets</th>
<th>Waverley</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kerbside collection</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Household coverage</td>
<td>11,000 out of 79,400</td>
<td>30,000 out of 48,000</td>
</tr>
<tr>
<td>Collection frequency</td>
<td>Fortnightly</td>
<td>Once a week</td>
</tr>
<tr>
<td>No of collection points</td>
<td>4,400</td>
<td>15,000</td>
</tr>
<tr>
<td>Distance between collection points</td>
<td>20 m</td>
<td>45 m</td>
</tr>
<tr>
<td>Truck</td>
<td>Multi-compartment (17 t)</td>
<td>Two-compartment (18 t)</td>
</tr>
<tr>
<td>Shared collection</td>
<td>glass, cardboard, paper</td>
<td>paper</td>
</tr>
<tr>
<td><strong>Bring site collection</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No of can banks</td>
<td>29</td>
<td>59</td>
</tr>
<tr>
<td>No of domes</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>Collection frequency</td>
<td>Fortnightly</td>
<td>Fortnightly</td>
</tr>
<tr>
<td>Truck (can bank)</td>
<td>Two-compartment (18 t)</td>
<td>Two-compartment (18 t)</td>
</tr>
<tr>
<td>Truck (dome)</td>
<td>Single load (26 t)</td>
<td></td>
</tr>
<tr>
<td>Shared collection (can bank)</td>
<td>paper</td>
<td>paper</td>
</tr>
<tr>
<td><strong>Total Al recovery rate</strong></td>
<td>3%</td>
<td>19%</td>
</tr>
</tbody>
</table>
5.4 Case studies

Table 5.2: Parameters for increased kerbside collection scenarios.

<table>
<thead>
<tr>
<th>Recovery rate (%)</th>
<th>30</th>
<th>50</th>
<th>70</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower Hamlets</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No of collection points</td>
<td>27515</td>
<td>44701</td>
<td>61850</td>
<td>79000</td>
</tr>
<tr>
<td>Distance between collection points (m)</td>
<td>16</td>
<td>12</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>Waverley</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No of collection points</td>
<td>18882</td>
<td>25941</td>
<td>33000</td>
<td>48000</td>
</tr>
<tr>
<td>Distance between collection points (m)</td>
<td>40</td>
<td>34</td>
<td>30</td>
<td>66</td>
</tr>
</tbody>
</table>

Deposit system

Another way of increasing the recovery, as mentioned before, is to use a deposit system. The transport requirement has been calculated for 30, 50, 70 and 90% recovery. This has been done in two different ways:

- **Case A**: Having a fixed number of machines and retailers independent of the recovery rate, but increasing the frequency of collection with increasing recovery rate.

- **Case B**: Having a fixed frequency of collection independent of recovery rate, but increasing the number of machines with increasing recovery rate.

Table 5.3 shows the corresponding numbers of retailers, machines and collection frequencies. Appendices B and C explain how these figures have been obtained and also include transport calculations, while appendix F gives the names and locations of the retailers included in the study.
5.5 Results

Table 5.3: Parameters for deposit scenarios.

<table>
<thead>
<tr>
<th></th>
<th>Case A</th>
<th></th>
<th>Case B</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovery rate (%)</td>
<td>30</td>
<td>50</td>
<td>70</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>70</td>
<td>90</td>
</tr>
</tbody>
</table>

Tower Hamlets

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>No of retailers</td>
<td>67</td>
<td>67</td>
<td>67</td>
<td>67</td>
</tr>
<tr>
<td>No of reverse vending machines</td>
<td>85</td>
<td>85</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>Collections per year</td>
<td>13</td>
<td>21</td>
<td>30</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>39</td>
<td>39</td>
<td>39</td>
<td>39</td>
</tr>
</tbody>
</table>

Waverley

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>No of retailers</td>
<td>34</td>
<td>34</td>
<td>34</td>
<td>34</td>
</tr>
<tr>
<td>No of reverse vending machines</td>
<td>44</td>
<td>44</td>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td>Collections per year</td>
<td>13</td>
<td>21</td>
<td>30</td>
<td>39</td>
</tr>
<tr>
<td></td>
<td>39</td>
<td>39</td>
<td>39</td>
<td>39</td>
</tr>
</tbody>
</table>

5.5 Results

Initially, as described in section 5.4, two different cases were studied for the deposit systems in Tower Hamlets and Waverley. The results show that there is little difference in transport need in terms of distance between these cases. Hence, the strategy for installing the deposit system does not seem to have any discernible effect on the required transport; therefore when presenting the results only case B will be referred to, i.e. the case of having a fixed frequency of collection independent of recovery rate, but increasing the number of reverse vending machines with increasing recovery rate.
5.5 Results

5.5.1 Environmental impact

The analysis showed that when the environmental impacts of the whole life cycle of the aluminium can are normalised to the impacts of Western Europe in 1990, the largest contribution are in the impacts: Global Warming Potential (GWP), Abiotic depletion and Marine aquatic ecotoxicity. This is the case when using solely primary aluminium but also when using part recycled aluminium. This is due to the energy intensive production of aluminium and also to emissions to soil and water that are released in the extraction and processing of the bauxite. Only these three main impacts will therefore be discussed.

Figure 5.9A shows the global warming potential (GWP) per tonne of collected UBCs for the two different types of collection systems in Tower Hamlets. The transport need decreases with increasing recovery rate, both for the kerbside collection structure (collection from both kerbsides and can banks) and for the deposit system. There is a very rapid decrease in GWP from 3 to 30% recovery for the kerbside structure. The reason is that in the current situation (3%), collection from bring sites requires a lot more transport than collection from kerbsides, and it has been assumed that only the kerbside collection increases and that the collection from can banks stays constant in the scenarios of higher recovery. It therefore seems that the current collection structure could be much more efficient if kerbside collection covered all households and people really used this service. The deposit system requires a little more transport than does the kerbside scheme, in part due to the fact that it is a single load transport whereas the kerbside scheme is a shared-load transport, but also due to the different transport routes of the two systems.

In the Waverley scenarios, the GWP per collected tonne changes non-linearly with the recovery rate for both systems, although the effect is not dramatic (Figure 5.9B). In the kerbside scheme, it has been assumed that the number of households is increased to include all households in the four main towns in Waverley at 70% recovery. For 90% recovery all households in the whole borough have been included, resulting in a larger average distance between households. That is why the transport increases at 90% recovery compared to 70% recovery. In comparison with Tower Hamlets, both systems in Waverley require more transport per collected tonne. This is, of course, due to the larger distances between households and between retailers.
Figure 5.9: GWP per tonne of collected Al for the two different collection systems. A: Tower Hamlets, B: Waverley.
5.5 Results

Table 5.4: GWP (kg CO$_2$ eq) per kg of Al cans - Area: Tower Hamlets.

<table>
<thead>
<tr>
<th>Recycling rate (%)</th>
<th>3</th>
<th>50</th>
<th>70</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin Al production</td>
<td>$1.1 \times 10^1$</td>
<td>$7.6 \times 10^0$</td>
<td>$5.5 \times 10^0$</td>
<td>$3.4 \times 10^0$</td>
</tr>
<tr>
<td>Rolling sheet</td>
<td>$4.4 \times 10^{-1}$</td>
<td>$4.4 \times 10^{-1}$</td>
<td>$4.4 \times 10^{-1}$</td>
<td>$4.4 \times 10^{-1}$</td>
</tr>
<tr>
<td>Remelting of UBCs</td>
<td>$1.3 \times 10^{-2}$</td>
<td>$1.3 \times 10^{-1}$</td>
<td>$2.1 \times 10^{-1}$</td>
<td>$2.9 \times 10^{-1}$</td>
</tr>
<tr>
<td>Miscellaneous processes</td>
<td>$3.4 \times 10^{-1}$</td>
<td>$3.4 \times 10^{-1}$</td>
<td>$3.4 \times 10^{-1}$</td>
<td>$3.4 \times 10^{-1}$</td>
</tr>
</tbody>
</table>

Kerbside system

| Collection of UBCs  | $2.9 \times 10^{-3}$ | $1.6 \times 10^{-2}$ | $2.7 \times 10^{-2}$ | $3.7 \times 10^{-2}$ | $4.7 \times 10^{-2}$ |
| Contribution to total | 0.03% | 0.19% | 0.42% | 0.83% | 1.90% |

Deposit system

| Collection of UBCs  | - | $1.9 \times 10^{-2}$ | $3.1 \times 10^{-2}$ | $4.3 \times 10^{-2}$ | $5.5 \times 10^{-2}$ |
| Contribution to total | - | 0.22% | 0.48% | 0.95% | 2.20% |

...in Waverley.

The collection stage put into the context of the whole life cycle of aluminium cans can be seen in Tables 5.4 to 5.9 in terms of GWP, abiotic depletion and marine aquatic ecotoxicity. Each life cycle scenario includes a different collection system. The UBC collection here incorporates both local collection to a depot and transport to the remelter. It is clear that the environmental significance of the collection stage is negligible in all life cycle scenarios regardless of how the UBCs have been collected.

5.5.2 Economic cost

The cost of collection, including local collection transport and transport to the remelting plant in Warrington, has been estimated for the different scenarios. The collection cost takes into account the cost of fuel, driver, discounting of vehicle and overheads. The cost of the deposit is not...
5.5 Results

<table>
<thead>
<tr>
<th>Recycling rate (%)</th>
<th>19</th>
<th>30</th>
<th>50</th>
<th>70</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin Al production</td>
<td>$8.8 \times 10^0$</td>
<td>$7.6 \times 10^0$</td>
<td>$5.5 \times 10^0$</td>
<td>$3.4 \times 10^0$</td>
<td>$1.3 \times 10^0$</td>
</tr>
<tr>
<td>Rolling sheet</td>
<td>$4.4 \times 10^{-1}$</td>
<td>$4.4 \times 10^{-1}$</td>
<td>$4.4 \times 10^{-1}$</td>
<td>$4.4 \times 10^{-1}$</td>
<td>$4.4 \times 10^{-1}$</td>
</tr>
<tr>
<td>Remelting of UBCs</td>
<td>$8.0 \times 10^{-2}$</td>
<td>$1.3 \times 10^{-1}$</td>
<td>$2.1 \times 10^{-1}$</td>
<td>$2.9 \times 10^{-1}$</td>
<td>$3.8 \times 10^{-1}$</td>
</tr>
<tr>
<td>Miscellaneous processes</td>
<td>$3.4 \times 10^{-1}$</td>
<td>$3.4 \times 10^{-1}$</td>
<td>$3.4 \times 10^{-1}$</td>
<td>$3.4 \times 10^{-1}$</td>
<td>$3.4 \times 10^{-1}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Kerbside system</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Collection of UBCs</td>
<td>$1.7 \times 10^{-2}$</td>
<td>$2.4 \times 10^{-2}$</td>
<td>$3.8 \times 10^{-2}$</td>
<td>$5.2 \times 10^{-2}$</td>
<td>$7.8 \times 10^{-2}$</td>
</tr>
<tr>
<td>Contribution to total</td>
<td>0.17%</td>
<td>0.28%</td>
<td>0.58%</td>
<td>1.16%</td>
<td>3.10%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Deposit system</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Collection of UBCs</td>
<td>-</td>
<td>$3.8 \times 10^{-2}$</td>
<td>$6.2 \times 10^{-2}$</td>
<td>$7.8 \times 10^{-2}$</td>
<td>$1.0 \times 10^{-1}$</td>
</tr>
<tr>
<td>Contribution to total</td>
<td>-</td>
<td>0.44%</td>
<td>0.94%</td>
<td>1.71%</td>
<td>4.02%</td>
</tr>
</tbody>
</table>

considered as the consumer is reimbursed for this. The cost figures have been gathered from the Freight Transport Association (FTA 1998). The cost has then been compared to the amount that is paid at the factory gate for baled UBCs (MetalBulletin 2001). Tables 5.10 and 5.11 show that the cost of collection is much smaller than the value of the collected UBCs. This holds true for both collection systems in both areas, although the Waverley collection is more costly than the Tower Hamlets collection due to longer transport distances locally but also because Waverley is situated further away from the remelting plant.
5.6 Discussion and Conclusions

<table>
<thead>
<tr>
<th>Recycling rate (%)</th>
<th>3</th>
<th>30</th>
<th>50</th>
<th>70</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin Al production</td>
<td>$5.3 \times 10^{-2}$</td>
<td>$3.8 \times 10^{-2}$</td>
<td>$2.8 \times 10^{-2}$</td>
<td>$1.7 \times 10^{-2}$</td>
<td>$6.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>Remelting of UBCs</td>
<td>$9.7 \times 10^{-5}$</td>
<td>$9.7 \times 10^{-4}$</td>
<td>$1.6 \times 10^{-3}$</td>
<td>$2.3 \times 10^{-3}$</td>
<td>$2.9 \times 10^{-3}$</td>
</tr>
<tr>
<td>Miscellaneous processes</td>
<td>$5.4 \times 10^{-3}$</td>
<td>$5.4 \times 10^{-3}$</td>
<td>$5.4 \times 10^{-3}$</td>
<td>$5.4 \times 10^{-3}$</td>
<td>$5.4 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Kerbside system

| Collection of UBCs | $1.8 \times 10^{-5}$ | $1.0 \times 10^{-4}$ | $1.7 \times 10^{-4}$ | $2.3 \times 10^{-4}$ | $2.9 \times 10^{-4}$ |
| Contribution to total | 0.03% | 0.23% | 0.49% | 0.94% | 1.95% |

Deposit system

| Collection of UBCs | - | $1.2 \times 10^{-4}$ | $1.9 \times 10^{-4}$ | $2.7 \times 10^{-4}$ | $3.4 \times 10^{-4}$ |
| Contribution to total | - | 0.26% | 0.55% | 1.07% | 2.26% |

5.6 Discussion and Conclusions

Overall, it can be said for both areas that the deposit system requires slightly more transport than does the kerbside scheme; however, the differences are not significant. But there might be other aspects that separate the two systems; is it feasible to assume that a 90% recovery rate can be achieved just by providing a kerbside collection service that covers all households? It has been estimated that only 60% of used cans arise in the households; achieving very high recovery rates relying on kerbside collection alone will therefore be difficult (Griffin 2001). In the deposit system, consumers have a financial incentive to return their cans, making it more realistic perhaps to achieve a 90% recovery rate. It is also worth mentioning that collection from retailers could in practice be combined with delivery of new stock to the retailer, resulting in even less transport required for collection in the deposit system.

In the context of the whole life-cycle of aluminium cans, the analysis of the systems shows that the collection stage is quite insignificant in terms of contributing to the environmental bur-
5.6 Discussion and Conclusions

Table 5.7: Abiotic depletion (kg Sb eq) per kg of Al cans - Area: Waverley.

<table>
<thead>
<tr>
<th>Recycling rate (%)</th>
<th>19</th>
<th>30</th>
<th>50</th>
<th>70</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin Al production</td>
<td>$4.4 \times 10^{-2}$</td>
<td>$3.8 \times 10^{-2}$</td>
<td>$2.8 \times 10^{-2}$</td>
<td>$1.7 \times 10^{-2}$</td>
<td>$6.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>Remelting of UBCs</td>
<td>$6.1 \times 10^{-4}$</td>
<td>$9.7 \times 10^{-4}$</td>
<td>$1.6 \times 10^{-3}$</td>
<td>$2.3 \times 10^{-3}$</td>
<td>$2.9 \times 10^{-3}$</td>
</tr>
<tr>
<td>Miscellaneous processes</td>
<td>$5.4 \times 10^{-3}$</td>
<td>$5.4 \times 10^{-3}$</td>
<td>$5.4 \times 10^{-3}$</td>
<td>$5.4 \times 10^{-3}$</td>
<td>$5.4 \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Kerbside system

| Collection of UBCs | $1.0 \times 10^{-4}$ | $1.5 \times 10^{-4}$ | $2.4 \times 10^{-4}$ | $3.3 \times 10^{-4}$ | $4.8 \times 10^{-4}$ |
| Contribution to total | 0.21% | 0.33% | 0.68% | 1.30% | 3.20% |

Deposit system

| Collection of UBCs | -     | $2.4 \times 10^{-4}$ | $3.8 \times 10^{-4}$ | $4.9 \times 10^{-4}$ | $6.3 \times 10^{-4}$ |
| Contribution to total | -     | 0.53% | 1.10% | 1.93% | 4.13% |

dens. The savings in environmental impact of recovering and recycling the cans after use far outweigh the impact from collecting them. This very much highlights the need for functional and easy to use recovery structures for aluminium cans in the UK. Furthermore, the cost of collection is lower than the economic value of the collected cans, providing an economic incentive to perform the collection.

This study might be limited as it explores the potential environmental and economic cost of the collection of cans in only two local authorities in the UK. However, as the analysis shows, there are only small differences in transport requirements between the different types of collection systems in both areas, it is unlikely the difference will be more significant in any other area. Consequently, the way the aluminium packaging is collected is less important; what is important is that it is collected.

It is important to point out that the environmental and economic costs of collection is small compared to the savings in recycling the cans in the case of aluminium, but for other materials the results might be very different. Exploring the significance of the collection stage in the context...
5.6 Discussion and Conclusions

Table 5.8: Mar. eq. ecotox. (kg 1,4-DB eq) per kg of Al cans - Area: Tower Hamlets.

<table>
<thead>
<tr>
<th>Recycling rate (%)</th>
<th>3</th>
<th>30</th>
<th>50</th>
<th>70</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin Al production</td>
<td>3.3 x 10^3</td>
<td>2.4 x 10^3</td>
<td>1.8 x 10^3</td>
<td>1.1 x 10^3</td>
<td>4.1 x 10^2</td>
</tr>
<tr>
<td>Rolling sheet</td>
<td>1.8 x 10^2</td>
<td>1.8 x 10^2</td>
<td>1.8 x 10^2</td>
<td>1.8 x 10^2</td>
<td>1.8 x 10^2</td>
</tr>
<tr>
<td>Remelting of UBCs</td>
<td>1.5 x 10^1</td>
<td>1.5 x 10^2</td>
<td>2.5 x 10^2</td>
<td>3.6 x 10^2</td>
<td>4.6 x 10^2</td>
</tr>
<tr>
<td>Miscellaneous processes</td>
<td>2.4 x 10^2</td>
<td>2.4 x 10^2</td>
<td>2.4 x 10^2</td>
<td>2.4 x 10^2</td>
<td>2.4 x 10^2</td>
</tr>
</tbody>
</table>

Kerbside system

| Collection of UBCs | 1.2 x 10^-1 | 6.9 x 10^-1 | 1.2 x 10^0 | 1.6 x 10^0 | 2.0 x 10^0 |
| Contribution to total | 0.00% | 0.02% | 0.05% | 0.08% | 0.15% |

Deposit system

| Collection of UBCs | 8.0 x 10^-1 | 1.3 x 10^0 | 1.8 x 10^0 | 2.3 x 10^0 |
| Contribution to total | 0.03% | 0.05% | 0.10% | 0.18% |

of the whole life cycle of packaging for other materials therefore represents a research need. Furthermore, the economic costs considered here are the costs directly related to transport; in further analyses other operational costs should also be taken into account.
### 5.6 Discussion and Conclusions

#### Table 5.9: Mar. eq. ecotoxicity (kg 1.4-DB eq) per kg of Al cans - Area: Waverley.

<table>
<thead>
<tr>
<th>Recycling rate (%)</th>
<th>19</th>
<th>30</th>
<th>50</th>
<th>70</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virgin Al production</td>
<td>$2.8 \times 10^3$</td>
<td>$2.4 \times 10^3$</td>
<td>$1.8 \times 10^3$</td>
<td>$1.1 \times 10^3$</td>
<td>$4.0 \times 10^2$</td>
</tr>
<tr>
<td>Rolling sheet</td>
<td>$1.8 \times 10^2$</td>
<td>$1.8 \times 10^2$</td>
<td>$1.8 \times 10^2$</td>
<td>$1.8 \times 10^2$</td>
<td>$1.8 \times 10^2$</td>
</tr>
<tr>
<td>Remelting of UBCs</td>
<td>$9.7 \times 10^1$</td>
<td>$1.5 \times 10^2$</td>
<td>$2.6 \times 10^2$</td>
<td>$3.6 \times 10^2$</td>
<td>$4.6 \times 10^2$</td>
</tr>
<tr>
<td>Miscellaneous processes</td>
<td>$2.4 \times 10^2$</td>
<td>$2.4 \times 10^2$</td>
<td>$2.4 \times 10^2$</td>
<td>$2.4 \times 10^2$</td>
<td>$2.4 \times 10^2$</td>
</tr>
</tbody>
</table>

**Kerbside system**

| Collection of UBCs    | $7.0 \times 10^{-1}$ | $1.0 \times 10^0$ | $1.6 \times 10^0$ | $2.2 \times 10^0$ | $3.3 \times 10^0$ |
| Contribution to total | 0.02%               | 0.03%             | 0.07%             | 0.12%             | 0.25%             |

**Deposit system**

| Collection of UBCs   | -                       | $1.6 \times 10^0$ | $2.6 \times 10^0$ | $3.3 \times 10^0$ | $4.3 \times 10^0$ |
| Contribution to total| -                       | 0.05%             | 0.11%             | 0.18%             | 0.33%             |

#### Table 5.10: Cost of collection compared to economic value of baled UBCs delivered at remelting plant - Area: Tower Hamlets.

<table>
<thead>
<tr>
<th>Recycling rate (%)</th>
<th>3</th>
<th>30</th>
<th>50</th>
<th>70</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value of collected UBCs (£)</td>
<td>4 711</td>
<td>41 067</td>
<td>68 444</td>
<td>95 822</td>
<td>123 200</td>
</tr>
</tbody>
</table>

**Kerbside system**

| Cost of collection (£) | 566 | 3 067 | 5 206 | 7 095 | 8 762 |

**Deposit system**

| Cost of collection (£) | -   | 3 984 | 6 537 | 8 948 | 11 309 |
Table 5.11: Cost of collection compared to economic value of baled UBCs delivered at remelting plant - Area: Waverley.

<table>
<thead>
<tr>
<th>Recycling rate (%)</th>
<th>19</th>
<th>30</th>
<th>50</th>
<th>70</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value of collected UBCs (£)</td>
<td>13 705</td>
<td>21 226</td>
<td>35 377</td>
<td>49 528</td>
<td>63 678</td>
</tr>
<tr>
<td><strong>Kerbside system</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of collection (£)</td>
<td>1 960</td>
<td>2 751</td>
<td>4 270</td>
<td>5 780</td>
<td>9 124</td>
</tr>
<tr>
<td><strong>Deposit system</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost of collection (£)</td>
<td></td>
<td>5 039</td>
<td>8 105</td>
<td>9 960</td>
<td>13 077</td>
</tr>
</tbody>
</table>
Concluding remarks

In the context of aiming to close the cycles of iron, steel and aluminium in the UK, this thesis set out to address three main issues that need to be taken into account if a more sustainable use of these metals is to be achieved. In short, the issues are: (1) How closed are the cycles of these metals at present? (2) How can contamination in the scrap cycle be avoided? and finally, (3) How can dispersed scrap be recovered? The next section will summarise how these questions have been addressed in the study and what conclusions can be drawn from the findings of the analyses.

6.1 SUMMARY

6.1.1 Recycling rates

The first issue concerns the size and location in the material cycle of losses of iron, steel and aluminium in the UK. To investigate this, a time series material flow analysis (MFA) methodology has been developed. The methodology enables tracking the flows of iron, steel and aluminium through the UK economic system. For materials like these, where the goods life-spans can be significant and the life-spans differ between applications, it is vital to include a temporal dimension in the MFA as different products available as scrap entered use at quite different past times.
In this analysis, residence time distribution theory used in chemical engineering science has been successfully applied to simulate the delay of goods in use. This has not been done previously and we demonstrate that this methodology proves useful when dealing with materials that are contained in products with significant life-spans.

The analysis shows that using a distribution of the life-span when modelling the delay of goods in the use phase is more important when the input of goods into use shows a significant increase or decrease over time. In the case of iron and steel in the UK, the input into use of iron and steel containing goods has been fairly stable over the past 25 years, so the modelled overall recycling rate was not significantly affected by the representation of service lives. However, in the case of aluminium, where there has been a dramatic increase of aluminium input into society over the past two decades, it then proved more important to model the end-of-life scrap arisings using distributions to describe the lives of goods in use.

The iron and steel MFA shows that for 2001, the estimated release of end-of-life scrap and prompt scrap significantly exceeds the documented amount of scrap that is consumed within the country or is exported. This indicates a loss of end-of-life scrap of around 30%, corresponding to three and a half million tonnes per annum. Possible scenarios of recycling for each sector have been modelled, using literature recycling rates where available. The scenarios suggest that a significant part of the scrap loss originates from products like domestic appliances, hand tools, metal furniture and other products that are included in the goods categories, metal goods, electrical and mechanical engineering. Current take-back legislation that concerns metals is mostly focused on increasing recovery from packaging, vehicles and electronic waste (see section 1.2.2). Our results indicate that the focus is appropriate but that general metal goods, such as furniture, non-electric tools, kitchen articles etc, needs further drivers for recovery.

For aluminium, the analysis also shows that for 2001 the estimated amount of released prompt and end-of-life scrap exceeds the documented amount of scrap that is consumed within the country or is exported. There is a loss of end-of-life scrap of around 160 thousand tonnes. Recycling scenarios of each sector suggest a significant part of the scrap loss originates from products in the categories, packaging and consumer durables. Again, this indicates that the focus of current take-back legislation is appropriate, but that general consumer durables, such as furniture, needs
6.1 Summary

Further attention.

It is well recognised that successful application of the methodology depends largely on data availability. Difficulties in acquiring the necessary data were experienced, but guidance from experts in the industries and their respective trade organisations helped in clearing most of the data gaps. For both metals, a level of closure was achieved in the MFAs, in that metal emerging from use could be largely balanced with metal being recycled and metal sent to landfill. This demonstrates that the methodology developed is reliable and can be used to explore other materials used in society.

Use of the kind of model developed in this work could prove a vital instrument in formulating comprehensive recycling policies. By identifying potential leakage problems and highlighting product groups that contribute to the largest material losses, this gives valuable direction on where the focus should be put to increase the recovery. Furthermore, the model can also be used to predict future scrap arisings, in particular for product groups with long life-spans, which can facilitate metal production capacity planning and policy developments.

6.1.2 Scrap quality

There is room for improvements in terms of increasing the recovery of end-of-life scrap in the UK. What will happen if high recycling rates are achieved and maintained—will there be a problem with contamination build-up? A methodology for exploring potential contamination build-up in the metal cycle has been developed. The methodology builds on the MFA methodology, incorporating the temporal dimension. The contamination model includes the production of metal in the UK, so that different alloying elements added to this process can be taken into account. The study has focused on developing a general methodology for examining the concentration of a particular element in metal cycles in the UK. It examines consequences to the composition of the scrap flows depending on different future scenarios.

A case study of exploring potential build-up of tin in the iron and steel cycle between 2000 and 2020 was performed to demonstrate the model. The different scenarios examined are: constant recycling rates and scrap export over time, increased recycling rates and decreased scrap export over time. Two ways of aggregating the scrap before remelting were also examined: (1)
by mixing all the scrap together independently of how much tin it contains and (2) by separating
the scrap into its original metal product components and recycling it in a 'closed loop' recycling
pattern. When the recycling rates and scrap export are kept constant in time at the 2000 level,
no build-up occurs in the system. As so much scrap is exported (about four million tonnes per
year), quite a lot of virgin material is needed in UK production, which means the tin content is di­
luted. Not surprisingly, both increasing the recycling rates and decreasing the scrap export leads
to increases in the concentration of tin in the metal products. By separating the scrap before
remelting and choosing more carefully what type of scrap goes to which production, build-up
can be avoided. However, for a metal product like tin coated sheet, recycling all old tin sheet
back into this product naturally results in a dramatic increase in the tin concentration. At least
this is the case when the system is relatively 'closed', having a 90% EOL recycling rate and not
exporting any scrap. In products such as this it is therefore necessary to either separate the tin
from the sheet before remelting or to use this scrap in a product with higher acceptance of tin,
e.g. cast iron.

The tin case study shows the flexibility of the model to explore concentrations of contami­
nants in the scrap cycle depending on different future scenarios of trade, recycling rates and scrap
disaggregation. Studies exploring potential contamination build-up and how it can be avoided are
vital to ensure the long-term sustainable use of metals. The model allows different scenarios to
be examined and if more realistic data can be obtained in the future, the model could be useful in
predicting the build-up of contamination of different elements; the model can be used to explore
build-up in not only the steel cycle, but in other metal cycles too.

6.1.3 Collection

The MFA studies show there are still improvements to be made in recovering end-of-life iron/steel
and aluminium scrap. Small products as packaging stand out as a major challenge for both met­
als. Therefore, a study was performed to investigate possible ways of collecting beverage cans.
Two main issues are explored: (1) Does the transport intensity differ significantly between differ­
ent types of collection systems, recovery rates and population density? and (2) How significant is
the environmental impact of the collection stage compared to the whole life cycle of the can? To
explore this, a case study was performed, analysing collection of used aluminium beverage cans (UBCs). Two areas were investigated: Tower Hamlets in London with high population density and Waverley in Surrey with lower population density. The current collection systems in both areas, kerbside collection combined with bring site schemes, was compared to a deposit system in which consumers return the UBCs to their retailer. The environmental impact of the transport in the collection systems was analysed using Life Cycle Assessment (LCA) methodology.

Overall, it can be said for both areas that the deposit system requires slightly more transport than the kerbside scheme, translating into higher environmental impact for the transport in the deposit system. However, the difference between the systems is not significant. But there might be other aspects that separate the two systems: is it feasible to assume that very high recycling rates can be achieved just by providing a kerbside collection service that covers all households? It has been estimated that only 60% of used cans arise in the households; achieving very high recovery rates relying on kerbside collection alone will therefore be difficult (Griffin 2001). In the deposit system, consumers have a financial incentive to return their cans, making it more realistic perhaps to achieve a 90% recovery rate. It is also worth mentioning that collection from retailers could in practice be combined with delivery of new stock to the retailer, resulting in even less transport required for collection in the deposit system.

In the context of the whole life-cycle of aluminium cans, the analysis of the systems shows that the collection stage is quite insignificant in terms of contributing to the environmental burdens. The savings in environmental impact of recovering and recycling the cans after use far outweigh the impact of collecting them. This very much highlights the need for functional and easy to use recovery structures for aluminium cans in the UK. Furthermore, the cost of collection is lower than the economic value of the collected cans (transport costs were between 12 and 24% of the value), providing an economic incentive to perform the collection.

This collection study might be limited as it explores the potential environmental and economic cost of collection of cans in only two local authorities in the UK. However, as the analysis shows there are small differences in transport requirements between the different types of collection systems in both areas, it is unlikely the difference will be more significant in any other area. Consequently, the way the aluminium packaging is collected is less important, what is important
6.2 Recommendations for further work

is that it is collected.

6.2 RECOMMENDATIONS FOR FURTHER WORK

6.2.1 Data quality

In the MFAs the goods containing iron, steel and aluminium was grouped into fairly broad categories, this is due to the data being available in this format. It would have been more beneficial to have less aggregated information on metal containing goods as this would produce more interesting results. For example, the goods category ‘Electrical engineering’ contains various types of goods, ranging from domestic appliances to large electrical machines, goods that might have very different life-spans. This is captured to a certain extent in the modelling, in that a distribution is used for the life-span. Nevertheless, more disaggregated data would benefit the results as more information would then be available as to from which specific types of goods losses occur.

Overall, there is need for more detailed information on the distribution of life-spans, or age distribution of different types of goods. Furthermore, the life-spans distributions of goods vary over time, as pointed out by van Schaik & Reuter (2004), and further data on this aspect is also needed. This is particularly important when analysing material that is contained in goods with significant life-spans and that has large fluctuations in demand over time. In general, there is a lack of information regarding the statistical quality of the data used in this analysis, as in most MFA studies. Highlighting this, and presenting the model and showing what data it requires, shows the information which industry needs to provide for this kind of modelling approach to be of practical value.

6.2.2 Modelling end-of-life scrap arisings

In this work, life-span distribution data have been used to estimate the arisings of end-of-life scrap. As was outlined in section 3.3.1, by using the theory of residence time distribution, it should be possible to estimate the EOL arisings by using information on the distribution of age of the goods in use. To collect the necessary data and explore if this theory works in reality,
would be an interesting research task.

6.2.3 Alloy composition

There are a vast number of alloying elements used in iron, steel and aluminium production, and it is quite difficult to acquire information on alloy consumption and specifications of each different metal product produced in the UK. This means that the type of modelling developed in this study can become very data intensive and thereby it can be a major challenge to attain the necessary information. In order to attain a more complete picture of possible future build-up scenarios, more detailed information on metal products and their alloy composition needs to be collected so that further analysis can be performed exploring potential contamination of several elements, especially as some elements only cause concern in conjunction with other elements. Furthermore, metals participate in a system of linked cycles and should therefore not be studied independently. To understand the interdependence of metal cycles, further studies which incorporate all significant metal flows need to be carried out, following the approach initiated by Verhoef et al. (2004).

6.2.4 Collection of other materials

In the study of collection of beverage cans it was pointed out that the environmental cost of collection was insignificant compared to the savings in recycling the cans. This is the case for aluminium, but for other materials the results might be very different. Exploring the significance of the collection stage in the context of the whole life cycle of materials used for packaging and other dispersed products therefore represents a research need.

6.2.5 Material flow analysis

Material flow analyses of other materials than iron, steel and aluminium are also needed to provide the prerequisite for creating a sustainable industrial ecology. The methodology developed here, could prove useful when exploring other metals or materials with significant life-spans. To further improve the understanding of material flows and their environmental implications, MFA
6.2 Recommendations for further work

could usefully be linked to streamlined Life Cycle Assessment (LCA). Some initial work has been carried out at the University of Surrey in this respect (Azapagic & Sinclair 2004), and also at Delft University of Technology by Verhoef et al. (2004), but further work is needed.


References


Harris, David 2000. Aluminium Federation Ltd. Personal communication.


Appendix A

Categories of traded goods

Trade statistics are given according to SITC (Standard Industry Trade Classifications) codes. These classifications have been revised three times since 1968; only the latest classification codes are shown here. In the material flow analysis, the classifications valid for the particular year to which data refer have been used. Data on product groups that contain iron/steel and aluminium have been collected; the product groups are given in tables A.1 and A.2 for iron & steel and aluminium respectively. The goods are grouped into the categories applied in the material flow analysis.

### Table A.1: SITC codes of traded iron and steel containing goods.

<table>
<thead>
<tr>
<th>SITC code</th>
<th>Goods category</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical engineering</strong></td>
<td></td>
</tr>
<tr>
<td>721</td>
<td>agricultural machinery (excl. tractors) and parts thereof</td>
</tr>
<tr>
<td>722</td>
<td>tractors (O/T those of 744)</td>
</tr>
<tr>
<td>73</td>
<td>metalworking machinery</td>
</tr>
<tr>
<td>725</td>
<td>paper mill and pulp mill machinery</td>
</tr>
<tr>
<td>724</td>
<td>textile and leather machinery, and parts thereof, NES</td>
</tr>
<tr>
<td>726</td>
<td>printing and bookbinding machinery</td>
</tr>
<tr>
<td>727</td>
<td>food-processing machines (excl. domestic)</td>
</tr>
<tr>
<td>728</td>
<td>other machinery, NES</td>
</tr>
<tr>
<td>74</td>
<td>general industry machinery and equipment, NES</td>
</tr>
<tr>
<td>712</td>
<td>steam turbines and other vapour turbines, and parts thereof, NES</td>
</tr>
<tr>
<td>713</td>
<td>internal combustion piston engines, and parts thereof, NES</td>
</tr>
<tr>
<td>714</td>
<td>engines and motors (O/T those of 712, 713 &amp; 718); parts, NES, of these engines</td>
</tr>
<tr>
<td></td>
<td>and motors</td>
</tr>
<tr>
<td>716</td>
<td>rotating electric plant and parts thereof, NES</td>
</tr>
<tr>
<td>718</td>
<td>other power generating machinery and parts thereof</td>
</tr>
<tr>
<td><strong>Electrical engineering</strong></td>
<td></td>
</tr>
<tr>
<td>697.31</td>
<td>domestic cooking appliances (eg cookers) &amp; plate warmers, non-el., of I or S</td>
</tr>
<tr>
<td>697.32</td>
<td>domestic stoves, grates &amp; similar non-el. space heaters, of I or S</td>
</tr>
<tr>
<td>697.33</td>
<td>parts of I or S, of the appliances of .31 and .32</td>
</tr>
<tr>
<td>76</td>
<td>telecommunications and sound recording and reproducing apparatus and equipment</td>
</tr>
<tr>
<td>SITC code</td>
<td>Goods category</td>
</tr>
<tr>
<td>-----------</td>
<td>-------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>77</td>
<td>electrical machinery, apparatus and appliances, NES and electrical parts thereof</td>
</tr>
<tr>
<td>75</td>
<td>office machines and automatic data processing machines</td>
</tr>
<tr>
<td></td>
<td><strong>Shipbuilding</strong></td>
</tr>
<tr>
<td></td>
<td>(only reported in its own category in the first classifications (R0), now in category 79)</td>
</tr>
<tr>
<td></td>
<td><strong>Vehicles</strong></td>
</tr>
<tr>
<td>781</td>
<td>motor cars and other m/vehicles principally for transport of persons</td>
</tr>
<tr>
<td></td>
<td>(O/T public transport vehicles)</td>
</tr>
<tr>
<td>782</td>
<td>motor vehicles for the transport of goods and spec. purposes vehicles</td>
</tr>
<tr>
<td>783</td>
<td>road motor vehicles, NES</td>
</tr>
<tr>
<td>784</td>
<td>parts and accessories of motor vehicles</td>
</tr>
<tr>
<td>785</td>
<td>motor cycles (incl. mopeds) and cycles, motorized and non-motorized</td>
</tr>
<tr>
<td>786</td>
<td>trailers and semi-trailers; other vehicles not mech. propelled</td>
</tr>
<tr>
<td>79</td>
<td>other transport equipment (incl. railway vehicles, aircraft, ships etc)</td>
</tr>
<tr>
<td></td>
<td><strong>Structural steelwork, building and civil engineering</strong></td>
</tr>
<tr>
<td>691.1</td>
<td>-structures (O/T pre-fab. buildings) &amp; parts of I or S; plates shapes etc,</td>
</tr>
<tr>
<td></td>
<td>PRD for structures, of I/S</td>
</tr>
<tr>
<td>694.1</td>
<td>nails, tacks, drawing pins &amp; similar articles, of I or Steel</td>
</tr>
<tr>
<td></td>
<td>(incl. those with heads of other material except Cu)</td>
</tr>
<tr>
<td>694.2</td>
<td>screws, bolts, nuts, screw hooks, rivets, cotters, cotter-pins, coach screws &amp; similar articles of I or S</td>
</tr>
</tbody>
</table>
Table A.1: (continued)

<table>
<thead>
<tr>
<th>SITC code</th>
<th>Goods category</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Metal goods</strong></td>
<td></td>
</tr>
<tr>
<td>695</td>
<td>tools for use in the hand or in machines; eg saws, files, spanners, hammers, chisels, drilling tools, knives etc</td>
</tr>
<tr>
<td>696</td>
<td>cutlery incl scissors, razor blades etc</td>
</tr>
<tr>
<td>697.41</td>
<td>household articles and parts thereof, NES, of I or S</td>
</tr>
<tr>
<td>697.44</td>
<td>I or S wool, pot scourers and scouring or polishing pads, gloves and the like, of I or S</td>
</tr>
<tr>
<td>697.51</td>
<td>sanitary ware and parts thereof, NES, of I or S</td>
</tr>
<tr>
<td>697.8</td>
<td>household appliances, decorative articles, frames and mirrors, of base metal, NES</td>
</tr>
<tr>
<td>699.1</td>
<td>locksmiths' wares, safes, strong boxes, etc and hardware, NES, of base metal</td>
</tr>
<tr>
<td>699.2</td>
<td>chain and parts thereof, of I or S</td>
</tr>
<tr>
<td>699.31</td>
<td>sewing and knitting needles, crochet hooks etc, of I or S</td>
</tr>
<tr>
<td>699.32</td>
<td>safety pins and other pins, of I or S</td>
</tr>
<tr>
<td>699.41</td>
<td>springs and leaves for springs, of I or S</td>
</tr>
<tr>
<td>699.5</td>
<td>miscellaneous articles of base metal; eg bells, signs, electrodes etc.</td>
</tr>
<tr>
<td>699.6</td>
<td>articles of I or S, NES; eg anchors, cast articles, wire etc.</td>
</tr>
<tr>
<td>821.3</td>
<td>furniture, NES, of metal</td>
</tr>
<tr>
<td>693.11</td>
<td>stranded wire, ropes, cables, plaited bands, slings and the like, of I or S, not electrically insulated</td>
</tr>
<tr>
<td>693.2</td>
<td>barbed wire of I or S, twisted hoop/single flat wire, barbed or not, of a kind used for fencing</td>
</tr>
<tr>
<td>SITC code</td>
<td>Goods category</td>
</tr>
<tr>
<td>-----------</td>
<td>----------------</td>
</tr>
<tr>
<td>693.51</td>
<td>cloth, grill, netting &amp; fencing, of I or S wire; expanded metal of I or S</td>
</tr>
<tr>
<td></td>
<td>Cans and metal boxes</td>
</tr>
<tr>
<td></td>
<td>not reported</td>
</tr>
<tr>
<td></td>
<td>Boilers, drums and other vessels</td>
</tr>
<tr>
<td>812.1</td>
<td>central heating boilers and radiators, air heaters &amp; hot air distributors,</td>
</tr>
<tr>
<td></td>
<td>not ele. heated of I or S</td>
</tr>
<tr>
<td>711</td>
<td>steam or other generating boilers, super-heated water boilers,</td>
</tr>
<tr>
<td></td>
<td>&amp; aux. plant for use therewith</td>
</tr>
<tr>
<td>692.11</td>
<td>reservoirs, tanks, vats and similar containers, of I or S, ≥300 litres</td>
</tr>
<tr>
<td>692.41</td>
<td>tanks, casks, drums, cans, boxes &amp; similar CTR of I or S, ≥300 litres,</td>
</tr>
<tr>
<td></td>
<td>O/T for compressed or liquefied gas</td>
</tr>
<tr>
<td>692.43</td>
<td>containers of I or S for compressed or liquefied gas</td>
</tr>
<tr>
<td></td>
<td>Other industries</td>
</tr>
<tr>
<td>723</td>
<td>civil engineering and contractors' plant and equipment</td>
</tr>
</tbody>
</table>


### Table A.2: SITC codes of traded aluminium containing goods.

<table>
<thead>
<tr>
<th>SITC code</th>
<th>Goods category</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transport</strong></td>
<td></td>
</tr>
<tr>
<td>781</td>
<td>motor cars and other m/vehicles principally for transport of persons (O/T public transport vehicles)</td>
</tr>
<tr>
<td>782</td>
<td>motor vehicles for the transport of goods and spec. purposes vehicles</td>
</tr>
<tr>
<td>783</td>
<td>road motor vehicles, NES</td>
</tr>
<tr>
<td>784</td>
<td>parts and accessories of motor vehicles</td>
</tr>
<tr>
<td>785</td>
<td>motor cycles (incl. mopeds) and cycles, motorized and non-motorized</td>
</tr>
<tr>
<td>786</td>
<td>trailers and semi-trailers; other vehicles not mech. propelled</td>
</tr>
<tr>
<td>79</td>
<td>other transport equipment (incl. railway vehicles, aircraft, ships etc)</td>
</tr>
<tr>
<td><strong>Building/Construction</strong></td>
<td></td>
</tr>
<tr>
<td>691.2</td>
<td>aluminium structures (O/T prefab buildings) &amp; parts thereof; plates rods etc, PRD for use in structures</td>
</tr>
<tr>
<td>694.4</td>
<td>nails, tacks, staples, screws, bolts, nuts, screw hooks, rivets &amp; similar articles of aluminium</td>
</tr>
<tr>
<td><strong>Engineering</strong></td>
<td></td>
</tr>
<tr>
<td>711</td>
<td>steam or other generating boilers, super-heated water boilers, &amp; aux plant for use therewith</td>
</tr>
<tr>
<td>712</td>
<td>steam turbines and other vapour turbines, and parts thereof, NES</td>
</tr>
<tr>
<td>713</td>
<td>internal combustion piston engines. and parts thereof, NES</td>
</tr>
<tr>
<td>714</td>
<td>engines and motors (O/T those of 712, 713 &amp; 718); parts, NES, of these engines and motors</td>
</tr>
<tr>
<td>SITC code</td>
<td>Goods category</td>
</tr>
<tr>
<td>-----------</td>
<td>----------------</td>
</tr>
<tr>
<td>716</td>
<td>rotating electric plant and parts thereof, NES</td>
</tr>
<tr>
<td>718</td>
<td>other power generating machinery and parts thereof</td>
</tr>
<tr>
<td>724</td>
<td>textile and leather machinery, and parts thereof, NES</td>
</tr>
<tr>
<td>725</td>
<td>paper mill and pulp mill machinery</td>
</tr>
<tr>
<td>726</td>
<td>printing and bookbinding machinery</td>
</tr>
<tr>
<td>728</td>
<td>other machinery, NES</td>
</tr>
<tr>
<td>73</td>
<td>metalworking machinery</td>
</tr>
<tr>
<td>74</td>
<td>general industry machinery and equipment, NES</td>
</tr>
<tr>
<td>76</td>
<td>telecommunications and sound recording and reproducing apparatus and equipment</td>
</tr>
<tr>
<td>77</td>
<td>electrical machinery, apparatus and appliances, NES and electrical parts thereof</td>
</tr>
<tr>
<td>721</td>
<td>agricultural machinery (excl. tractors) and parts thereof</td>
</tr>
<tr>
<td>727</td>
<td>food-processing machines (excl. domestic)</td>
</tr>
</tbody>
</table>

**Packaging**

(Not reported)

**Consumer durables**

<table>
<thead>
<tr>
<th>SITC code</th>
<th>Goods category</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>office machines and automatic data processing machines</td>
</tr>
<tr>
<td>697.43</td>
<td>household articles and parts thereof, NES, of aluminium</td>
</tr>
<tr>
<td>699.79</td>
<td>articles of aluminium, NES</td>
</tr>
<tr>
<td>821.3</td>
<td>furniture, NES, of metal</td>
</tr>
<tr>
<td>697.53</td>
<td>sanitary ware and parts thereof, NES, of aluminium</td>
</tr>
<tr>
<td>697.8</td>
<td>household appliances, decorative articles, frames and mirrors, of base metal, NES</td>
</tr>
<tr>
<td>SITC code</td>
<td>Goods category</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>693.13</td>
<td>stranded wire, ropes, cables, plaited bands, slings and the like, of aluminium, not electrically insulated</td>
</tr>
<tr>
<td>699.1</td>
<td>locksmiths' wares, safes, strong boxes, etc and hardware, NES, of base metal</td>
</tr>
<tr>
<td>699.5</td>
<td>miscellaneous articles of base metal; eg bells, signs, electrodes etc.</td>
</tr>
<tr>
<td>Other</td>
<td></td>
</tr>
<tr>
<td>692.44</td>
<td>containers of aluminium for compressed or liquefied gas</td>
</tr>
<tr>
<td>692.12</td>
<td>reservoirs, tanks, vats and similar containers, of aluminium, (300 \text{ litres})</td>
</tr>
<tr>
<td>692.42</td>
<td>tanks, casks, drums, cans, boxes &amp; similar CTR of aluminium, (300 \text{ litres}), O/T for compressed or liquefied gas</td>
</tr>
</tbody>
</table>
Appendix B

Estimation of iron/steel and aluminium scrap sent to landfill in the UK

Table B.1 summarises the data used to estimate the amount of iron/steel and aluminium waste that went into landfill in 2001. According to (Barton et al. 1984), the percentages of municipal waste that is ferrous and non-ferrous metal are 7% and 0.6% respectively. We assume that most of the non-ferrous waste, 0.5% out of the total of 0.6%, is aluminium. The waste for Scottish industrial waste is given as a total aggregated figure, i.e. the weight of specific materials is not specified; here, we assume the same metal content as the municipal waste stream: 7% and 0.5% for iron/steel and aluminium respectively.

Summing up the table and using the percentages above, this results in a total of 2,495,489 tonnes (ca two and a half million tonnes) of UK iron and steel waste and 198,135 (ca 200,000 tonnes) of aluminium waste going to landfill in 2001.
Table B.1: Data and references on estimation of metal scrap sent to landfill.

<table>
<thead>
<tr>
<th>Type</th>
<th>Year</th>
<th>Tonnes</th>
<th>Source</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>England</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industrial and commercial, iron</td>
<td>1998/1999</td>
<td>13600</td>
<td>(Bell 2003)</td>
<td>Dito</td>
</tr>
<tr>
<td>Industrial and commercial, aluminium</td>
<td>1998/1999</td>
<td>23000</td>
<td>(Bell 2003)</td>
<td>Dito</td>
</tr>
<tr>
<td>Wales</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Municipal waste</td>
<td>2000</td>
<td>1526989</td>
<td>(Defra 2003d)</td>
<td></td>
</tr>
<tr>
<td>Scotland</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industrial, construction/demolition, comm.</td>
<td>2000</td>
<td>8700000</td>
<td>(Defra 2003c)</td>
<td></td>
</tr>
<tr>
<td>Household</td>
<td>2000</td>
<td>2500000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Northern Ireland</td>
<td></td>
<td></td>
<td></td>
<td>No information available</td>
</tr>
</tbody>
</table>
Appendix C
Matlab code used in contamination modelling

% Model for contamination build-up
% Given parameters
p = 12; % No. metal products
n = 9; % No. goods categories
q = 120; % No. years accounted for (100 in the past (1900-2000) and 20 in the future (2001-2020) to be simulated)

% Load initial data
load touse_1.txt; load touse_2.txt; load touse_3.txt; load touse_4.txt;
load touse_5.txt; load touse_6.txt; load touse_7.txt; load touse_8.txt;
load touse_9.txt; load touse_10.txt; load touse_11.txt; load touse_12.txt;
goods_to_use_bc(:,1) = touse_1;
goods_to_use_bc(:,2) = touse_2;
goods_to_use_bc(:,3) = touse_3;
goods_to_use_bc(:,4) = touse_4;
goods_to_use_bc(:,5) = touse_5;
goods_to_use_bc(:,6) = touse_6;
goods_to_use_bc(:,7) = touse_7;
goods_to_use_bc(:,8) = touse_8;
goods_to_use_bc(:,9) = touse_9;
goods_to_use_bc(:,10) = touse_10;
goods_to_use_bc(:,11) = touse_11;
goods_to_use_bc(:,12) = touse_12;
load A_goods_to_use_bc_9.txt; load A_goods_to_use_bc_11.txt;
A_goods_to_use_bc(:,1) = zeros(n,q-1);
A_goods_to_use_bc(:,2) = zeros(n,q-1);
A_goods_to_use_bc(:,3) = zeros(n,q-1);
A_goods_to_use_bc(:,4) = zeros(n,q-1);
A_goods_to_use_bc(:,5) = zeros(n,q-1);
Appendix C

\[
A_{\text{goods\_to\_use\_bc}(;,:,6)} = \text{zeros}(n,q+1);
A_{\text{goods\_to\_use\_bc}(;,:,7)} = \text{zeros}(n,q+1);
A_{\text{goods\_to\_use\_bc}(;,:,8)} = \text{zeros}(n,q+1);
A_{\text{goods\_to\_use\_bc}(;,:,9)} = A_{\text{goods\_to\_use\_bc}_9};
A_{\text{goods\_to\_use\_bc}(;,:,10)} = \text{zeros}(n,q+1);
A_{\text{goods\_to\_use\_bc}(;,:,11)} = A_{\text{goods\_to\_use\_bc}_11};
A_{\text{goods\_to\_use\_bc}(;,:,12)} = \text{zeros}(n,q+1);
\]

% Load "external" boundary conditions
Net_export_mp = \text{zeros}(p,q+1);
Net_export_ng = \text{zeros}(n,q+1,p);
load EOL部副.txt;
load EOL部副2.txt;

%%%%%%%%%%%%%%%% SCRAP EXPORT %%%%%%%%%%%%%%%%%%
Net_export_EOL(:, :) = EOL部副2.txt;
% Load "internal" boundary conditions
load metalproduction.txt;
M_bc(:, :) = metalproduction(:, :);
Pr_rate_bc(1,:) = [0.01 0.1 0.1 0.05 0.01 0.017 0.01 0.1 0.1];
load productsplit.txt;
prod_to_goods_bc(:, :) = productsplit(:, :);

%Recycling rates
load eol_rec_rates.txt;
load eol_rec_rates2.txt;
Pr_rec_rate = [1 1 1 1 1 1 1 1 1];

%%%%%%%%%%%%%%%% SOL RECYCLING RATES %%%%%%2
EOL_rec_rate = eol_rec_rates2;

%Scrap aggregation
load scrapsplit_EOL_1.txt; load scrapsplit_EOL_2.txt;
load scrapsplit_EOL_3.txt; load scrapsplit_EOL_4.txt;
load scrapsplit_EOL_5.txt; load scrapsplit_EOL_6.txt;
load scrapsplit_EOL_7.txt; load scrapsplit_EOL_8.txt;
load scrapsplit_EOL_9.txt; load scrapsplit_EOL_10.txt;
load scrapsplit_EOL_11.txt; load scrapsplit_EOL_12.txt;
load scrapsplit_EOL_12_1.txt; load scrapsplit_EOL_12_2.txt;
load scrapsplit_EOL_12_3.txt; load scrapsplit_EOL_12_4.txt;

181
load scrapsplit_eol2_5.txt; load scrapsplit_eol2_6.txt;
load scrapsplit_eol2_7.txt; load scrapsplit_eol2_8.txt;
load scrapsplit_eol2_9.txt; load scrapsplit_eol2_10.txt;
load scrapsplit_eol2_11.txt; load scrapsplit_eol2_12.txt;
load scrapsplit_pr_1.txt; load scrapsplit_pr_2.txt;
load scrapsplit_pr_3.txt; load scrapsplit_pr_4.txt;
load scrapsplit_pr_5.txt; load scrapsplit_pr_6.txt;
load scrapsplit_pr_7.txt; load scrapsplit_pr_8.txt;
load scrapsplit_pr_9.txt; load scrapsplit_pr_10.txt;
load scrapsplit_pr_11.txt; load scrapsplit_pr_12.txt;
load scrapsplit_pr2_1.txt; load scrapsplit_pr2_2.txt;
load scrapsplit_pr2_3.txt; load scrapsplit_pr2_4.txt;
load scrapsplit_pr2_5.txt; load scrapsplit_pr2_6.txt;
load scrapsplit_pr2_7.txt; load scrapsplit_pr2_8.txt;
load scrapsplit_pr2_9.txt; load scrapsplit_pr2_10.txt;
load scrapsplit_pr2_11.txt; load scrapsplit_pr2_12.txt;

scrap_to_prod_eol(:,:,1) = scrapsplit_eol2_1;
scrap_to_prod_eol(:,:,2) = scrapsplit_eol2_2;
scrap_to_prod_eol(:,:,3) = scrapsplit_eol2_3;
scrap_to_prod_eol(:,:,4) = scrapsplit_eol2_4;
scrap_to_prod_eol(:,:,5) = scrapsplit_eol2_5;
scrap_to_prod_eol(:,:,6) = scrapsplit_eol2_6;
scrap_to_prod_eol(:,:,7) = scrapsplit_eol2_7;
scrap_to_prod_eol(:,:,8) = scrapsplit_eol2_8;
scrap_to_prod_eol(:,:,9) = scrapsplit_eol2_9;
scrap_to_prod_eol(:,:,10) = scrapsplit_eol2_10;
scrap_to_prod_eol(:,:,11) = scrapsplit_eol2_11;
scrap_to_prod_eol(:,:,12) = scrapsplit_eol2_12;

scrap_to_prod_pr(:,1) = scrapsplit_pr2_1;
scrap_to_prod_pr(:,2) = scrapsplit_pr2_2;
scrap_to_prod_pr(:,3) = scrapsplit_pr2_3;
scrap_to_prod_pr(:,4) = scrapsplit_pr2_4;
scrap_to_prod_pr(:,5) = scrapsplit_pr2_5;
scrap_to_prod_pr(:,6) = scrapsplit_pr2_6;
scrap_to_prod_pr(:,7) = scrapsplit_pr2_7;
scrap_to_prod_pr(:,8) = scrapsplit_pr2_8;
scrap_to_prod_pr(:,9) = scrapsplit_pr2_9;
scrap_to_prod_pr(:,10) = scrapsplit_pr2_10;
scrap_to_prod_pr(:,11) = scrapsplit_pr2_11;
scrap_to_prod_pr(:,12) = scrapsplit_pr2_12;

% define matrices and vectors
M_p = zeros(p,q+1);
M_n = goods_to_use_bc;
Prompt = zeros(n,q+1,p);
EOL = zeros(n,q+1,p);
EOL_rec = zeros(p,q+1);
prompt_rec = zeros(p,q+1);
A_p = zeros(p,q+1);
A_n = A_goods_to_use_bc;
A_load = zeros(p,1);
A_prompt = zeros(n,q+1,p);
A_EOL = zeros(n,q+1,p);
Appendix C

\begin{verbatim}
A_EOL_rec = zeros(p,q+l);
A_prompt_rec = zeros(p,q+l);
conc_A_trade = zeros(p,q+l);
A_EOL_rec(:,101) = [0.0429 0.1515 0.1515 0.3233 0.0227 0.1402
                    0.1515 0.2374 0.0657 0.0972 0.2576 0.0859]';
A_prompt_rec(:,101) = [0.0170 0.1875 0.1875 0.2557 0.1363
                    0.1193 0.1875 0.2216 0.1534 0.1023 0.1023 0.0341]';

% START
% *****************************************
for i=1:q+l
    M_p(:,i) = M_locator(:,i);
end

% Compute for years 2001 to 2020
for i=1:q+l
    % 1 A is added if alloy concentrations are below limit
    A_p(:,i) = A_EOL_rec(:,i-1) + A_prompt_rec(:,i-1);
    A_loadl(:,i) = 0;
    for k=1:p
        if A_p(k,i)/M_p(k,i) < A_p_conc(k,i)
            A_loadl(k,i) = A_loadl_init(k,i) - A_p(k,i);
        else
            A_loadl(k,i) = 0;
        end
        if A_loadl(k,i) < 0
            A_loadl(k,i) = 0;
        end
    end
    A_p(:,i) = A_p(:,i) + A_loadl(:,i);

    % Tincoat is added to tinplate
    A_loadl(9,i) = 5.04;
    A_p(9,i) = A_p(9,i) + A_loadl(9,i);

    % Trade of metal products
    M_p(:,i) = M_p(:,i) - Net_export_mp(:,i);
    A_p(:,i) = A_p(:,i) - Net_export_A_mp(:,i);

    % From products to goods
    % Loop over sectors
    for j=1:n
        for k=1:p
            M_n(j,i,k) = prod_to_goods_bc(j,k)*M_p(k,i);
            A_n(j,i,k) = prod_to_goods_bc(j,k)*A_p(k,i);
        end
    end
\end{verbatim}
% Prompt scrap rates are given from boundary data
Pr_rate(1,:) = Pr_rate_bc(1,:);

% Prompt scrap is generated
Prompt(j,i,k) = Pr_rate(1,j)*M_n(j,i,k);
A_prompt(j,i,k) = Prorate(1, j) * A_n(j,i,k);

% Trade of new goods
M_n(j,i,k) = M_n(j,i,k) - Prompt(j,i,k) + ...
Net_export_ng(j,i,k);
A_n(j,i,k) = A_n(j,i,k) - A_prompt(j,i,k) + ...
Net_export_A_ng(j,i,k);
end

% Delay of goods in use
t = linspace(0,100,102);
load dist.txt;
et = dist(1,j);
beta = dist(2,j);
y = two_parameter_weibull(t,beta,eta);
y(1) = 0;
for k=1:101
for m=1:p
EOL(j,i,m) = EOL(j,i,m) + M_n(j,i+1-k,m) * y(k);
A_EOL(j,i,m) = A_EOL(j,i,m) + A_n(j,i+1-k,m) * y(k);
end
end

% Scrap is recovered according to the recycling rate
for k=1:p
EOL(j,i,k) = EOL_rec_rate(j,i)*EOL(j,i,k);
Prompt(j,i,k) = Pr_rec_rate(1,j)*Prompt(j,i,k);
A_EOL(j,i,k) = EOL_rec_rate(j,i)*A_EOL(j,i,k);
A_prompt(j,i,k) = Pr_rec_rate(1,j)*A_prompt(j,i,k);
end

% Scrap is aggregated
for m=1:p
for j=1:p
for k=1:n
A_EOL_rec(j,i) = A_EOL_rec(j,i) + ...
scrap_to_prod_eol(j,k,m)*A_EOL(k,i,m);
A_prompt_rec(j,i) = A_prompt_rec(j,i) + ...
scrap_to_prod_pr(j,k,m)*A_prompt(k,i,m);
EOL_rec(j,i) = EOL_rec(j,i) + ...
scrap_to_prod_eol(j,k,m)*EOL(k,i,m);
prompt_rec(j,i) = prompt_rec(j,i) + ...
scrap_to_prod_pr(j,k,m)*Prompt(k,i,m);
end
end
end
Appendix C

\% Trade of prompt and end-of-life scrap

\[
\text{conc}_A\_\text{trade}(i) = \text{A\_EOL\_rec}(i)/\text{EOL\_rec}(i);
\]
\[
\text{EOL\_rec}(i) = \text{EOL\_rec}(i) - \text{Net\_export\_EOL}(i);
\]
\[
\text{prompt\_rec}(i) = \text{Prompt\_rec}(i) - \text{Net\_export\_prompt}(i);
\]
\[
\text{A\_EOL\_rec}(i) = \text{A\_EOL\_rec}(i) - \ldots
\]
\[
\text{Net\_export\_EOL}(i) \cdot \text{conc}_A\_\text{trade}(i);
\]
\[
\text{A\_prompt\_rec}(i) = \text{A\_prompt\_rec}(i) - \ldots
\]
\[
\text{Net\_export\_A\_prompt}(i);
\]

for i = 1:q+1

\[
\text{tid}(i) = 1899+i;
\]
end

plot(tid, (A_p ./ M_p)*100, '-o')
axis([2001 2020 0.4 1.1]);
xlabel('Years');
ylabel('Concentration [%]');

\%******************************************************************************

function y = two\_parameter\_weibull(x,beta,eta)

\[
y = (\beta/\eta) \cdot (x/\eta) \cdot (1-1/\eta) \cdot \exp(-(x/\eta)^\beta);
\]

mean\_value = eta * gamma((1/beta)+1);

median\_value = eta * log(2)^(1/beta);

mode\_value = eta * ((1-(1/beta))^(1/beta));

stand\_dev\_value = eta * sqrt(gamma((2/beta)+1)-gamma((1/beta)+1)^2);

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Appendix D

System parameters and transport calculations for Tower Hamlets

Current collection system.
Cans are currently collected in the borough by kerbside collection and by can banks. Information on collection in Tower Hamlets (TH) has been gathered from personal communication with Jocelyn Sekibo at the Council of Tower Hamlets (Sekibo 2001) and Emminie Moore at Onyx Ltd (Moore 2002).

- Kerbside collection:
  There are 79 400 households in total in TH; the kerbside scheme covers 11 000 of these. However, the participation of these 11 000 households is about 40%, so the number of collection points is ca 4 400. The houses that are included in the scheme are all terraced houses. Most of the households that are not included in the scheme are situated in blocks of flats and there are safety issues\(^1\) that make it difficult to include these households in the scheme. Collection occurs every two weeks. Aluminium cans are collected together with steel drinks cans and food cans, glass (clear, green and brown), cardboard, paper and textiles. The vehicle used is called a Labrie with a payload of about 5.7 tonnes in total

\(^1\)e.g. fire hazard - recycling boxes with paper and textiles standing outside people’s doors, inside the building, might be put on fire
Appendix D

(gross weight 17 tonnes). The vehicle is emptied every day and the usual collection weight of one day is 180 kg cans and 3000 kg other material.

- **Can banks:**
  There are 58 can banks situated in the borough, half of which are domes and half are bins. All are emptied every two weeks. The vehicle that empties the domes weighs 26 tonnes and has a capacity of 13 tonnes. The vehicle that empties the bins is a two-compartment vehicle weighing 17 tonnes and with a 7 tonnes capacity.

Cans collected from can banks and kerbsides are taken to a depot in Tower Hamlets: Gillender Street (E14 6RH). The other materials are taken to a depot on the Isle of Dogs (E14 9RG).

**Calculation of required transport:**

- **Collection from kerbsides**
  Over a period of two weeks (10 days) 4 400 collection points are visited. It has been assumed that 440 households per daily collection round are visited. An average distance of 20 m between collection points has been assumed (based on personal observation of kerbside collection in TH). Each day the truck is emptied; the transport for emptying at the depots has been calculated with Optrak (Optrak 1999). Allocation of the transport to the aluminium cans has been performed according to weight (180 kg cans*0.28/3180 kg material in total)^2. This results in 60.3 km with 17 tonne truck to collect 5.994 tonnes of Al cans.

- **Collection from bring sites - domes**
  Collection occurs on average every two weeks: 26/ year. Each collection round collects from 29 domes and then empties at Gillender street. The transport has been calculated with Optrak (Optrak 1999). Allocation to aluminium has been performed on the basis of weight (see kerbside collection). This results in 228.45 km with 26 tonne truck to collect 1.568 tonnes of Al cans.

^2There is no information on how much of the collected amount of metal is aluminium. It has been assumed that 28% of the collected metal is aluminium, based on information from Alupro and Corus packaging on the amount of aluminium and steel cans recovered in the UK in 2000.
- **Collection from bringsites - bins**
  Collection occurs on average every two weeks: 26/year. Each collection round collects from 29 bins and then empties at Gillender Street and Isle of Dogs. The transport has been calculated with Optrak (Optrak 1999). Allocation to aluminium has been performed on the basis of weight (see kerbside collection). This results in 109.41 km with 17 tonne truck to collect 1.176 tonnes Al cans.

**Scenario of higher recovery in TH - increased kerbside scheme** It has been assumed that the amount of cans collected from can banks remains at its current level (2.744 tonnes) while only the kerbside collection amount increases. The transport required for collection from can banks will therefore be the same as in the current situation: 228.45 km with 26 tonne truck to collect 1.568 tonnes of Al cans and 109.41 km with 17 tonne truck to collect 1.176 tonnes Al cans. For the increased kerbside scheme, the number of participating households at a particular recovery rate and the distance between the households have been derived by:

- **Number of participating households**
  Starting from the current situation at 3% recovery and 4,400 points of collection, assuming that all households need to participate in the kerbside scheme if 90% recovery is to be achieved; 90% recovery then corresponds to 79,000 points of collection. Intermediate collection rates are estimated by linear interpolation between these two points (3% and 90%).

- **Distance between participating households**
  Starting from the current situation of 4,400 collection points with an average distance of 20 m between them, assuming an average distance of 2 m for the 90% recovery scenario covering all households, and then interpolating linearly between these two points (3% and 90%).

**Calculation of required transport for increased kerbside collection:**
In order to scale up the kerbside scheme, it has been assumed that for every 440 points of collection, the truck is emptied (this is the number of households that are visited before emptying in the current situation). The trip for emptying requires 5.841 km of travel. It has also been assumed
Table D.1: Required transport for kerbside collection in Tower Hamlets at different recovery rates (allocation to aluminium performed).

<table>
<thead>
<tr>
<th>Recycling rate (%)</th>
<th>3</th>
<th>30</th>
<th>50</th>
<th>70</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Points of collection per day (no)</td>
<td>440</td>
<td>2,755</td>
<td>8,940</td>
<td>12,370</td>
<td>15,800</td>
</tr>
<tr>
<td>Required transport in one year (km)</td>
<td>60</td>
<td>328</td>
<td>930</td>
<td>1,141</td>
<td>1,004</td>
</tr>
</tbody>
</table>

that collection will occur fortnightly for 30 and 50% recovery but will increase to weekly at 70 and 90% recovery to boost recovery. The transport requirement for each recovery rate can be seen in Table D.1.

Scenario of higher recovery in TH - deposit system

The system is defined by the following parameters:

*The opening hours of the retailers, 62 h/week, are assumed to be the same regardless of the characteristics of the store, corresponding to opening seven days a week, from 10 a.m. to 8 p.m. on weekdays and from 10 a.m. to 4 p.m. on weekends.*

*The number of cans consumed per capita* is derived by dividing the annual consumption (kg per capita) by the average weight of an Al can: 0.016 kg.

*The number of reverse vending machines* is a limiting factor as it takes time to manage each can. To deposit one can into the machine takes less than five seconds, but the stream of people passing through the store is not uniform over time. The maximum load has therefore been set to *one can per minute & machine* in this study.

*Amount collected from each retailer at each collection* is derived from the capacity of the reverse vending machines. The compressed cans are put into a cardboard box containing 2500 cans (1,459 m$^3$). This type of box, the "Jumbo box", is one of the containers used in the Swedish system and is assumed to be used in this study. It has been assumed that two full boxes for each...
machine are collected from the retailers at each collection, i.e. 5,000 cans (80 kg) per machine are collected per collection. It is assumed that the returned cans are distributed equally over the number of machines included in each scenario.

A truck capacity of 20 m³ has been assumed for the collections. The collection is a dedicated single load collection, i.e. only cans are collected and the collection is not combined with any delivery.

Calculation of required transport for the deposit system:
The transport requirement has been calculated for 30, 50, 70 and 90% recovery in two ways - A and B. The number of participating retailers and number of reverse vending machines at each retailer, as well as frequency of collection, are described in each case below.

Case A
In this case the number of retailers and reverse vending machines are fixed independent of the recovery rate. The required number of machines that can handle the maximum return of 90% is used for all recovery rates. The number of machines at 90% recovery is determined by (maximum return load on each machine is 1 can per minute):

$$\frac{1 \text{ can}}{\text{minute}} = \frac{\text{population} \times 97.5 \text{ cans}}{\text{opening hours} \times 52 \times 60 \times x},$$

(D.1)

where the factor $52 \times 60$ simply transforms opening hours per year into minutes and $x$ is the required number of machines. This gives 85 vending machines in total for 90% recovery rate. The number of shops in Tower Hamlets is 67, i.e. some stores will have more than one machine. In this case retailers R1-R8 have three machines each, retailers R9-R10 two each and retailers R11-R67 one each. It has been assumed that the cans are distributed equally over all 85 machines and that they are collected when each machine has filled two boxes. The only difference between the scenarios of varied recovery rate in case A is thereby the number of collections to be made over one year. The resulting transport per year can be seen in Table D.2.

Case B
In this case the number of retailers and reverse vending machines is taken to increase with increasing recovery rate. The required number of machines for each recovery rate is determined by equation D.1. The same ratio (no of retailers with 3 machines/total no of retailers, etc.) as
Table D.2: Required transport for deposit systems A and B in TH.

<table>
<thead>
<tr>
<th>Recycling rate (%)</th>
<th>30</th>
<th>50</th>
<th>70</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yearly transport - case A (km)</td>
<td>1 781</td>
<td>2 969</td>
<td>4 158</td>
<td>5 337</td>
</tr>
<tr>
<td>Yearly transport - case B (km)</td>
<td>2 114</td>
<td>3 362</td>
<td>4 388</td>
<td>5 337</td>
</tr>
</tbody>
</table>

in case A has been used to distribute the "spare" machines. The frequency of collection is fixed independent of recovery rate. The resulting transport per year can be seen in Table D.2.
Appendix E

System parameters and transport calculations for Waverley

Current collection system
Cans are collected in the borough by kerbside collection and via can banks. Information on collection of cans in Waverley has been gathered from personal communication with Antony Buchan at Waverley Borough Council (Buchan 2001) and Will Lamport at Arkeco (Lamport 2002), supplemented by better understanding of the collection procedure obtained by spending a day on the kerbside collection truck.

- Kerbside collection:
  There are 48 000 households in total in Waverley; the kerbside scheme covers 30 000 of these. However, the participation of these 30 000 households is about 50%, so the number of collection points is about 15 000. Most households in Waverley are situated in houses, with few blocks of flats in the borough. Collection occurs every week. Aluminium cans are collected together with steel drinks cans, food cans and paper. The split-bodied vehicle used has a payload of about 7 tonnes in total (gross weight 18 tonnes). The two compartments of the truck are both equipped with compressors. The truck is emptied of paper and cans once a week. The usual collection weight before emptying is 5 tonnes of paper and 0.5 tonnes of cans. At the time of the study, three trucks, all based in Farnham,
were used for kerbside collection.

- **Can banks:**
  There are 59 can banks situated in the borough. The frequency of collection varies from weekly to on demand. In this study it has been assumed that all the can banks are emptied every two weeks. The split-bodied vehicle used has a payload of about 7 tonnes in total (gross weight 18 tonnes). The two compartments of the truck are both equipped with compressors. The truck is emptied of paper and cans once a week. The usual collection weight before emptying is 5 tonnes of paper and 0.5 tonnes of cans. Two trucks, both based in Farnham, are used for collection from can banks.

Cans collected from can banks and kerbsides are taken to a depot in Aldershot (GU11 2PX). The paper from the kerbside collection is taken to a site in Guildford (GU8 4HF). The trucks are all based in Farnham (GU9 9PZ). There is no information on the origin of collected metal (kerbside or can bank); there is only a figure for the total amount collected. As three trucks perform kerbside collection every week (6 truckloads of cans in two weeks) and two trucks perform can bank collection every two weeks on average (2 truckloads of cans every two weeks) it has been assumed that 75% of the cans come from kerbside collection.

**Calculation of required transport:**

- **Collection from kerbsides**
  Over a period of one week (5 days) 15 000 collection points are visited. That is 1 000 per daily collection round and truck. An average distance of 45 m between collection points has been assumed, with the truck emptied each week. The transport for emptying at the depots has been calculated with Optrak (Optrak 1999). Allocation of the transport to the aluminium cans has been performed according to weight (0.5 t cans*0.281/5.5 t material in total). This results in 1 354 km with 18 tonne truck to collect 21.869 tonnes of Al cans.

\[ \text{There is no information on how much of the collected amount of metal is aluminium. It has been assumed that } 28\% \text{ of the collected metal is aluminium, based on information from Alupro and Corus packaging on the amount of aluminium and steel cans recovered in the UK in 2000.} \]
Appendix E

• Collection from bringsites
Collection occurs on average every two weeks: 26/year. Each collection round collects from 59 can banks and then empties at Aldershot and Guildford (assuming paper collection occurs in parallel). The transport has been calculated with Optrak (Optrak 1999). Allocation to aluminium has been performed on the basis of weight (see kerbside collection). This results in 115.43 km with 18 tonne truck to collect 7.290 tonnes of Al cans.

Scenario of higher recovery in W - increased kerbside scheme
It has been assumed that the amount of cans collected from can banks in the current situation stays constant (7.290 tonnes) and it is only the amount collected by kerbside collection that increases. The required transport from collecting from can banks will therefore be the same as in the current situation: 115.43 km with 18 tonne truck to collect 7.290 tonnes of Al cans. For the increased kerbside scheme, the number of participating households at a particular recovery rate and the distance between the households have been derived by:

• Number of participating households
Starting from the current situation of 19% recovery and 15 000 points of collection, assuming that all households in the four main towns Farnham, Godalming, Haslemere and Cranleigh need to participate in the kerbside scheme if 70% recovery is to be achieved; 70% recovery then corresponds to 33 000 points of collection. Intermediate collection rates are estimated by linear interpolation between these two points (19% and 70%). At 90% recovery all households in the entire borough are assumed to participate, corresponding to 48 000 points of collection.

• Distance between participating households
The average distance between the households in the four main towns has been estimated by dividing the area\(^2\) of the towns with the number of households collected from (according to the recovery rate) to obtain average area per household. It has been assumed that the households are distributed evenly over the area. The average area per household has been assumed to be the shape of a square with the household in the middle of it, thus the closest

\(^2\)Estimates of areas have been taken from (Philip's 1992)
distance between a household and its neighbouring households is the side of the square. This distance has been assumed to be the average distance between collection points. The average distance between collection points at 90% recovery has been estimated in a similar way by dividing the area of Waverley outside the four main towns with the number of households outside these towns to obtain the average area per household. The average of the distance between the collection points in the four towns at 70% recovery and the distance between collection points outside the four towns has been used at 90% recovery.

**Calculation of required transport for increased kerbside collection:**

In order to scale up the kerbside scheme, it has been assumed that the truck is emptied once a week as in the current situation. The trip for emptying requires 52 km of driving. The number of trucks needed for the weekly collections has been calculated according to the weekly return and the truck capacity. It has been assumed that collection will continue to occur weekly for 30, 50, 70 and 90% recovery. The transport requirement for each recovery rate can be seen in Table E.1.

---

**Table E.1: Required transport for kerbside collection in Waverley at different recovery rates (allocation to aluminium performed).**

<table>
<thead>
<tr>
<th>Recycling rate (%)</th>
<th>19</th>
<th>30</th>
<th>50</th>
<th>70</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Points of collection per week (no)</td>
<td>15 000</td>
<td>18 236</td>
<td>24 118</td>
<td>33 000</td>
<td>48 000</td>
</tr>
<tr>
<td>Required transport in one year (km)</td>
<td>1 354</td>
<td>1 715</td>
<td>2 443</td>
<td>3 157</td>
<td>6 738</td>
</tr>
</tbody>
</table>
Table E.2: Required transport for deposit systems A and B in TH.

<table>
<thead>
<tr>
<th>Recycling rate (%)</th>
<th>30</th>
<th>50</th>
<th>70</th>
<th>90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yearly transport - case A (km)</td>
<td>4 343</td>
<td>7 237</td>
<td>10 135</td>
<td>13 029</td>
</tr>
<tr>
<td>Yearly transport - case B (km)</td>
<td>5 406</td>
<td>8 551</td>
<td>9 804</td>
<td>13 029</td>
</tr>
</tbody>
</table>

Scenario of higher recovery in W - deposit system

The deposit system in Waverley has been defined by the same parameters as in the deposit scenario of Tower Hamlets (see Appendix B). The transport requirement has been calculated for 30, 50, 70 and 90% recovery in two ways - A and B. The same assumptions as in the Tower Hamlets scenario have been used for the different cases (see Appendix D). The number of reverse vending machines at each recovery rate is derived from equation E.1.

\[
\frac{1 \text{ can}}{\text{minute}} = \frac{\text{population} \times 81.3 \text{ cans/capita}}{\text{opening hours} \times 52 \times 60 \times x'}
\]  

(E.1)

where the factor \(52 \times 60\) simply transforms opening hours per year into minutes and \(x'\) is the required number of machines. The resulting transport per year for case A and B can be seen in table E.2.
## Appendix F

Retailers in Tower Hamlets and Waverley

<table>
<thead>
<tr>
<th>Number</th>
<th>Name of retailer</th>
<th>Postcode</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>Sainsbury</td>
<td>E1 5SD</td>
</tr>
<tr>
<td>R2</td>
<td>Iceland</td>
<td>E1 2PP</td>
</tr>
<tr>
<td>R3</td>
<td>Asda</td>
<td>E14 3BT</td>
</tr>
<tr>
<td>R4</td>
<td>Safeway</td>
<td>E3 5ES</td>
</tr>
<tr>
<td>R5</td>
<td>Safeway</td>
<td>E1 5SD</td>
</tr>
<tr>
<td>R6</td>
<td>Tesco</td>
<td>E14 5AB</td>
</tr>
<tr>
<td>R7</td>
<td>Tesco</td>
<td>E3 3DY</td>
</tr>
<tr>
<td>R8</td>
<td>Somerfield</td>
<td>E14 6AQ</td>
</tr>
<tr>
<td>R9</td>
<td>Somerfield</td>
<td>E14 6NP</td>
</tr>
<tr>
<td>R10</td>
<td>Mon Ami Supermarket</td>
<td>E1 7QD</td>
</tr>
<tr>
<td>R11</td>
<td>Tahira Superstore</td>
<td>E1 2PS</td>
</tr>
</tbody>
</table>
## Table F.1: (continued)

<table>
<thead>
<tr>
<th>Number</th>
<th>Name of retailer</th>
<th>Postcode</th>
</tr>
</thead>
<tbody>
<tr>
<td>R12</td>
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Table F.1: (continued)
Table F.2: Retailers used in deposit scenarios in Waverley

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