A Study of Plastic Recycling Supply Chain

A research project sponsored by

The Chartered Institute of Logistics and Transport (UK)

'Seed Corn' Research Fund 2009-2010

October 2010

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Published By: The Chartered Institute of Logistics and Transport UK

ISBN 1-904564-36-4

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Acknowledgement

I would like to thank Chartered Institute of Logistics and Transport (UK) for the provision of the Seed Corn Fund for this research project. I would like to further thank my mentor Professor Chandra Lalwani for his invaluable support and guidance, Professor Martin Christopher for his encouragement, and the University of Hull Business School and Logistics Institute for the provision of a conducive and encouraging environment for research.

I am thankful to the various individuals and organisations for their assistance in this project. The organisations participated in this research and provided valuable time and assistance are: Hull City Council, East Riding of Yorkshire Council, North Lincolnshire Council, Hambleton District Council, Wakefield Metropolitan District Council, Greenstar, and Waste Recycling Group. I also like to thank Yorkshire Post their helps in promoting the research project.

Foreword

All production and consumption activities we engage in create waste that is costly to handle and environmentally damaging. Environmental impact is one of the most pressing issues facing logistics and transport managers today. Since the last two decades there has been an increasing effort to examine better approaches and logistics systems to reduce congestion, conserve natural resources and reduce emission. Research in this area predominantly focuses on the 'forward' supply chain i.e. the movements of goods from the origins of goods to the end consumers. However, the consideration of a 'forward' supply chain without the end-of-life (EOL) or 'reverse' flow is simply inadequate in helping logistics and transport managers to make informed decisions. Even though reuse and recycling are recognised as essential means to conserve natural resources and reduce GHG emission, such activities involve transportation and production which consume energy and produce emissions/pollutions. Without understanding the environmental impacts of recycling logistics systems, managers will not be able to make better decisions on product design, choice of materials, and the design of recycling logistics systems. It is therefore essential to understand the environmental impacts of various logistics solutions for managing product end-of-life (EOL).

Recycling of metal, paper, wood, glass, and plastic is generally perceived as an environmental-friendly practice because it saves energy, reduces raw material extraction and combats climate change. However, some previous studies discovered that plastic recycling supply chains are logistically inefficient, expansive, fragile, and even environmentally harmful. This research project identifies and maps logistical and ecological flows of plastic waste within the Yorkshire and Humber region. It identifies problems faced by the various parties involved in the collection, trading, transportation, sorting, storage, and reprocessing of plastic waste, and further identifies opportunities and logistics solutions to improve the efficiency of plastic recycling supply chain. It involves several local authorities and waste companies within and beyond the region. It employs a "cradle-to-grave" approach called life cycle assessment (LCA) to assess environmental impacts of post-consumer plastics throughout their end-of-life cycles.

This research is valuable for specifically local authorities. The analysis of environmental impacts based on LCA allows local authorities to understand the impacts of not just the waste collection scheme, but also the wider issues related to the design of a recycling logistics system. The research also answers the question about the environmental impacts of exporting plastic waste to other countries such as China. It provides logistics and transport research communities with further understanding of the use of LCA methods and recycling logistics systems in general. Above all, this research provides insights to retailers and packaging companies on the choices of packaging materials and the environmental impacts of their decisions given particular recycling logistics systems in particular countries.

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1. Introduction

1.1 Background of the study

Plastics play a significant role in the environmental, societal and economical dimensions of sustainable development (Plastic*Europe*, 2009). Plastics are light, durable, clean and versatile and therefore have been increasingly used to make packaging, automotive, building, electronic and electrical products. If we use other materials to replace plastics, the cost and environmental impacts will more likely to increase. For example, Americans use 100 billion plastics bags a year, made from about 12 million barrels of oil; instead, the use of 10 billion paper bags each year means cutting down 14 million trees (Science World, 2008). The use of crude oil for producing plastics consumes a scarce resource (energy) but the use of paper means the reduction of the capability of the planet earth to absorb CO_2.

Recognising the importance of plastics and the fact that plastics are made of scarce resources, there have been a lot of efforts in research and development to make plastics reusable and recyclable. According to the Department for Environment, Food and Rural Affairs (Defra)'s Waste Strategy 2007, the UK government has set out to achieve 45% recycling target by 2015. In 2008-09, 27.3 million tonnes of municipal waste was collected by UK local authorities but 50.3% was sent to landfill, 36.9% was recycled or composted, 12.2% was incinerated for energy recovery (Defra, 2010a). Despite knowing that plastics are difficult to be degraded naturally, UK is throwing away four plastic bottles out of every five (WRAP, 2009c). There appears to be a lack of emphasis and research on the management of the end-of-life (EOL) of products made of plastics and other scarce resources.

There are a lot of research efforts in many different disciplines attempting to find technologies and ways to make a cleaner and sustainable world. From a simple question such as the use plastic or paper bags for shopping in the supermarkets to the more complex questions about the most sustainable approaches to design, manufacture, distribute, and recycle a product, more research is required to help logistics and supply chain managers to make informed decisions. The trouble is that most of the research efforts are carried out in isolation without a "cradle-to-grave" or life-cycle approach. Even though recycling is believed to conserve materials and reduce green house gas (GHG) emission, recycling activities involve transportation and production activities which consume energy and natural resources and simultaneously produce emissions/pollutions. Without understanding of the environmental impacts of recycling logistics systems, managers will not be able to make better decisions on product design, production, distribution, choice of materials, and the design of recycling logistics systems. Understanding of the environmental impact of various logistics solutions for managing product life cycle including product end-of-life (EOL) is a crucial step towards a cleaner and sustainable world.

1.2 Environmental impacts of logistics, supply chain and recycling activities

Environment is becoming one of the most significant issues facing contemporary logistics managers (Murphy *et al.*, 1994). Freight transport is frequently a major component of life-cycle impact. Logistics managers have to become more sophisticated in their understanding of how they can reduce the environmental impact of their logistics operations, without negatively affecting the cost or effectiveness of these operations (van Woensel *et al.*, 2001). Since 1990s there has been an increasing effort to examine the best ways to reduce congestion, conserve resources, reduce of emission, and recycle in the logistics activities (Pohlen and Farris, 1992; Murphy *et al.*, 1994; van Woensel *et al.*, 2001; McKinnon *et al.*, 2009; Leonardi and Browne, 2009).

The concept "carbon footprint" is now a buzzword in the logistics research community. A "carbon footprint" is the total amount of CO_2 and other greenhouse gases (GHG), emitted over the full life-cycle of a process or product. The understanding of environmental impacts of a process or product cannot be achieved without a 'cradle-to-grave' or life-cycle approach. In addition to transport logistics activities, the need to include product design, manufacturing, use and end-of-life (EOL) stages of a product has been recognised. In recent years, much has been learned about the importance of considering the implications of design decisions on manufacturing and logistics activities, which gives rise to the fields of design for manufacturing (DFM) and design for logistics (DFL) (Tibben-Lembke, 2002). Furthermore, the product design and manufacturing research communities have adopted the idea of environmental conscious design and manufacturing (ECDM) which takes into account post-use process such as reuse, remanufacture, recycle and disposal while designing a product (Zhang *et al.*, 1997). Previous research has shown that product design decisions can have a through-life cost impact throughout the full life cycle of design, manufacture, packaging, distribution, use, repair, recycle and ultimate disposal of a product (Fabrycky and Blanchard, 1991; Kumaran, 2001; Xie and Simon, 2006; Kleyner and Sandborn, 2008). Though it is important to consider life-cycle environmental impacts of a product, it is also essential to ensure a product and the associated businesses are profitable. Thus, Sharifi *et al* (2006) suggest the concept of "design for supply chain" (DFSC) as part of the NPD process, which is concerned with the designing of products while taking into account the impact on the performance and success of the supply chain.

Many companies are just beginning to understand the importance of reverse logistics, and to grapple with how to best manage their reverse logistics processes (Tibben-Lembke, 2002), even though the logistics of recycling has long been discussed (Lambert and Towle, 1980). One of the issues being addressed is the management of reverse channel. Several options for reverse channels is available in the literature, for example reverse channel using traditional middlemen, reverse channel using secondary materials dealers, reverse channel including manufacturingcontrolled recycling centres, reverse channels including resource recovery centres (Guiltinan and Nwokoye, 1975). Stock (1998) further suggested that it is more efficient to use a centralised returns centre to sort products and packaging in the reverse flow than performing these activities in the forward distribution centre. Plastic packaging materials are typically recycled through a centralised reverse flow, and in countries like the UK, collected by the local authorities and material recovery facilities (MRFs).

In addition the challenges in the design of reverse channels, there are other engineering challenges. Often, due to low recovery rate, the quantity of secondary raw materials realised by collecting used packaging is certainly not large enough to overcome potential scarcity of raw materials (Bruck, 2000). The pressing challenges facing engineering and logistics research are the design of recycling systems, the development of dismantling techniques, and the methods to reduce recycling costs (Zhang *et al.*, 1997). Very often cost is the major reason for low recovery rate in many countries.

The next pressing issue is the lack of capabilities to assess the life-cycle impacts of the design of products, process and recycling systems. Life-cycle approach has now become an essential tool for companies to assess the environmental impacts of their products. There is a common perception that the environmental impacts of most products are contributed by manufacturing and transportation activities but the environmental impacts during product use and end-of-life (EOL) stages should not be ignored. Especially for products which consume energy during use, the total environmental impact during use could be more significant. For example, 80% of the total environmental impact of a washing machine is contributed by the use of water, energy and detergent consumption; only 20% of the environmental impact is due to manufacturing and distribution activities.

1.3 Objectives of the research

This research project aims to identify and map logistical and ecological flows of post-consumer plastic waste in the UK. An addition, the research aims to identify problems faced by the various parties involved in the collection, trading, transportation, sorting, storage, and reprocessing of plastic waste, and further identifies opportunities and logistics solutions to improve the efficiency of plastic recycling supply chain. The research involved several local authorities and waste management companies within the Yorkshire and Humber region. The research employed a “cradle-to-grave” approach called life cycle assessment (LCA) to assess environmental impacts of plastic products throughout their end-of-life (EOL) cycles.

The research is set out to achieve the following objectives:

1. Identify and map logistical and ecological flows of plastic waste taking case study of Yorkshire and Humber region;
2. Identify problems faced by the various parties involved in the collection, trading, transportation, sorting, storage, and reprocessing of plastic waste;
3. Identify opportunities and logistics solutions to improve the efficiency of plastic recycling supply chain;

This research aims to benefit local authorities in general. The analysis of environmental impacts based on life cycle assessment will allow local authorities to understand the impacts of not just the recycling collection scheme, but also the wider issues related to the design of a recycling logistics system. The research also the environmental impacts of exporting plastic waste to other countries with the environment impacts of re-processing plastic waste within the UK. As far as logistics and transport research communities as concern, the research provides an example of the use of life-cycle assessment (LCA) methods and issues related to reverse logistic or recycling logistics systems in general. Above all, the results of this research provide insights to retailers and packaging companies on the choices of packaging materials and the environmental impacts of their decisions given particular recycling logistics systems in particular countries.

1.4 Methodologies of the research

To achieve the above research objectives, this study first conducted a comprehensive review of existing literature both to build up academic foundations for the research as well as to review the current state of practices and problems in the plastic recycling supply chains. Next, several case studies focusing on post-consumer plastics recycling at Yorkshire and Humber region were conducted. Both methods are explained below.

The review of literature aims at understanding plastic forward supply chain and plastic recycling supply chain so that we can assess the environmental impacts of plastic from material extraction until end-of-life management and disposal. Academic literature, practitioner reports and policy information are searched and summarised. Next the literature review evaluates methods for assessing environmental impacts of a supply chain or product life cycle. The main focus is to understand life cycle assessment (LCA) methods which can be used for the research. Furthermore, existing studies which assess the environmental impacts of plastics production and recycling activities are examined. Major statistics about plastics production, consumption and recycling at European and UK levels are examined. Finally, the literature review summaries some current development in plastics recycling supply chain such that readers will have a fundamental understanding of the some of the latest development and efforts in plastics recycling supply chain.

Next, case studies focused on mainly post-consumer plastics recycling supply chains are conducted. To maintain a manageable scope, Yorkshire and Humber is chosen as the unit of analysis. This region has a land area of 5950 miles^2 and 22 local council areas with a minimum density 14 populations per mile^2 and a maximum density of 1346 populations per mile^2. The total plastic waste collected in this region was 6,739 tonnes in 2008. Data for the research are collected by a mixed of survey, interviews and workshop which involved local councils and their material recovery facilities (MRFs) in the Yorkshire and Humber region, and a visit to a new state-of-the art plastic recycling factory. The survey and interview data allow the research to map logistical and ecological flows of plastic waste and identify problems and opportunities faced by the various parties involved in the plastics recycling supply chain. Local councils such as Hull City Council, East Riding of Yorkshire Council, North Lincolnshire Council, Hambleton District Council, Wakefield Metropolitan District Council provided a lot of data related to the their recycling system. Data collected in this study are restricted to kerbside collection scheme. Other MRFs such as Greenstar and Waste Recycling Group (WRG) have also provided valuable data to this research. Visits to MRFs outside of the Yorkshire and Humber were also conducted in order to trace the flows of plastics waste.

In order to map logistical and ecological flows of plastic waste within Yorkshire and Humber region, life cycle assessment (LCA) is utilised. LCA is a tool to evaluate the environmental consequences of a product holistically, across its entire life (see more detail at www.setec.org). LCA was developed in the 1960s due to the concern over the limitations of raw materials and energy resources. It is a well established method within the fields of resource conservation and industrial ecology but it is not widely used by logistics research. Applied to study a jeans supply chain, Browne *et al.* (2005) concluded that LCA is a useful research technique. A complete LCA consists of three complementary components: inventory analysis, impact analysis, and improvement analysis (Vigon, 1994). For this research, environmental inventories are estimated by using material flow analysis (MFA) and life cycle inventory analysis (LCIA), borrowed from the LCA and industrial ecology literature.

2. Review of current literature

Nowadays, many disciplines are trying to find ways to make a cleaner world and at the same time ensuring sustainable supply of energy and resource for the growing population. In the logistics literature, there are a lot of studies which investigate ways to reduce fuel consumption and emission in transportation activities. In the cleaner production literature, there are attempts to reduce materials and energy consumptions in production activities. Meanwhile, the supply chain research has been dominated by the 'forward' supply chain view focusing in the efficient movements of materials and goods from supply sources to end-consumers but very few attempts are made to study reverse and recycling supply chains.

2.1 Plastic forward supply chain

Historically plastics are made of resins derived from vegetable matters such as cellulose from cotton, furfural from oat hulls, oil from seeds and various starch derivatives. Today, most plastics are produced from petrochemicals. Figure 1 illustrates a typical forward supply chain for plastics.

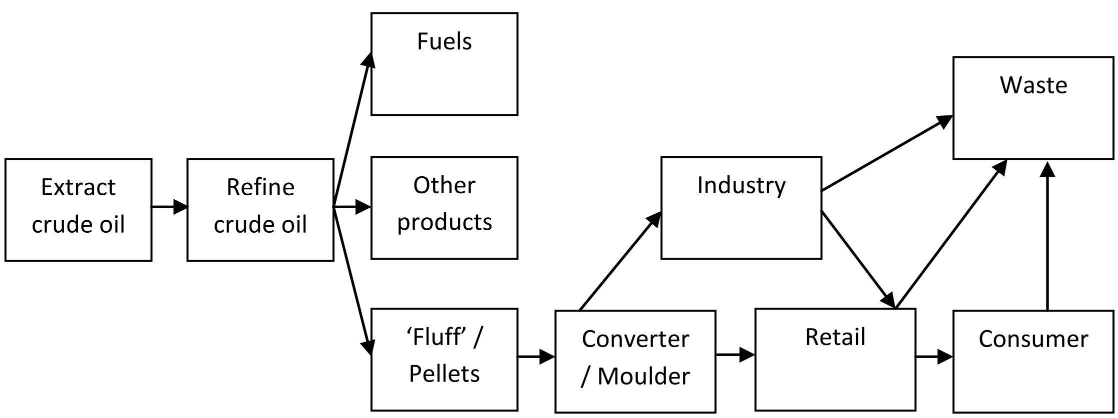

Figure 1 A typical forward plastic supply chain

The forward supply chain for plastics typically involves the extraction and refinery of crude oil. It is estimated that up to 4% of the world's annual oil production is used to produce and manufacture plastic products. The oil refinery process produces derivatives for producing plastics in 'fluff' and then 'pellets' forms. These pellets are shipped to customers such as converter and plastics moulder who then produce different types of plastics materials such as packaging materials, window frames, plastics for electrical and electronics apparatus, etc. The next section provides more information about the production processes of plastics.

2.1.1 Production of virgin plastic (polymer)

Virgin plastics (polymers) are made of derivatives of crude oil. The first step to produce virgin plastic occurs at the oil extraction platforms. Crude oil and natural gas extracted from the ground are then transported to petrochemical refinery plants and they are refined into ethane, propane, petrol and hundreds of other petrochemical products. Ethane and propane are derivatives of crude oil essential for plastics production. They are 'mixed' together under high-temperature furnaces to produce into Ethylene and Propylene. Ethylene or propylene are then combined with catalyst is combined in a reactor to produce 'fluff' which is a powdered material (polymer). Fluff is combined with additives in a continuous blender and further melted in an extruder. When the melted plastic (polymer) is cooled then it is transformed into pellets by a pelletizer. Converter and moulders produce plastics products by adding plastics pellets and other additives into extruders. Plastics products of different shapes and mechanical characteristics are produced by different types of extrusion moulding and injection moulding machines. In polymer markets, plastics in pellet forms are called 'primary plastics' and plastics products made from pellets can be called 'plastics products'. The production of virgin plastics consumes energy because it consumes derivatives of crude oil. The production of virgin plastics also consumes water, electrical energy and other solid materials (additives). The production of virgin plastics also produces air, solid and waterborne emissions, in addition to heat.

The plastics 'forward' industry basically consists of plastic producers, converters and machine manufacturers. In the UK, the industry employs about 1.6 million people and many times more in industries depending on plastics for their business. In 2008, converter in the UK produced approximately 3.7 million tonnes of plastics (1.5% of global total production). The plastics producers and converters also contributed together around € 13 billion in trade surplus to EU27 in 2008. The global production of plastics had been increasing exponentially from 1950 to 2007 and only declined in 2008 due to the financial crisis. The total global production of plastics grew to 245 million tonnes in 2008 from 1.5 million tonnes in 1950 (PlasticEurope, 2009). In 2008, NAFTA produced 23%, China and the rest of Asia produced 15% and 16.5%, and European countries produced 25% of the global plastics. Other producers of plastics include those from the Middle East, Africa, Japan and Latin America (PlasticEurope, 2009).

The increasing demand for plastics can be explained by the applications and demand of plastics in the next section. Nowadays there it is increasingly popular for crude oil producers to own refinery plants and produce plastics pellets. Also, there are increasing number of converters and moulding companies established at low-cost countries. This means there is an increase emission of green house gases when it comes to the transportation of plastics from factories to factories and to the end consumers.

2.1.2 Distribution of plastic (primary polymer)

Nowadays more and more oil refinery plants are built nearby the sources of oil production. Oil refinery plants produce and sell petrol and other fuels and raw materials for producing plastics. Raw materials for producing plastics are required by converter located at different corners of the world. Raw materials such as Ethylene or Propylene are normally packed, palletised and distributed globally using international transport and shipping. The demand of plastics raw materials by converter is often driven by the needs of plastics products. According to Plastic*Europe* Market Research Group (PEMRG), the demand of converter from European countries (EU27 + Norway and Switzerland) was about 48.5 million tonnes in 2008. Figure 2 indicates the percentages of these tonnages used in packaging, building & construction, automotive, electrical and electronics and other applications.

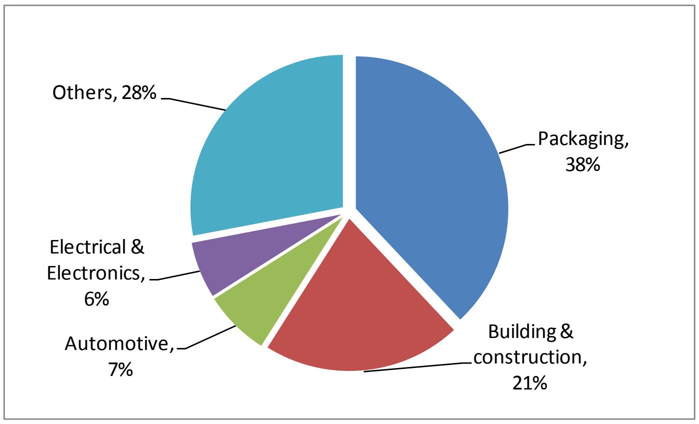

Figure 2 Plastic demands by converter from European countries

As indicated in Figure 2, plastics are primarily used to make packaging material for commercial and industrial purposes. Plastics packaging is essential for processing, storing, transporting, protecting and preserving products. Packaging sector is the largest consumer of plastics. The increasing use of plastics packaging instead of other packaging materials has resulted in the reduction of packaging weight, which helps to reduce green house gas (GHG) emission during transportation. Plastics are also widely used in building and construction sector. Plastics are durable, strong, resist to corrosion and above all, require low maintenance. Plastic insulation further helps homes and buildings to stay warm. It is estimated that energy required to produce plastic insulation could be saved after one year of use as insulation materials in homes and buildings. Plastics pipes are ideal for water transportation. Plastics are a hygienic choice for household surfaces and floor coverings because they are easy to clean and impermeable. Plastics are also widely used in electrical and electronic applications. The use of plastics in LCD (liquid crystal display) flat screens consumes much less electricity than ordinary screens with cathode ray tubes. The use of plastics is often associated with the efficient use of resources, weight reduction, miniaturisation, and insulation in the design of electrical and electronics applications.

2.1.3 Types and applications of plastic (polymer)

The exponential increase in the production of plastics is largely driven by a wide application of plastics. Plastics (polymers) have excellent thermal and electrical insulation properties. They resist corrosion to many substances which attack other materials. Some plastics are transparent, making optical devices possible. They are also easy to mould into complex shapes and forms, allowing integration of different materials and functions. Plastics can be modified with the addition of reinforcing fillers, colours, foaming agents, flame retardants, plasticisers etc. to meet the demands of the specific application.

Symbol	Types of plastics	Common use
1 PETE	Polyethylene Terephthalate	As one of the most recycled plastic materials, PET is primary used for soft drink bottles, cooking oil bottles, peanut butter jars, etc.
2 HDPE	High Density Polyethylene	As one of the most recycled plastic materials, HDPE is primary used for bottles, milk jugs, detergent bottles, margarine tubes, grocery bags, nursery pots, pesticide and oil containers
3 V	Polyvinyl Chloride	PVC (or vinyl) is used to produce products such as pressure pipes, outdoor furniture, food packaging, shrink wrap, liquid detergent containers, etc.
4 LDPE	Low Density Polyethylene	LDPE is used to produce films or bags, trash can liners, food storage containers, and stretch wrap
5 PP	Polypropylene	PP is used in products such as yarn, fabrics, food packaging, meat trays, nursery pots, row covers, etc.
6 PS	Polystyrene	PS is used to make yoghurt pots, egg cartoons, meat trays, and disposable utensils, video cassettes, televisions, packaging pellets or “Styrofoam peanuts
7 OTHER	Other types of plastics	May contain several types of plastics, used to make some food containers such as “Tupperware”

Figure 3 Types and applications of plastic

Figure 3 shows that there are different types of plastics; each can be used in various applications. The coding of different types of plastics is developed by the Society of the Plastics Industry (SPI) and it is used globally as a standard. The coding system is developed to allow for an efficient separation of different types of plastics for recycling. The symbols used in the code consist of arrows that cycle clockwise to form a rounded triangle and enclosing a number, each representing a major type of plastic. The numbers are often misunderstood as indicators of the difficulty in recycling or how often the plastic is recycled. They are actually arbitrarily-assigned numbers that have no other meaning aside from identifying the specific plastic.

Polyethylene Terephthalate (PETE /PET) is very light. PET can be semi-rigid to rigid, depending on its thickness. It is a good gas and fair moisture barrier, as well as a good barrier to alcohol and solvents. It is strong and impact-resistant. It is naturally colorless with a high transparency. PET is primarily used for synthetic fibres and plastic bottles for soft drinks, cooking oil, etc. The vast majority of recovered PET is used in the polyester fibre industry although there is a growing demand for PET for closed-loop packaging (BPF, 2010). However, PET is usually more expensive than PP.

High Density Polyethylene (HDPE) has stronger intermolecular forces and tensile strength than lower-density polyethylene (LDPE). HDPE is resistant to many different solvents so it is suitable for making bottles, milk jugs, detergent bottles, margarine tubes, grocery bags, nursery pots, pesticide, and oil containers. It takes 1.75 kilograms of petroleum (in terms of energy and raw materials) to make one kilogram of HDPE. Products made of High Density Polyethylene (HDPE) include pipes, pots, crates and other moulded products while recovered films are turned into sacks, bags and damp-proof membranes. Low Density Polyethylene (LDPE) materials can be translucent or opaque. LDPE is quite flexible, and tough but breakable. LDPE is used to make containers, bottles, plastic bags, and stretch wrap.

Polyvinyl Chloride (PVC) is the third most widely produced plastic, after polyethylene (PE) and polypropylene (PP). It is biologically and chemically resistant, making it the plastic of choice for most household sewerage pipes and other pipe applications instead of using metal. It is used in making clothing, upholstery, flexible hoses/tubes, flooring and electrical cable insulation. It is used to make leather-like materials. It is also used to produce products such as outdoor furniture, food packaging, shrink wrap, liquid detergent containers.

Polypropylene (PP) is resistant to fatigue. It is used to make plastic living hinges. PP is also used to make products such as yarn, fabrics, food packaging, meat trays, nursery pots, row covers, etc. Many plastic items for medical or laboratory use can be made from PP because it can withstand heat. PP is widely used in ropes because of its light weight. PP can be used as electrical insulators instead of PVC. PP can be used as parts of diapers or sanitary products. Polystyrene (PS) is used to make plastic models, CD and DVD cases, food trays and yogurt pots.

PS is flexible and can be easily made into different forms. PP can be used in microwave but not many other plastics.

2.2 Plastic recycling supply chain

Plastics help us to reduce the use of other materials which are often more harmful to the planet earth. In many instances, the use of plastics instead of other materials saves energy and reduces CO_2 emissions. Taking a lifecycle perspective, if all plastics in all applications were substituted with a mix of alternative materials, it is estimated that 22.4 million additional tonnes of crude oil would be needed each year (Plastic*Europe*, 2009). The production of plastics consumes relatively lower energy. The use of plastics packaging water, soft drinks and detergents or thinner plastic packaging film for food (instead of paper, metal or wood) usually means reduced use of resources. Furthermore, plastics can be reused in many ways. Plastics soft drink bottles are reused in many countries. Carrier bags are reused in a variety of ways and plastic supermarket trays provide a clean, robust and cost-effective way of transporting fresh food from producer to customer.

Plastics can be recycled at the end of use, typically for a maximum of six times. Most plastic waste can be re-processed to form plastic products. If it does not make economic or environmental sense to recycle, used plastics should go to energy from waste to provide much needed energy. Used plastics should not be sent to landfill. It is a waste of a valuable resource. Furthermore, landfill current costs around £40 to £61 per tonne (WRAP, 2007).

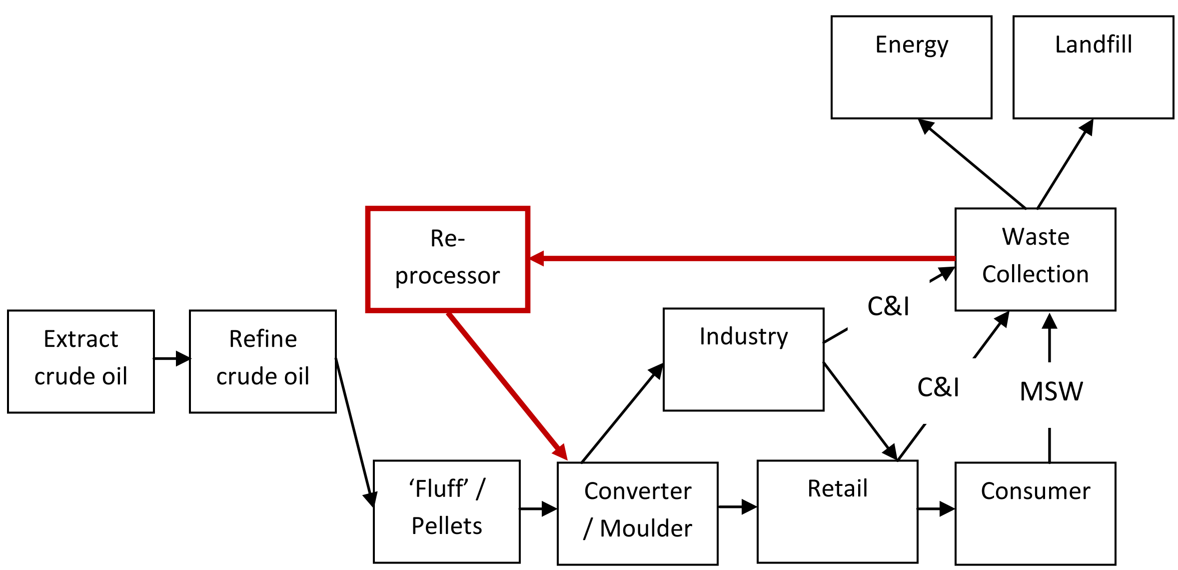

Figure 4 Plastic recycling supply chains

As illustrated in Figure 4, there are typically two major waste streams – municipal solid waste (MSW) and commercial and industrial (C&I) waste streams. Municipal solid waste (MSW) consists of mainly post-consumer plastics packaging materials such as bottles, trays, tub, bags and films and electrical and electronics products. Commercial waste stream consists of moulding scrapes, packaging materials, plastics pallets and containers. Industrial waste streams especially from plastics industry consists of mainly plastics waste from moulding production, which is often not contaminated and has identifiable specification.

Plastic waste can be recycled by two major processes – mechanical recycling and feedstock recycling. Mechanical recycling involves melting, shredding or granulation of plastic waste. Plastics must be sorted prior to mechanical recycling. At the moment in the UK most sorting for mechanical recycling is done by trained staffs who manually sort the plastics into polymer type and/or colour. New technology is being introduced to sort plastics automatically, using various techniques such as X-ray fluorescence, infrared and near infrared spectroscopy, electrostatics and flotation. Following sorting, the plastic is either melted down directly and moulded into a new shape, or melted down after being shredded into flakes and then processed into granules called re-granulate.

Feedstock recycling breaks down polymers into their constituent monomers, which in turn can be used again in refineries, or petrochemical and chemical production. A range of feedstock recycling technologies is currently being explored. These include: pyrolysis, hydrogenation, gasification and thermal cracking. Feedstock recycling has a greater flexibility over composition and is more tolerant to impurities than mechanical recycling, although it is capital intensive and requires very large quantities of used plastic for reprocessing to be economically viable (e.g. 50,000 tonnes per year).

The establishment of efficient recycling systems is a vital part of sustainable development (Bruck, 2000). However, the quantity of secondary raw materials realised by collecting used packaging is certainly not large enough to overcome potential scarcity of raw materials. Plastics which are not recyclable should not end up in landfill sites. Plastic is an energy source. It should at least be used for energy recovery. Instead of using primary fossil fuel, un-recyclable plastic waste can be used to heat cooling and electricity.

2.2.1 Recycling of plastics in major sectors

Plastic waste arising from packaging, buildings, transport vehicles, farming and industrial processes are valuable resources. The total plastics waste arising in the UK is estimated to be around 4.7 million tonnes while the global production exceeds 500 million tonnes (Collings, 2007). As far as packaging as concern, the use of plastics is indeed much more environmental friendly than paper. According to Science World (2008), the production of every tonne of paper bags consumes 4 times more than the production of plastics bags, the production of paper bags produces more air and waterborne pollution than the production of plastics bags, and furthermore, the recycling of paper consumes 85 times more energy than the recycling of plastics bags

Packaging application has the longest history of plastic recovery; it contributes to about 63% of end-of-life quantity (PlasticEurope, 2009) Plastic packaging constitutes to around 8% of the household or municipal waste stream and only 5% of waste goes to landfill (BPF, 2010). 40% of bottles and industrial film are now being mechanically recycled and well over 90% of crates and boxes are recycled across Europe. Recycling rates for the remaining mixed plastics are still low – below 10% across Europe. In total the collection for recycling of post-consumer packaging grew in 2008 to an average of 29%, up from 28% in 2007 (PlasticEurope, 2009).

Each year more than 50 million vehicles reach the end of their service life worldwide (Pomykala *et al*., 2007). End-of-life vehicles (ELVs) are normally sent to recycling infrastructures that dismantle auto parts. Many auto parts are profitably recycled and reused. The automotive industry has recently put more emphasis on recyclability of their parts. ELV Directive 2000/53/EC acts as the main legislative driver. There are targets but they are not material specific. Members of the Automotive Consortium on Recycling and Disposal (ACORD) agreement set a target to achieve recovery rates of material of 85% in 2002 rising to 95% in 2015. However, the actual recycling rate is still low, which is under 10% in 2008 (WRAP, 2008b). The main reason is that separation at the dismantling stage is less cost effective and there is a need for new technologies and designs of parts. The focus of automotive designers nowadays is to design parts which can be easily identified, dismantled and separated. Plastic auto parts are usually made of mixed plastics so they are generally more difficult to be dismantled or separated than metal parts. Consequently, new manufacturing process technologies are required to produce parts suitable for recycling and plants using such technologies are being built. For example, Polyurethane which was not recyclable is now recyclable with new technology. Nissan claims that they have developed separating, sorting and recycling technologies which recycle bumpers, instrument panels, ventilation ducts and floor carpets. Also, new technologies are developed to dismantle automotive parts more effectively.

The electrical and electronic (E&E) sector faces problems similar to those in the automotive sector. E&E sector produces complex products with materials intermingled in a way which makes sorting labour and energy intensive. It is not suitable for mechanical processing. Instead, thermal treatment via feedstock recycling or energy recovery becomes the most appropriate option. An example of growing recycling in the E&E sector is the inner liner of a refrigerator.

There is also some uncertainty about the actual volumes of discarded E&E equipment. It can be assumed that some is exported outside Europe.

Plastic plays a crucial role in farming. Farms in England and the UK produce more than 100,000 and 200,000 tonnes of waste plastics each year respectively (Collings, 2007). The disposal of used farming machineries, wrapping materials (films) and packaging materials represent a great challenge to farmers. At the moment there are some waste management companies focusing on waste collection from farmers in the UK. However, only about a fifth of all farms take recycling option (Collings, 2007). The number of farmers taking recycling option is expected to increase because there are already regulations in place to prevent the incineration of plastic waste. However, the recycling of plastics waste from farms is facing some difficulties. First farms are large and they are scattered. The logistics costs associated with the collection will be high. Secondly, the volume of plastics collected is usually small. Thirdly, due to the wide range of plastics materials collected, it is still very difficult for recycling companies to sort and get the best price out of the collected materials. Profitability is often depends on the difference between the prices of virgin plastics and recovered plastics.

2.2.2 Plastics recycling in EU2

Figure 5 illustrates plastics recycling flows for EU27. In 2008 EU27 exported approximately 2.0 million tonnes of primary plastics and 0.24 million tonnes of plastics products. During the same year EU27 imported approximately 0.58 million tonnes of primary plastics and 0.13 million tonnes of plastics products. Overall, converters from EU27 consumed 48.5 million tonnes of plastics and consumers from EU27 produced 24.9 million tonnes of post-consumer plastics waste in 2008. Sadly more than 48% of the plastics waste (12.1 million tonnes) ended in landfill sites.

Currently, seven of the EU member states plus Norway and Switzerland recover more than 80% of their used plastics. There is little landfill in Switzerland, Germany, Sweden and Denmark. These countries adopt an integrated resource management strategy using a range of complementary options to address each different waste stream with the best environmental and economic option. These countries maximise the use of waste for energy recovery when reuse and recycling are economically not viable. The UK instead has not invested much in energy recovery facilities.

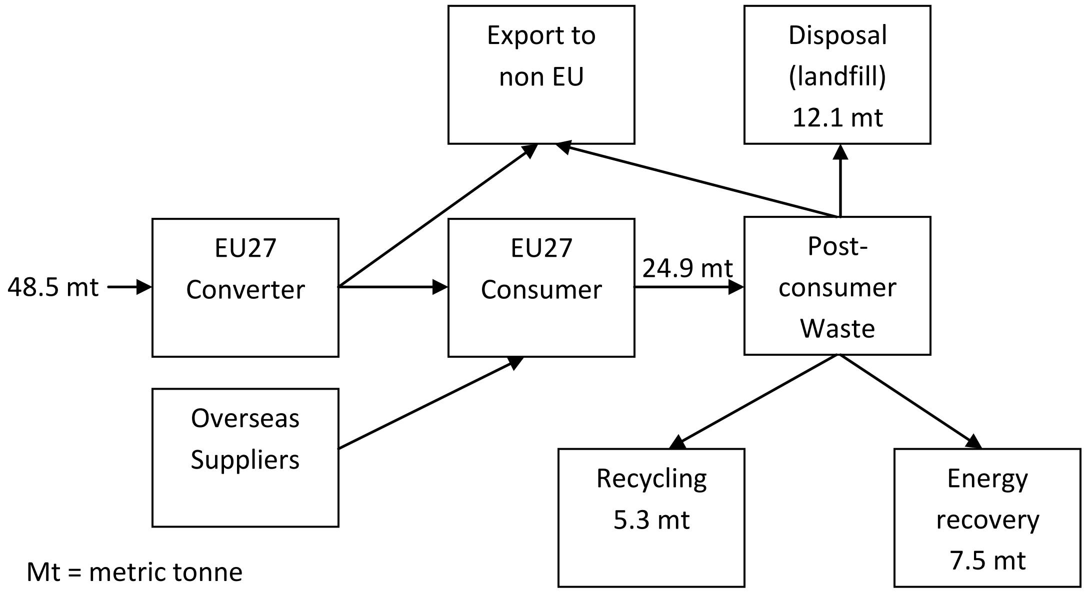

Figure 5 EU27 plastic recycling

2.2.3 Global plastics recycling markets

China is the world's largest importer of recovered plastics. Major countries which export recovered plastics to China are Japan, USA, UK, Germany, Netherlands, Belgium, and others. UK exported 80% or 517,000 tonnes of recovered plastics to China in 2008, which is 9% of China's imports of recovered plastics (WRAP, 2009c). The vast majority (55%) of UK recovered plastics exported to China are plastic bottles and packaging films largely made of Polyethylene (WRAP, 2009c), mainly due to the shortage of processing capacity in the UK. Most of the exported recovered plastics are sorted according to types of plastics and shipped to Hong Kong Port or Mainland China Ports. Guangdong is a major province for plastics recycling. Other provinces importing recovered plastics from the UK are Zhejiang, Shandong, Fujian, Jiangsu and Hebei in China. The exports of recovered plastics and other recyclates to China is also partly driven the lower shipping cost from Europe to China and lower production cost in China. In fact, China has built up many modern recycling facilities due to the demand for more plastic products. However, plastics reprocessing industry in China is highly fragmented. With foreseen shortage of primary plastics the demand for recovered plastics is expected to increase in the future.

The exports of recovered plastics from EU to other countries are regulated. The EU Regulation commonly referred to as the Waste Shipments Regulation (WSR) is the principal legal instrument setting out controls on waste imports and exports from the UK. Basically, only recycled materials sent for re-processing (but not waste for dumping) are allowed to be exported. To export recovered materials to China, there is a need to obtain Chinese SEPA (State Environmental Protection Administration) licence and AQSIQ (General Administration of Quality Supervision, Inspection and Quarantine) licence. There is also nowadays a requirement to satisfy to a certain level of contamination. Recovered plastic bottles are required to be broken into pieces. China has also recently banned the import of post-consumer plastics films such as carrier bags and agricultural films. Whilst there are registrations controlling the international trade of recovered plastics for reprocessing, there is no restriction in terms of the CO_2 emission as a result of such an increasingly important international trade. Furthermore, the global plastics recycling industry is also facing challenges when it comes to the use of child labour, unfair wages and unacceptable working conditions at waste dumping sites and reprocessing factories especially at the developing countries.

2.2.4 Efficient use and recycling of plastics

The efficient use and recycling of plastics should not be restricted to the assessment of transportation and logistics activities. The waste hierarchy framework in Figure 6 used by the Waste Strategy for England 2007 (WS2007) has clearly defined hierarchical means to use natural resources. The very first step to efficiently use plastic is to consider the choice of materials and design so that we can prevent waste. Businesses have to look at their product design and production processes to increase their usage of recycled materials and decrease their dependency on newly extracted raw materials. They need to take responsibility for the environmental impact of their products throughout their life cycle.

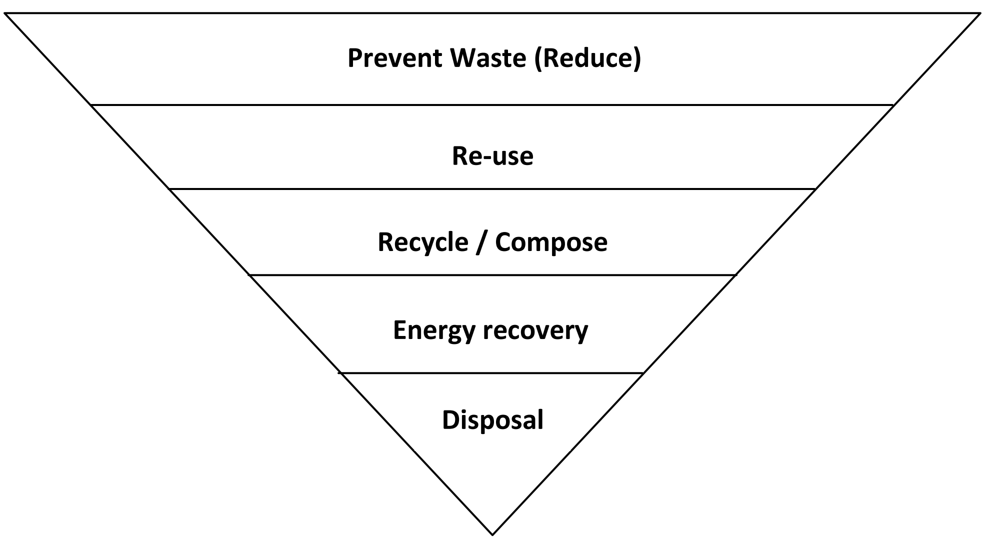

Figure 6 Waste hierarchies (WS2007)

There are generally two approaches to environmental conscious design and manufacturing. The first approach assumes that the environmental impact of a product during its life cycle can be reduced to zero. For example, the development of bio-degradable packaging materials will have a minimum impact of the environment during the end-of-life. For a material or product whose manufacture is energy intensive, reuse may be the best option for decreasing overall environmental impacts; it is also often the least expensive option (Anatas and Lankey, 2000). The chemical industry is in the forerun in developing processes which consume less energy. For example, GE Plastics has developed a catalyst that enables them to synthesize their ULTEM® thermoplastic resin in a more environmentally friendly manner. The new process uses 25% less energy per unit of resin, consumes 50% less catalyst generates 90% less organic waste, and produces 75% less waste in the manufacture of the catalyst itself (Anatas and Lankey, 2000). Several major supermarkets in the UK have already committed to increase the use of compostable packaging materials and the reduction of packaging materials in the Courtauld Commitment (WRAP, 2009b). Furthermore, the design for life cycle (DFLC) or design for product retirement (DFPR) literature has long started looking into ways to re-design products to improve product disassembly and reprocessing (Ishii, 1994). Ishii (1994) proposed a concept called "clumping" e.g. to group components sharing common characteristics together so that they are easily dissembled and separated for recycling, reused, and disposal. Obviously the production of any material or product will have an impact on the environment. The second approach assumes that there is a certain amount of negative impact from the current process cycle. The environmental impact can be reduced based on some improvement in technology that is named as incremental waste lifecycle control (Zhang *et al.*, 1997).

The next waste hierarchy is to re-use. Retailers have to reduce packaging as well as source and market products that are less wasteful, and help consumers to be less wasteful. In the UK and many other European countries, major supermarkets have already providing or selling re-usable shopping bags and providing incentives for the use of reusable shopping bags to consumers. When reuse of a product is technically or economically infeasible, recycling the materials may be an option. When materials are recycled after consumer use, the recovered material may either be used as an input to make the same product again, termed 'closed-loop recycling', or it may be used to make lower-value products, called 'open-loop recycling'. Currently the recycling of plastics and polymers is not profitable, and the goal of closed-loop recycling is complicated by different colours of plastics and polymers that are used. A third option is 'equivalent closed-loop' recycling, where although a recovered material is not used to make the same product again, it is used in place of virgin material as the input for a similar product. Further chemical research for plastics and polymer recycling is still needed to provide more technically and economically feasible options to facilitate closed-loop and equivalent closed-loop recycling. A basic concept of industrial ecology is to design or modify an industrial system such that the wastes and by-products of one industry can become the feedstock for another process or another industry (Anatas and Lankey, 2000).

From the governmental policy point of view, the WS2007 (Defra, 2008) set the future direction of waste policy and made a number of key proposals or action. WS2007 suggests the use of incentivise efforts to reduce, re-use, recycle waste and recover energy from waste. In addition, there is a need to reform regulation to drive the reduction of waste and diversion from landfill while reducing costs to compliant business and the regulators. To take into account the specific economical situations in different sectors, there is also a need for target actions on materials, products and sectors with the greatest scope for improving environmental and economic outcomes. The lack of recycling capacity can be addressed by stimulating investment in collection, recycling and recovery infrastructure, and markets for recovered materials that will maximise the value of materials and energy recovered. Since local authorities are the major waste collectors, there is also a need to improve national, regional and local governance, with a clearer performance and institutional framework to deliver better coordinated action and services on the ground. The local authorities are the drivers for directing collected wastes for recycling, composting, energy recovery and landfill. However, some of these actions are difficult to achieve especially during the economic crisis.

Off course everyone should be responsible for the environment and waste management. Consumers in the UK have plenty of opportunity to reduce their own waste, purchase products and services that generate less waste, and separate their waste for recycling. In the UK, household recycling rates have continued to increase. The latest figures (2006/07) show levels of 31%, a rise from 26.7% in 2005/06. And early indications are that this has risen again in the first part of 2007/08 to 33% (Defra, 2008). Local authorities have provided consumers with convenient recycling services for their residents and commercial customers and advice and information on how to reduce waste. Local authorities will also have to work with their communities to plan and invest in new collection and reprocessing facilities. Waste management industry has to invest in new recycling and recovery facilities and provide convenient waste services to customers. In the UK, residual household waste has decreased by 22% from 2000/01 to 2006/07. This is equivalent to an average of 16kg per person per year across England or 42kg per household (Defra, 2008). The total waste to landfill fell by a fifth between 2000/01 and 2006, from 80 million tonnes to 65 million tonnes. The amounts of commercial and industrial waste being sent to landfill continue to fall. The proxy indicator shows that this has fallen from an estimated 27 million tonnes in 2000/01 to 20.7 million tonnes in 2006, a decrease of 23% (Defra, 2008).

2.3 Environmental assessment of plastic recycling

According to BPF (2010), the plastics industry consumes only 4% of the world's oil production. The rest of the oil production is used for energy and transport. Actually, the production of most plastic products is not energy intensive compared to the production of metals, glass and paper. However, if plastics materials are re-used or recycled, then we can avoid consuming more crude oil. In order to gain a complete knowledge of the environmental impacts of plastic supply chain, it is also essential to consider emission as a result of production, transport and end-of-life flows of plastics.

This research employed a "cradle-to-grave" approach called life cycle assessment (LCA) to assess environmental impacts of a plastic throughout its end-of-life cycle. The term life cycle indicates that every stage of the life cycle of the service, from resource extraction to ultimate end-of-life treatment, is taken into account. LCA is a tool to evaluate the environmental consequences of a product holistically, across its entire life (see more detail at www.setec.org). The international standard ISO 14040-43 defines LCA as a compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (Arena *et al.*, 2003a). LCA methodology is an internationally standardized method that has been developed from chemical engineering principles and energy analysis. LCA was developed in the 1960s due to the concern over the limitations of raw materials and energy resources. It is a well established method within the fields of resource conservation and industrial ecology but it is not widely used by logistics research. LCA can also be applied to assess environmental impacts of recycling supply chains (Craighill and Powell, 1996). For this research, environmental inventories are estimated by using material flow analysis (MFA) and life cycle inventory analysis (LCIA), borrowed from the LCA and industrial ecology literature.

A complete LCA consists of three complementary components: inventory analysis, impact analysis, and improvement analysis (Vigon, 1994). Life cycle inventory analysis (LCIA) consists of an accounting of the resource usage and environmental release associated with a product, process, or activity throughout each stage of its life cycle. LCIA can be used for both internally to an organisation and externally to a supply chain for process analysis, material selection, product evaluation, product comparison, and policy-making. For example, during 1990s Coco-Cola Company developed a LCIA method to compare different beverage containers to determine which container had the lowest releases to environment and least affected the supply of natural resources (Vigon, 1994). The basic methodological framework for LCA (as defined by both SETAC and ISO) comprises of four main phases: (1) goal definition and scoping, (2) inventory analysis, (3) impact analysis and (4), improvement assessment (Arena *et al.*, 2003a).

Life-cycle inventory analysis (LCIA) is a technical, data-based process of quantifying energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other releases for the entire life of a product, package, process, material, or activity (Vigon, 1994). LCI is a "snapshot" of inputs to and outputs from a system. Inventory analysis begins with raw material extraction and continues through final product consumption and end-of-life (EOL) disposal. To conduct LCIA, there is a need to establish a baseline of information on an entire system given current or predicted practices in manufacture, use, and disposition of the product or category of products. The baseline model for plastic recycling may be established based on the energy and raw material usages, atmospheric emissions, waterborne emissions, solid wastes, and other releases involved in the production of virgin plastic materials.

The third step of LCA is impact assessment, which aims at understanding and evaluating the magnitude and significance of potential environmental impacts of a system. Based on LCIA inputs and outputs, impacts of the system are categorised into an aggregate indicator for interpretation and policy making. Policy makers will then be able to evaluate the impacts of the system and reach recommendations for improvement (Arena *et al.*, 2003a). However, very often LCA analysis is inadequate for policy makers to make informed decision because it does not include cost and economic analysis. LCA combined with economic evaluation or life-cycle costing (LCC) is thus recommended (Craighill and Powell, 1996; Hendrickson *et al.*, 1998; Reich, 2005). LCC is essential to inform for example future waste strategy, central government and local authorities.

In the UK, the Environment Agency developed a software or method called Waste and Resources Assessment Tool for the Environment (WRATE). WRATE is designed so that waste managers can easily apply complex life cycle techniques to manage municipal waste more sustainably. WRATE calculates the potential impacts of all stages in the collection, management and processing of municipal waste. The calculation takes account of the infrastructure and its operation as well as any benefits associated with materials recycling and energy recovery. The results of WRATE analysis is said to be easy to understand and interpret for financial and political decision-makers and stakeholders. WRATE has been designed for waste managers in waste disposal, collection authorities, waste management companies and other waste services providers, including waste technology suppliers. It is also useful as a training tool for those interested in waste management and researchers and other academics interested in waste management and life cycle assessment. Normally WRATE is used by local authorities to choose appropriate waste collection schemes and tendering of materials reclamation facilities (MRFs) but not the entire life cycle of plastics or other materials.

There are very few studies that investigate the life cycle of plastics production and recycling from material extraction to end-of-life recycling and disposal. Arena *et al.* (2003b) conducted a life cycle assessment of a plastics recycling system in Italy. The study estimated that the production of 1kg flakes of recycled PET requires a total amount of gross energy that is in the range of between 42 and 55 MJ. The production of 1kg of virgin PET requires more than 77MJ. The energy saving for each kg of recovered plastic is very high, with 40-49 MJ for recycled polymer and about 80MJ for the virgin polyolefin. The study is based on mechanical process. It was estimated that the overall sorting efficiency was 56%, with electrical and diesel consumptions of 0.16 and 0.11 MJ/kg of selected plastic. The study compared recycling with no recycling and landfill disposal of all collected plastic wastes, and concluded that mechanical recycling over landfill of all collected plastic would generate a considerable saving of energetic resources (93% of crude oil, 84% of gas/condensate and 93% of coal) and waste production (91%) and water consumption (13%), reduce air and water emissions with the only increase of green-house gases (53%). Arena *et al.* (2003a) claimed that the study shown that transportation (emissions to the air and water, and energy-use) played a negligible role.

When cost of recycling is considered, Craighill and Powell (1996) concluded that the net benefits for local authorities in the UK is £1769 for aluminium, £238 for steel, £226 for paper and £188 for glass but the net cost is £2.57 for HDPE, $4.10 for PVC and £7.28 for PET, per tonne of material. It is important to note that the study by Craighill and Powell (1996) does not consider the total life cycle cost but only the costs incurred by the local authorities studied. Instead, it is essential to consider investment costs, operative costs, decommissioning costs and sales revenues (Reich, 2005) and the shareholders, stakeholders and beneficiaries in the whole system.

2.4 Current development in plastics recycling supply chain

Over the year, there has been a lot of development in plastic recycling efforts. The general public has started to understand the benefits of recycling and plastics recycling in particular. More and more industries are using plastics over other materials. When plastics are used in a product, product design teams in many industries are trying to make sure that plastics components can be easily identified and disassembled. Policy makers (such as WS2007) specify legislation to encourage product labelling and recycling. Local authorities have been trying to improve waste collection schemes and work with MRFs to improve recycling rates. The following sections briefly discuss some of the current development of plastics recycling supply chain.

2.4.1 Choice of materials (plastics or others)

As discussed earlier plastic is versatile such that it is suitable for so many applications in every industry. Even though most plastics are not bio-degradable, the costs of production and transports of plastic materials are much lower than many other materials. The environmental impacts of the production and recycling of plastics are actually much lower than what we believe. The debate about use of plastics bags over paper bags for shopping has been going on for years.

Aspects	Polyethylene bags	Paper bags
Energy required to produce (mega joules)	580,000	1,340,000
Air pollutions produced (kg)		
Sulfur dioxide	198	388
Oxides of nitrogen	136	204
Hydrocarbons	76	24
Carbon monoxide	20	60
Dust	10	64
Wastewater discharged (kg)	10	512
Energy for recycling	Less than paper	More than plastic
Biodegradable	No	Yes
Volume	44	46
Weight	16	140

Table 1 Comparison of the use of plastic and paper bags

Table 1 compares the use of plastics over paper bags for shopping (Ciambrone, 1997). It is very clear that the production of plastic bags require much less energy than the production of paper bags. Furthermore, the production of plastic bags produces much less air-borne, water-borne and solid emissions than the production of paper bags. Furthermore, the use of paper bags mean the cutting down of trees which are essential for absorbing CO_2. The packaging industry has started to promote the use of PET and HDPE for making bottles, which are readily collectable and recyclable. However, for cost reason, some companies prefer to use PP, which is cheaper than PET and HDPE. In addition to PET and HDPE, PP and PS are also recyclable. To reduce the weight of packaging materials, the use of mixed plastics has become common. However, mixed plastics are not readily recyclable by most of the local authorities in the UK due to the relative unsophisticated sorting process used by major MRFs.

2.4.2 EU Directives

For packaging materials, EU Directive 94/62/EC of 20 December 1994 on packaging and packaging waste suggested member states to return/collect 60% of glass, paper and board, 50% of metals, 22.5% of plastic, and 15% of wood, by 2008. In addition to recycling, the incineration of waste for energy recovery is regarded as contributing to the realisation of these objectives. Directive 2008/98/EC in 2008 further increased the targets. By 2020, the preparing for re-use and the recycling of waste materials such as at least paper, metal, plastic and glass from households and possibly from other origins as far as these waste streams are similar to waste from households, shall be increased to a minimum of overall 50 % by weight. In addition, the EU Landfill Directive drives the reduction of the use of landfill (Defra, 2010b). Each member state is required to reduce biodegradable municipal waste landfill to 75% of that produced in 1995 by 2010, 50% of that produced in 1995 by 2013, and 35% of that produced in 1995 by 2020. Both EU directives on packaging waste and landfill are putting immense pressures on plastics recycling. These new requirements put a lot of pressures on the local authorities and government.

2.4.3 Current developments and issues

Currently, several developments in plastics recycling and waste management in general deserve some attention. In June 2008, a compromise agreement was reached between the Council of Environment Ministers and the European Parliament on revisions to the Waste Framework Directive. The main changes include EU-wide targets for reuse and recycling 50% of household waste by 2020, and for reuse, recycling and recovery of 70% of construction and demolition waste by 2020. There is also a requirement for separate collection of paper, glass, metals and plastic by 2015 where this is technically, environmentally and economically practicable. Once formally adopted, these revisions are expected to come into force in 2010.

Some recent projects are looking into the contributions of recycling in the CO_2 reduction efforts. Environment Agency and WRAP in the Waste Protocols Project (WPP) attempts to look closely at the risks associated with specific wastes. The project aims to cut through red tape and provide more certainty as to when recovered materials cease to be ‘waste’, making them easier to reuse. The WPP is currently developing a Quality Protocol for non-packaging plastic waste. It is estimated that this Quality Protocol, once enforced, could reduce CO_2 emissions by over 70,000 tonnes over 10 years and create a quality, desirable material which can be reused.

However, the recycling industry is still facing several pressing issues. Relatively high prices for a range of commodities including food and fuel may impact on levels of waste and recycling. The government needs to monitor this trend closely as well as working with business to ensure that benefits of improved waste management and resource efficiency can assist business in coping with commodity prices. Very often, high process of commodities and energy are absorbed by recycling businesses. The growth in waste quantity in the municipal sector is another major concern. The level of waste growth has a significant impact on both environmental impacts, costs and the amount of disposal infrastructure needed to meet the EU landfill diversion targets. Despite 3% annual growth in the past decade for post-consumer waste, landfill amounts have remained stable (Plastic*Europe*, 2009). While the quantity of waste is increasing waste prevention has continued at a significantly lower rate than up to about 5 years ago.

The lack of the right waste treatment infrastructure at the right location is one of reasons which prevent a faster growth of recycling rates. It remains important to ensure that the necessary infrastructure is provided without unnecessary delay, especially to ensure that we achieve our EU landfill diversion targets. The priority waste materials and sectors is another issue facing the recycling industry. Defra realised that there is a need to develop strategies for particular waste sectors and materials. Setting an overall target for all commercial and industrial waste was realised to be less helpful. The diversity of waste stream in different industries and commercial activities produces different types of environmental impacts from different kinds of waste. Defra has already taken steps to develop sectoral approaches, especially in relation to waste from the construction, food, packaging and retail sectors.

For packaging industry, Defra and WRAP are working with stakeholders to develop a broad vision for the longer term for packaging. This will include continuing close working with retailers and local authorities, as well as with other players. The Courtauld Commitment – an agreement between WRAP and the major grocery organisations – is set to deliver new packaging solutions and technologies so that less waste ends up in the household bin. Within the G8 Japan has promoted the 3R Initiative – reduce, reuse, recycle, a concept which is consistent with EU and UK thinking on waste prevention and resource efficiency. In May 2008 the G8 Environment Ministers meeting in Kobe agreed a 3R Action Plan, aimed at prioritising 3R policies and improving resource productivity at national level. An international sound material recycling society was established by facilitating trans-boundary movement of materials, subject to the safeguards in the Basel Convention. There is also a plea to assist developing countries building up their 3R capacities. 3R action plan is being included as one of the Defra's Waste Strategy.

Nothing can be improved without measurement. While the quality and timeliness of municipal waste data is generally very good, there is a great deal of scope for improvement in non-municipal waste data. Defra will take further as a priority the development of better statistics on non-municipal waste, noting that this will depend in part on inputs from the commercial sector. Already in place is the UK Waste Data Strategy under which Defra and the Environment Agency are working jointly to move from survey based estimates, of commercial and industrial waste data, to using statutory returns made by permitted waste facilities. Whilst these returns provide a good picture of waste to landfill, amounts handled by different treatment processes and the permitted waste infrastructure, there are a number of data gaps. Defra commissioned a study into these data gaps and the short, medium and long term options to resolve these. This concluded that to provide a complete picture, data returns from permitted sites need to be supplemented by analysis and other data sources. Defra, the Environment Agency and other key stakeholders, are working actively to improve the coverage and quality of our waste data.

Plastic bottle recycling (e.g. HDPE and PET bottles) has been quite successful but other remaining rigid plastics composed of two PP and PS are not yet widely recyclable. Many plastics pots, tubs and trays are made from Polypropylene (PP), Polystyrene (PS) and Polyvinylchloride (PVC). They are mostly are used for packing fruits, dairies, ice-cream and many others type of food. The next question is then if, and how, these packages could be sorted, reclaimed and then recycled in new applications. Some countries such as Germany, Italy and the UK have already automatic sorting facilities capable of sorting out these packages. Once sorted, they can be sent to MRFs, which have similar washing lines like bottle recyclers, equipped with grinding, washing, drying and in some cases extruding equipment. The reprocessed flakes or pellets can then be used to replace virgin material in new applications, such as hangers, flower pots, pallets, crates and car parts.

A number of UK retailers have recently introduced degradable carrier bags. These bags are made from plastic which degrades under certain conditions or after a predetermined length of time. There are two types of degradable plastic: bio-degradable plastics, which contain a small percentage of non oil-based material, such as corn starch; and photodegradable plastics, which will break down when exposed to sunlight. Degradable plastics are already being used successfully in Austria and Sweden, where McDonalds has been using bio-degradable cutlery for three years. This enables all catering waste to be composted without segregation. Carriers for packs of beer cans are now being manufactured in a plastic which photo-degrades in six weeks. There is also potential to use such plastics in non-packaging applications such as computer or car components.

The UK food industry accounts for 10 per cent of all industrial and commercial waste or 6.5 million tonnes, according to the government, and is under pressure to significantly reduce waste, especially from packaging. Only in the recent years, UK is building new recycling centres which are able to convert PET and HDPE plastics back into food grade raw materials for use in new plastic packaging. Such a close-loop recycling and reprocessing plant is based in Dagenham in London. Meanwhile, WRAP aims to have the UK's first mixed plastics reprocessing plant up and running by 2011.

3. Research findings

3.1 Plastic industry and recycling in the UK

3.1.1 Plastic industry in the UK

According to British Plastic Association (BPF, 2010), sales of plastics account for approximately £17.5 billion, which is equivalent to approximately 2.1% of UK GDP. Plastic industry employs 220,000 people in three major sectors - material and additive manufacture, material processors and machinery manufacture. They are more than 7,400 companies in the plastics industry, 3,000 of which primary processors. It is estimated that the UK produces annually approximately 2,500 kilo tonnes of plastics while the plastic processors in the UK Processors consumes 4,800 kilo tonnes of material.

3.1.2 Post-consumer plastic collection in the UK

In the UK, post-consumer plastics are largely collected by local authorities. Recycling of plastics bottles from households is one of the most significant solid waste collection activities of the UK's local authorities. Based on responses of 380 local authorities in the UK, WRAP (2008b) reported that 525,300 tonnes of plastics bottles were consumed in households throughout the UK in 2007. The total quantity of plastics bottles collected in the UK in 2007 was 181,887 tonnes. That means 35% of plastics bottles consumed by households are collected. Since there has been a considerable increase in the total quantity of plastics bottles collected mainly due to the increasing number of local authorities offering plastics bottle collection, the percentage of plastics bottle collection is expected to rise.

In some European countries, plastics bottles are collected by retailers. In the UK, plastic waste is not managed by retailers and manufacturers of products. For MSW, local authorities in the UK typically collect dry recyclables using kerbside collection schemes and bring schemes. Figure 7 illustrates how the single and two-stream collection schemes work. For kerbside sort collection scheme, it is possible to ask households to sort recyclables into different groups. If it is difficult to get households to do the sorting, local authorities will then offer two collections systems. A single-stream system collects or co-mingles all dry recyclables in one container / vehicle. Co-mingled dry recyclables are then sorted and washed manually and/or mechanically. In some instances pre-sorting are required. In twin-stream system there are two co-mingled inputs, usually one of co-mingled fibres (paper, card, etc) container and another container for bottles (HDPE, PET bottles, etc.). It is possible to avoid pre-sorting and cross contamination between fibre-based materials and containers in a twin-stream system. A study of the cost of different collection schemes by WRAP (2008c) indicated that the net cost of twin-stream co-mingled collections was similar to the net cost of kerbside sort scheme. Kerbside sort scheme potentially has lower cost than single-stream scheme, taking into account the sales of recovered materials. There is actually no systematic advantage for one recycling system for the "urban" and "rural" nature of the areas served (WRAP, 2008c).

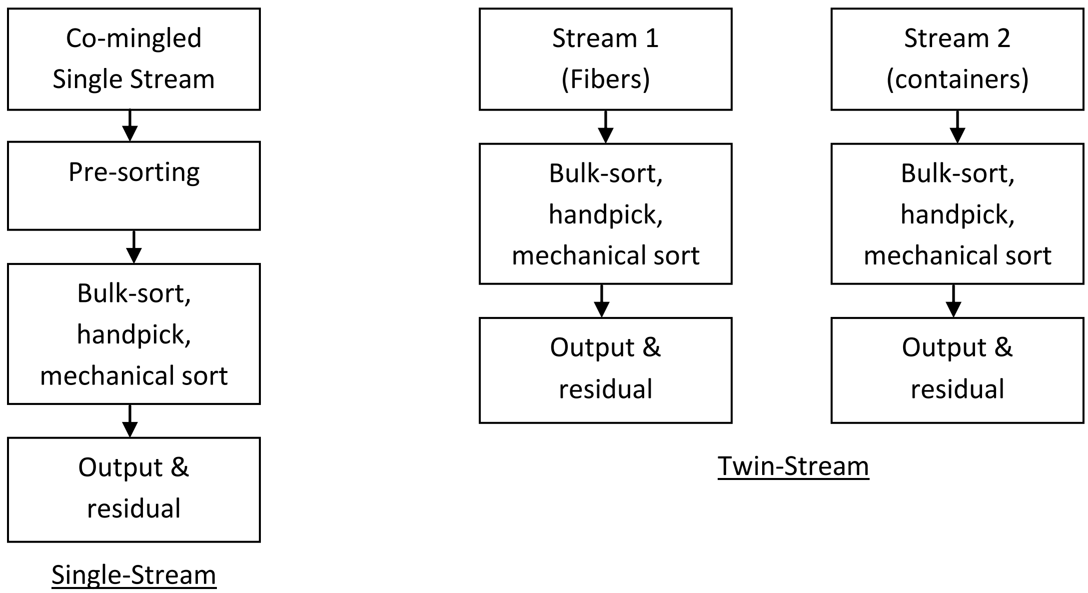

Figure 7 Single and two-stream collection schemes

The UK's local authorities use different plastics bottles collection schemes. In 2007, approximately 147,450 tonnes (81%) of plastics were recovered through kerbside collections, an increase of 77% from 2006. In 2007, 14.4 million households were given kerbside collection services by 304 local authorities (WRAP, 2008b). Other collection schemes such as the bring scheme is less popular. At the moment the main reason for not having a kerbside collections scheme for plastics bottle was "lack of spare compartments in kerbside collection vehicles". Due to cost pressure, local authorities prefer to use a single vehicle to collect as many types of waste a possible, but the need to collect plastics bottles and other plastics waste would mean investment in new vehicles and add cost. Another reason for the lack of investment in plastics collection schemes is the focus on heavier materials to hit recycling targets set by the central government. Recycling targets are set in terms of tonnage but plastics waste is lighter than other types of solid waste. Local authorities in the UK collected approximately 3.9 million tonnes of recyclable in 2007 and in terms of tonnage only about 5% of these are plastics bottles (WRAP, 2007 & 2008b). That explains why local authorities complained that their plastics bottle recycling schemes were a significant additional cost to their activities.

The majority of plastics bottles collected are made of HDPE and PET. Some UK local authorities indicated that they offer some form of 'other plastics' collection, even though the plastics bottle collection schemes do pull in other plastics'. These other plastics are often contaminated by other materials such as metals, food and plastics which are not currently recyclable.

Consumer recycling behaviour can be influenced by many factors. It is important to understanding households' views on different policy options to establish factors influence household recycling behaviour. Frequency of collection is a variable which influences the cost and effectiveness of waste collection schemes. When frequency of collection is reduced to reduce cost it is also possible that less recyclable is collected because containers for keeping household waste could be full and households might put recyclables to the waste containers (Tucker *et al.*, 2000). Disposal fee is found to be a significant economic incentive to Norwegian households (Kipperberg, 2006). Kipperberg (2006) suggested that recycling can be more effective when households are provided with convenient recycling options.

Each UK local authority typically collected 1 to 2,562 tonnes of plastics waste each year (WRAP, 2008b). Some local authorities own and operate their own kerbside collection facilities and material recovery facilities (MRFs). Many local authorities contracted sorting and baling operations to waste management companies or MRFs. Local authorities pay "gate fee" and "sorting fee" for every load of waste sent to the MRFs. Gate fees are influenced by factors such as competition, landfill tax, quality and quantity of material, energy cost, size of facility, and others (WRAP, 2008a). Some local authorities are aware of how their plastics sales were managed. Some of them have a contact with their MRFs and use spot markets to sell their plastics. Usually the contractors sell plastics on behalf of local authorities. In some cases the sales of plastics are earned by the local authorities so contracted MRFs may not have the interest in selling the plastics at the best price. Some local authorities have a revenue sharing contracts with their MRFs. To further encourage recycling, some local authorities pay their MFR contractors extra for any shortfall between the actual market price paid by the contractors for the recycling of sorted materials and the landfill charge. Another way to improve recycling quality is to charge MRFs extra for materials rejected from the material re-processors. In addition to encourage household recycling, incentive mechanisms discussed above resembles elements to further improve recycling efficiency and quality. The report about contractual arrangement between local authorities and MRF operators published by AEAT on behalf of WRAP provides more detail information about this issue (AEAT, 2006).

3.1.3 Post-consumer plastic re-processing in the UK

Material recovery/reclamation facilities (MRFs) play a key role in the creation of high-quality and high-value recovered/reprocessed plastics which become the feedstock for the plastics industry. MRF operations (for co-mingled materials) typically involve materials receipt, pre-sorting, managing flows, separating fibre (i.e. paper, card, cardboard) from containers (cans, plastics bottles, glass, bottles, jars), sorting of fibre into different grades, sorting of glass containers, metal containers, plastic containers, baling and shipping and managing residues.

MRF capacity in the UK plays an important role in the plastic recycling supply chain. The challenge is to provide the right capacity at the right place. A study by WRAP (2007) concluded that MRFs in the UK had a capacity of approximately 2.5 million tonnes per annum. However, it is estimated that only 55% of available MRF capacity was utilised in 2006. From a logistics perspective, many of the locations of MRFs do not match with the locations of waste arising (WRAP, 2008b). Also, the collection schemes of some local authorities do not match with the available MRF capacity. Many local authorities chose to use co-mingle collection scheme but there are inadequate co-mingle waste MRFs available. Due to the uncoordinated investment in MRFs and collection schemes, it is expected to see a greater gap between local authority's collection schemes and MRF capacity. Furthermore, the quality of re-processed plastics from co-mingled waste is usually too low for most plastics moulder. It is estimated that only 25% of dry recyclables would be send to MRFs in the UK in 2015 (WRAP, 2008b).

It is also essential to ensure that the quality of recovered / reprocessed plastics is acceptable and their prices are not too high. Efficient MRFs should be able to operate within the range of 2% to 5% residue but it is reported that the residual rates (due to contamination) of UK's MRFs ranged from 5% to 17% (WRAP, 2007). Poor quality feedstock produced by the plastics recycling industry is one of the reasons for the poor availability of recovered feedstock facing by the plastics industry.

The next challenge facing the plastics recycling industry in the UK is the lack of visibility. In many cases, local authorities did not know the primary market for their other plastics (WRAP, 2008b). Not many local authorities receive information whether their plastics waste was re-processed in the UK or exported elsewhere. There are many small and medium size waste management companies and traders and they do not trace the origins of the plastics they sell.

3.2 Major recycling players in Yorkshire and Humber

Yorkshire and Humber is divided into 22 local authorities. As indicated by Table 2, bring and kerbside collection schemes are used to collect plastics bottles and other plastics packaging materials. The majority of the 22 local authorities offer bring scheme (plastics bottle banks at the supermarkets and recycling sties). There are more than 300 bottle banks in the region. Hull is the smallest local authority in terms of land area but it is also the most populated local authority. Ryedale is the largest local authority in terms of land area but it has only in average 93 populations in each mile^2. Local authorities with very large land areas usually only afford to offer bring scheme, because kerbside collection scheme would be too expensive to run. Thus, it is estimated that less than half of the 22 local authorities offer both kerbside collection and bring schemes for plastics.

Local authorities	Area (mile^2)	Population density (mile^2)	Collection schemes
Scarborough	315.1	344.6	Bring & kerbside
Ryedale	581.7	93.3	Bring & kerbside
Richmondshire	509.1	101.0	Bring & kerbside
Craven	454.3	124.4	Bring & kerbside
Harrogate	504.9	318.7	Bring & kerbside
Hambleton	506.0	171.0	Bring & kerbside
York	105.0	1779.8	Bring & kerbside
Selby	231.3	354.9	Bring & kerbside
East Riding	929.9	360.1	Bring & kerbside
Hull	27.6	9031.1	Bring & kerbside
North Lincolnshire	326.7	489.6	Bring & kerbside
NE Lincolnshire	74.0	2137.3	Bring & kerbside
Leeds	213.0	3575.1	Bring & kerbside
Bradford	143.0	3341.9	Bring & kerbside
Calderdale	140.5	1424.9	Bring & kerbside
Kirkless	157.7	2562.2	Bring & kerbside
Wakefield DC	130.7	2466.3	Bring & kerbside
Barnsley	127.0	1779.8	Bring & kerbside
Doncaster	219.2	1329.0	Bring & kerbside
Sheffield	142.0	3764.2	Bring & kerbside
Rotherham	110.6	2295.3	Bring & kerbside

Table 2 Local authorities and collection schemes[1]

Of the 22 local authorities located in the Yorkshire and Humber region, almost every authority offers recycling collection facilities for plastic bottles (PET and HDPE). However, only very few local authorities collect other types of plastics such as plastics bags, yogurt ports and meat trays. The total plastics waste collected in this region in 2008 is estimated at 6,739 tonnes.

[1] Note: Data presented in this table is based on information from WRAP homepage and the survey study during the time of the study.

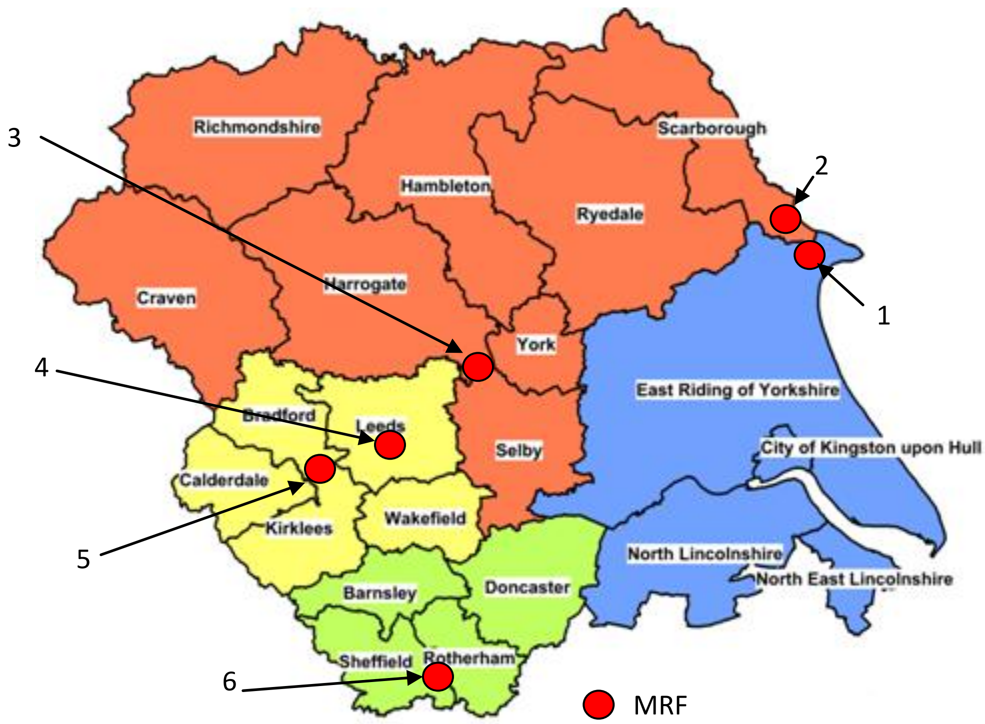

Figure 8 MRFs in Yorkshire & Humber region

All the 22 local authorities do not own material recovery facilities (MRFs); they are all owned by private businesses. Figure 8 shows the locations of the six major MRFs responsible for mostly post-consumer waste management in the Yorkshire and Humber region discovered during the study. They are contracted by local authorities to sort and bale plastics collected by local authorities in the region. There are many other small and medium-size waste management companies who collect waste from farms and industries. Most of these major MRFs are located close to highly populated areas such as York, Leeds, and Sheffield. Other less populated areas such as those at the North Yorkshire are mainly served by bring schemes and either the local authorities or the MRFs are responsible for collecting the waste from bring sites to the MRFs.

Table 3 summaries the details of the six major MRFs in Yorkshire and Humber region. Four of the MRFs provide single stream processing. That means local authorities collect all recyclable waste stream co-mingled in one bin from households and deliver all of them to the MRFs. The MRFs in Hessay and Beighton receive two-stream materials (e.g. fibres and containers). Many other smaller MRFs identified by a prior research by Recycling Action Yorkshire (RAY, 2006) are still operating but several local authorities have started to send their materials to larger MRFs outside to the region. Unfortunately, many of the existing MRFs are too old and operating with old and inefficient systems and processes. Furthermore the total capacity of all the six MRFs is not enough for the whole region. Some local authorities have to send a lot of the collected materials to other regions for sorting and baling.

Number	1	2	3	4	5	6
Location	Bridlington	Scarborough	Hessay	Leeds	Kirkless	Beighton
Owner	East Ridings	Yorwaste	Yorwaste	H.W. Martins	SITA	Veolia
Operator	WRG	Yorwaste	Yorwaste	H.W. Martins	SITA	Veolia
Year MRF opened	2005	2000	2003	2007	2001	2003
Form of processing	Single stream	Single stream	2 streams	Single stream	Single stream	2 streams
Maximum capacity	4.0 tonnes/hr	15.0 tonnes/hr	12.0 tonnes/hr	18.0 tonnes/hr	10/0 tonnes/hr	12.0 tonnes/hr
% household recyclables	100%	100%	100%	98%	100%	100%

Table 3 Details of MRFs

MRFs normally only sort and bale plastic waste and sell bales of plastics to the spot market, plastic re-processors or export markets. Plastic re-processors purchase these plastic bales and perform cleaning, shredding and regrinding and the finished products are called regrinds. Regrinds are them compounded and extruded into granules (pellets). Some plastic re-processors only produce regrinds; some other re-processors also perform compounding and extrusion and produce granules or pellets which are then sold to plastics injection moulding companies (converters) as secondary materials (instead of using virgin polymers). Plastics bales can also be sold to foreign countries for re-processing.

Within Yorkshire and Humber region there are only a few large plastics re-processors. Linpac Packaging was established in 1991 at Castleford, West Yorkshire with an initial capacity of processing 2,000 tonnes post-consumer polystyrene (PS) products. The re-processing plant is now able to re-process polystyrene (PS), polyethylene (PE) and polypropylene (PP) from both industrial and post-consumer users at 30,000 tonnes, driven by demand from packaging automotive and electrical industries. The plant collects/purchases regrinds from bottles and yogurt ports, and injection moulding waste from the plastics industry. Regrinds are produced by some MRFs or local re-processers or purchased from spot markets. The plant has machineries and facilities for shredding, grinding, washing and compounding. The plant produces re-extruded granules (pellets) of secondary raw materials which can substitute for prime virgin materials needed by the plastics industry. The aim of the company is to supply specified recycled compounds that supplant prime in blue chip applications while supporting the customer's requirements on fitness for purpose, continuity of supply, cost and the environment. The growth of the company is limited by the limited availability of high quality plastics regrinds. sourcing material – they have excellent technical capabilities and a wide range of developed markets. Their main barrier to growth is the sourcing of increased volumes of plastic materials at prices that maintain the competitiveness of their end products.

Another re-processor in the region, i-plas (formerly Intruplas) was originally established in 1999 with the sole objective of developing the technology needed to efficiently and effectively treat and recycle plastic waste and to produce materials and products for the benefit of customers and the wider society. i-plas was initially established with support from the European Landfill Tax Scheme, Kirklees MBC and Calderdale MBC in recognition that plastic waste was a growing environmental concern. i-plas has developed a unique waste processing technology and it is one of the UK’s leading suppliers of manufactured innovative plastic composites for traditional and high performance applications. i-plas provides an extensive range of standard and bespoke products to a wide range of customers. Annually i-plas is able to process up to 6,000 tonnes of mixed waste plastic. When possible, i-plas also provides closed-loop recycling schemes i.e. collect waste materials from customers and re-process the waste materials and supply back the recovered materials to the customers.

3.3 Case studies methods and scopes

The flows of plastics waste at the Yorkshire and Humber region are studied by conducting interviews and cast studies of local authorities’ collection activities. This study collected detail information about five selected local authorities from Yorkshire and Humber region.

Local authorities	Population density (per mile^2)	Collection schemes	Sorting	Annual plastic recycling rates (kg/household)
Hambleton	171	Kerbside & Bring	Kerbside sort	8.33
Hull City	9031	Kerbside & Bring	2-stream co-mingled	17.96
East Ridings	360	Kerbside & Bring	1-stream co-mingled	6.90
Wakefield DC	2466	Kerbside & Bring	3-stream co-mingled	14.72
North Lincolnshire	489	Kerbside & Bring	2-stream co-mingled	4.56

Table 4 Plastic recycling of some selected councils

Table 4 summarises details of the studied local authorities. They are selected to cover some of the least and most populated areas, as well as local authorities with low and high plastics recycling rates. The boundaries for the case studies are indicated in Figure 9. The case studies include collection of waste from households, compacting, sorting, and possibly local re-processing (if not waste is exported), compared with the production of virgin plastics.

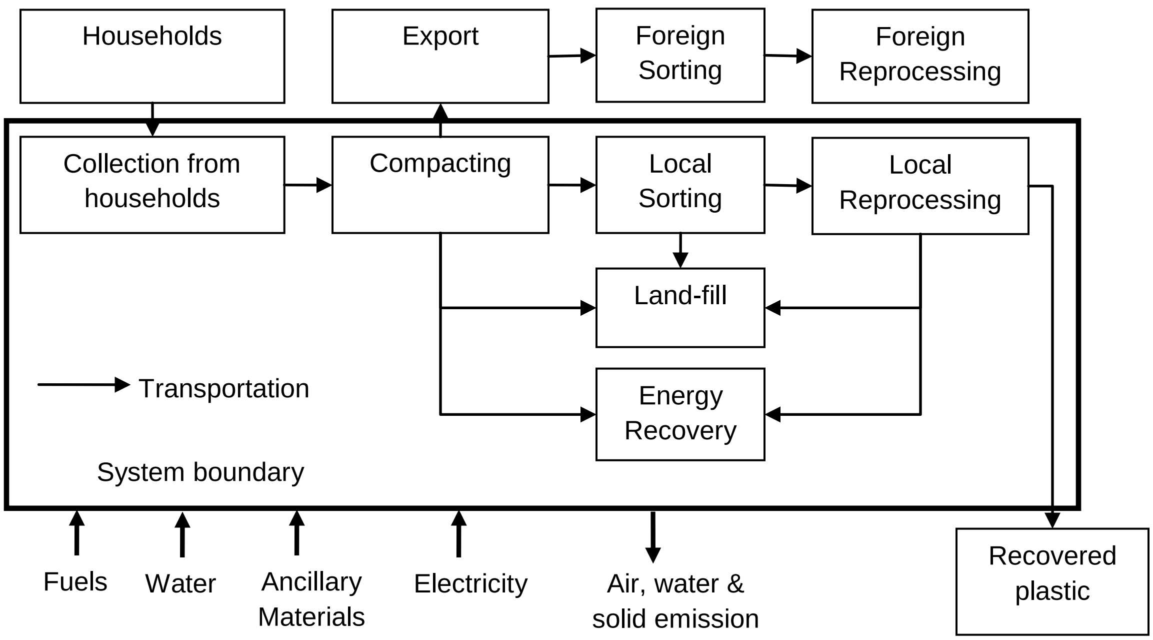

Figure 9 System boundaries for case studies

As indicated in Figure 9, the case studies consider energy, waster, solid and other ancillary materials as input and air, water and solid emission as output of the recycling system using life-cycle inventory analysis (LCIA) and material flow analysis (MFA). The case studies are presented below.

3.4 Case studies findings

Table 4 summarises the collection/sorting schemes and annual plastic recycling rates for the selected councils. It illustrates that plastic recycling rates vary greatly across councils. Factors such as land area, population density, collections & sorting schemes will influence the life cycle inventories and hence environmental impacts of the recycling efforts. A densely populated council (e.g., Hull City and Wakefield) with co-mingled kerbside and bring schemes will more likely to achieve higher plastic recycling rates; However, with this setup the cost and energy consumption during for sorting will increase and the reprocessing will be less efficient due to a higher level of contamination. Even though a kerbside sort will reduce contamination it will also increase the transportation cost and emission. This is why complete LCA and LCIA are useful tools for supporting decisions on collection and sorting schemes, and locations of MRFs and re-processors.

3.4.1 Baseline model and recycling model

It is useful to compare the life cycle inventories between the productions of plastic using virgin materials with the productions of recovered plastics using recycled plastics. Basically PET and HDPE are two commonly used and recycled plastic packaging materials. Table 5 illustrates the baseline model (production of virgin plastic, Polyethylene Terephthalate, PET) and the recycling model (production of recycled plastic, PET). The production of virgin plastic consumes energy (in the form of derivatives of crude oil), water, energy and other solid materials, and then produces air, solid and waterborne emissions, as well as heat. It is estimated that 4% of the world's annual oil production is used to produce and manufacture plastic. The production of recycled plastics require limited derivatives of crude oil but uses recovered plastic as feedstock, and it produces similar types of emissions at different amount.

Input and Output	1kg virgin plastic (PET)[2]	1kg recycled plastic (R-PET)[3]
Input		
Energy (& petroleum)	84MJ	7.97MJ
Waterborne	17.5kg	2.96kg
Other input materials	0.01kg	0.024kg
Output		
Atmospheric emission	6kg	3.5kg
Solid waste	45.13kg	0.31kg
Waterborne emission	21.46kg	12.82kg

Table 5 Environmental inventories of virgin vs. recycled plastic production

The energy consumptions of the production process of different virgin plastics range from 53MJ to 107MJ per kg plastic. According to a study of PET recycling in Italy, energy consumption of the collection, sorting, transportation and production of recycled PET (R-PET) was estimated at 7.97MJ/kg (Arena *et al.*, 2003a), resulting a saving of 76MJ/kg of R-PET produced (Note that the production recycled mixed plastic saves only one third of the energy, according to

[2] Data from http://www.wastereduction.org/Baxter/Bax5.htm and http://timeforchange.org/what-is-a-carbon-footprint-definition

[3] According to Arena *et al.* (2003a)

www.wasteonline.org.uk). Another obvious benefit of recycling plastic is the lower level of atmospheric emission (e.g., NO, SO_2, and CO_2). These data can provide direction to efforts for change by showing which activities require most energy or other resources, or which activities contribute the most pollution. The above comparison demonstrates great savings in inputs and substantial reduction in output in the forms of air, water and solid emissions due to the production of recovered plastics; however, it has not considered the activities associated with the collection, transportation, sorting, and reprocessing of recycled plastic.

3.4.2 Hambleton District Council case study

In North Yorkshire the provision of recycling facilities is shared between North Yorkshire County Council and the District Councils. Hambleton District Council (DC) has approximately 86,800 population and 38,943 households in a land area of 1,310 Km^2 (506 m^2), i.e. 171 people per $mile^2$. Hambleton DC provides bring scheme, kerbside-sort scheme and household waste collection centre (HWRC). The number of properties served by kerbside scheme is approximately 37,526 (96%). Kerbside collection operates once every two weeks. The reason for Hambleton to use kerbside-sort scheme is to avoid contamination in the collection vehicles.

Hambleton DC sub-contracts kerbside collection to a local company. The company uses five kerbside collection vehicles for collecting recycle materials. Dennis Eagle (Terberg) trucks are used. To collect 279 tonnes of recycle materials, the five vehicles run for approximately 140,000 miles last year. Bring sites are another source of recycle materials. Hambleton has about 150 bring sites located in major towns and villages. Altogether there are six bring sites with plastics bottle recycling facilities. Bring sites are emptied once weekly by other vehicles (Hooklife). The bring scheme collected only 45 tonnes of plastics last year. In total approximately 324 tonnes of plastics were collected last year, with only 8.3 kg of plastics collected for each household annually. The main issue with plastics collection is that the vehicles are filled very quickly with very low weight. With an overall recycling rate of 46.3%, Hambleton DC is hoping to expand its collection scheme to include mixed plastics such as food trays and yogurt pots in the future.

The life cycle inventory analysis (LCIA) results for Hambleton reflect its collection scheme and tonnage. The LCIA results for Hambleton are summaries in Figure 10. Typically recycling trucks can be 10-20 years old and less fuel efficient due to the use of low speed during waste collection. A study in the US suggested that a typical recycling diesel truck travels 2.8 miles per US gallons (3.6 miles per imperial gallons, mpg). Feedbacks from Hambleton DC suggested that 4 mpg as a reasonable average. Based on this, the amount of diesel consumed annual for the collection of dry recycled materials from households by Hambleton DC is estimated.

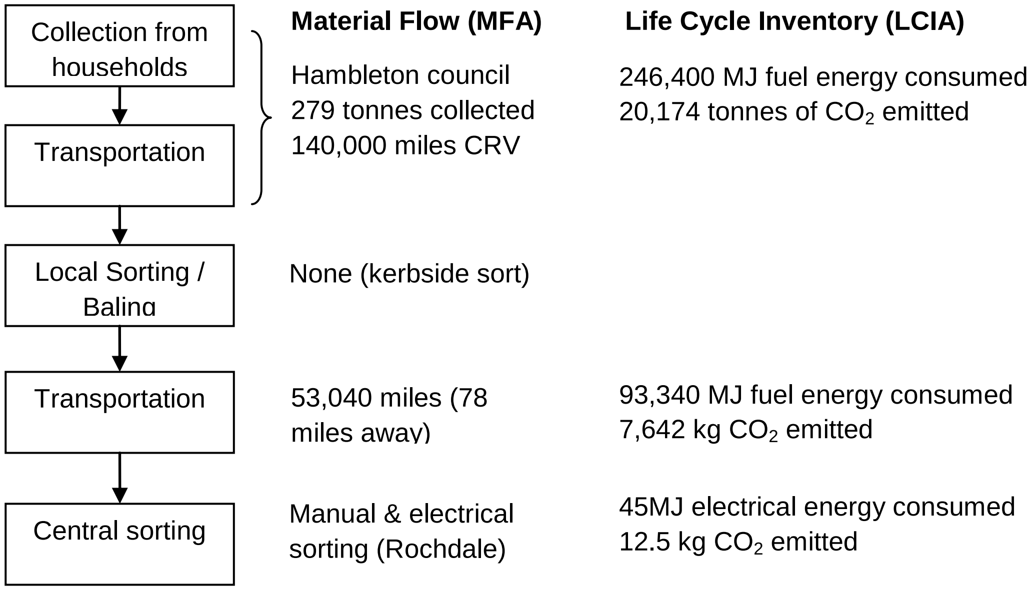

Figure 10 LCIA for Hambleton DC's plastics recycling

Based on five recycling trucks, Hambleton Council collected 279 tonnes of plastics waste in 2009 from 37,500 households covering a land area of 506 m^2. These trucks travelled a total of 140,000 miles in one year and consumed an estimated 35,000 gallons (based on 4 mpg) or 7700 liters of diesel (1 gallon = 4.546 liter), equivalent to 246,400 MJ (32MJ/liter) energy consumption and 20,174 tonnes of CO_2 (2.62 kg CO_2/liter). There is no MRF in Hambleton DC; thus, the collected waste needed to be sent to a central sorting MRF 78 miles away. In average one load was sent daily leading to 53,040 miles of transport, consuming 93,340 MJ of fuel energy and producing 7,642 kg of CO_2. Since the waste was sorted by households into plastic, glass and papers the sorting process at the MRFs was relatively simpler. According to Arena *et al.* (2003a), mechanical and manual sorting process consumes approximately 0.16 MJ/kg of electrical energy. Thus, the sorting of the 279 tonnes of plastic waste consumed 45MJ of electrical energy and produced 12.5 kg of CO_2 (estimated 1000 g CO_2/Kwh for a coal fired power plant). In summary, the collection, transportation and sorting of 279 tonnes of plastic waste from Hambleton DC consumed 339,740MJ of fuel energy and 45MJ of electrical energy, and produced 37,828.5kg of CO_2.

3.4.3 Hull City Council case study

Hull City Council has approximately 249,100 population and 116,712 households in a land area of 27.6 $mile^2$, with over 9031 people in each $mile^2$. Hull City Council provides bring scheme, kerbside scheme, and household waste collection centre (HWRC). Kerbside two two-stream (garden/food and dry recycle materials) co-mingled collection scheme is provided to 100% of households in the council area. Kerbside collection operates once every two weeks. Plastics bottles and mixed plastics (e.g. food tray and yogurt ports) are collected.

Hull City Council owns kerbside collection vehicles. The council has 12 kerbside collection vehicles for collecting recycle materials. 26-tonne CRV trucks are used. The council has no record of the mileage spent to collect the 2,000 tonnes of recycle materials. Bring sites are another source of recycle materials. Hull City Council has about 72 bring sites located in supermarkets, schools, and council amenity car parks. All the 72 bring sites provide plastics bottle recycling facilities. Bring sites are emptied once every month or ever two weeks by other vehicles (top loaders). The bring scheme collected only 82 tonnes of plastics last year. The four HWRS centers collected 15 tonnes of plastics. In total approximately 2,097 tonnes of plastics were collected last year, with only 17.9 kg of plastics collected for each household annually. The council achieved an overall recycling rate of 34.3% last year.

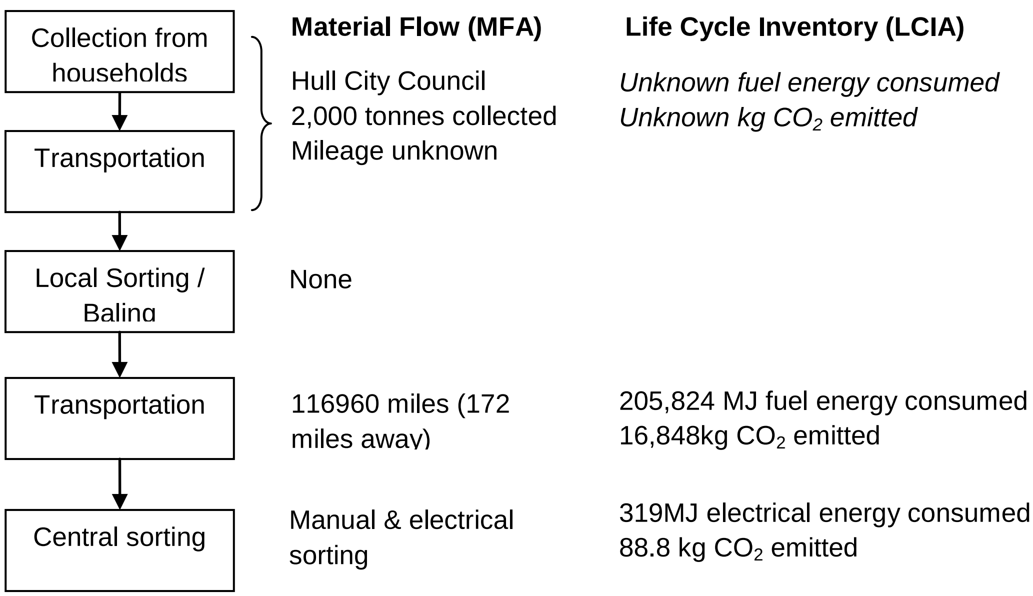

Figure 11 LCIA for Hull City Council's' plastics recycling

The life cycle inventory analysis (LCIA) results for Hull City Council reflect its collection scheme and tonnage. The LCIA results for the council are summaries in Figure 11. Hull City Council collected 2,000 tonnes of plastic waste from 116,712 households covering a land area of 27.6 mile^2 by unknown vehicle miles. Without the vehicle mileage information the LCIA is incomplete. However, with a highly populated area the energy consumption and carbon emission are expected to be lower than those from other councils such as Hambleton and East Ridings. Next, the collected waste is sent to transfer stations operated by a local MRF. The co-mingled waste is sent to another MRF outside of the Yorkshire and Humber region nearby Birmingham 172 miles away. In average two loads were sent daily leading to 116,960 miles of transport, consuming 205,824 MJ of fuel energy and producing 16,848 kg of CO_2. Based on the same assumptions of Arena *et al.* (2003), the sorting of the 2,000 tonnes of plastic waste consumed 319MJ of electrical energy and produced 88.8kg of CO_2. In summary, the collection, transportation and sorting of 2,000 tonnes of plastic waste in Hull City council consumed at least 205,824 MJ of fuel energy, and 319MJ of electrical energy and produced at least 16,848 kg of CO_2. It is noted that the plastics processed in the MRF near Birmingham could be either sold to sport markets locally, or exported to Europe or other foreign countries.

One of the problems facing Hull City Council was that plastic products are very light but with bulky. Bins can fill quickly and light loads are sent to the MRF. Transportation cost from the council to the MRF in Birmingham is high. There is some but insignificant contamination problem.

3.4.4 East Ridings Council case study

East Ridings of Yorkshire Council has approximately 335,049 population and 149,747 households in a land area of 930 m^2. East Ridings provides bring scheme, kerbside scheme and household waste collection centre (HWRC). Kerbside single-stream co-mingled collection scheme is provided to 100% of households in the council area. Kerbside collection operates once every four weeks to reduce costs of collection. So far only plastics bottles are collected.

East Ridings owns kerbside collection vehicles. The council has 43 kerbside collection vehicles for collecting recycle materials. 26-tonne CRV trucks are used. To collect 896 tonnes of recycle materials, the collection vehicles run for approximately 110,000 miles last year. Bring sites are another source of recycle materials. East Ridings has about 143 bring sites located in supermarkets, pub, and council amenity car parks in major towns and villages. Altogether there are 15 bring sites with plastics bottle recycling facilities. Bring sites are emptied once every month by other vehicles (HIAB). The bring scheme collected only 42 tonnes of plastics last year. The HWRS system collected 108 tonnes of plastics. In total approximately 1,046 tonnes of plastics were collected last year, with only 6.9 kg of plastics collected for each household annually. With an overall recycling rate of 33.8%, East Ridings is hoping to expand its collection scheme to include mixed plastics such as food trays and yogurt pots in the future.

The life cycle inventory analysis (LCIA) results for East Ridings reflect its collection scheme and tonnage. The LCIA results for the council are summaries in Figure 12. East Ridings collected 896 tonnes of plastic waste from 149,750 households covering a land area of 930 m^2 by a total of 110,000 miles of travel. This is equivalent to 27,500 gallons or 6050 liters of diesel, consuming 193,600 MJ of energy and emitting an estimated of 15,851 kg of CO_2. Next, the collected waste needed to be sent to a central sorting MRF in average 23 miles away (Bridlington). The MRF is owned by the council but operated by a contractor under a 25 years contract. In average one load was sent daily leading to 15,640 miles of transport, consuming 27,523 MJ of fuel energy and producing 2,253 kg of CO_2. Based on the same assumptions of Arena *et al.* (2003), the sorting of the 896 tonnes of plastic waste consumed 143MJ of electrical energy and produced 39.8 kg of CO_2. In summary, the collection, transportation and sorting of 896 tonnes of plastic waste in East Riding Council consumed 221,123MJ of fuel energy, and 143MJ of electrical energy and produced 18,143.80.5kg of CO_2.

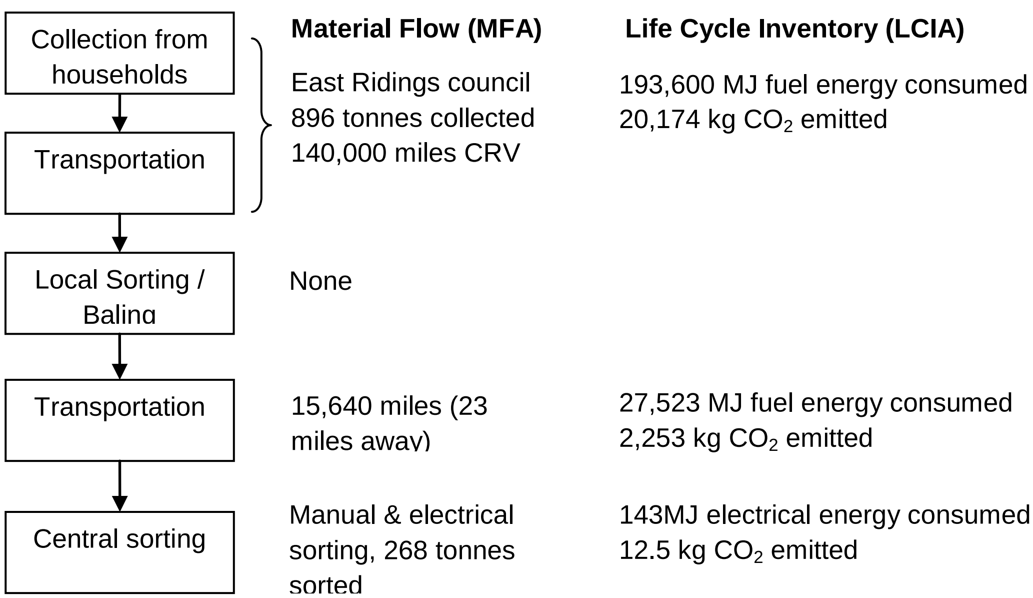

Figure 12 LCIA for East Ridings council's plastics recycling

One of the major problems facing East Ridings is the high cost involved in operating bring banks for plastic. Collection costs are high due to large size and rural nature of authority. Materials put into bring banks are bulky but there is no equipment for compaction. Materials sent to the MRF gets a degree of contamination with other plastic grades which are removed at the MRF and land-filled. There is less contamination in materials from the bring banks perhaps because there are very clearly labels and bottle sized openings at the bring banks' containers. Even though there is intention to collect mixed plastics, there is currently no MRF with the ability to process mixed plastics in the region. The current MRF cannot process mixed plastics so mixed plastics are considered contamination.

3.4.5 Wakefield Metropolitan District council case study

Wakefield Metropolitan District Council (DC) has approximately 322,319 population and 148,000 households in a land area of 130 mile^2, with over 2466 people in each mile^2. Wakefield Metropolitan DC provides brings scheme, kerbside scheme, and household waste collection centre (HWRC). Kerbside two-stream collection scheme is provided to 146,000 households in the district area. Kerbside collection operates once every two weeks.

Wakefield Metropolitan DC owns kerbside collection vehicles. The DC has 11 kerbside collection vehicles for collecting recycle materials. 26-tonne CRV trucks are used. The DC collected 1,979 tonnes of recycle plastics last year. Bring sites are another source of recycle materials. The DC has about 20 bring sites. Bring sites are emptied two to three times each week. The bring scheme collected only 200 tonnes of plastics last year. There are 7 HWRS systems but no report on plastics collection is available. In total approximately 2,179 tonnes of plastics were collected last year, with only 14.7 kg of plastics collected for each household annually, and an overall recycling rate of 36%. Plastic is estimated to cover 26% of all collected recyclable materials.

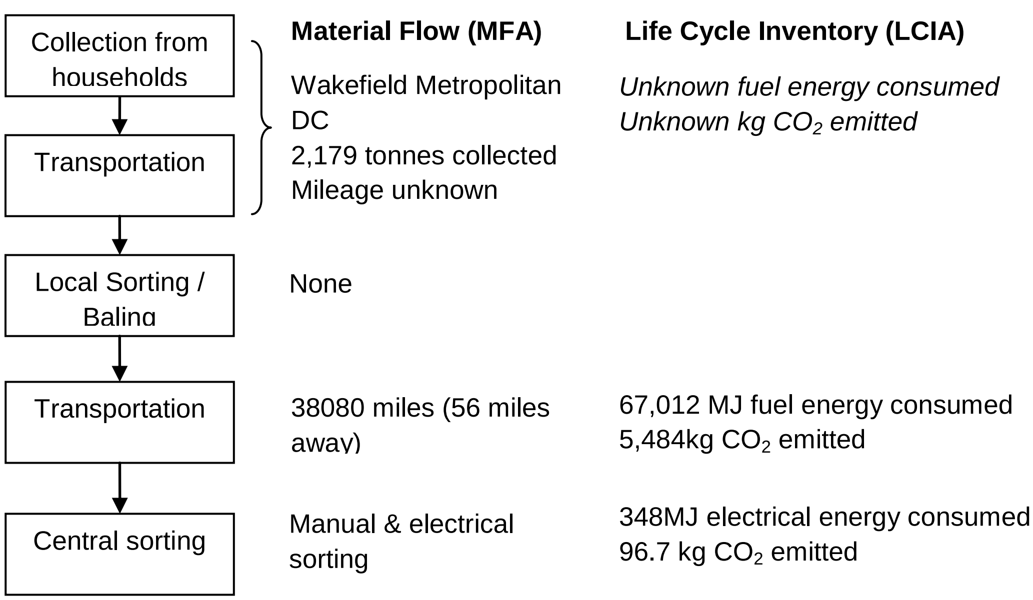

Figure 13 LCIA for Wakefield Metropolitan DC's plastics recycling

The life cycle inventory analysis (LCIA) results for Wakefield Metropolitan DC reflect its collection scheme and tonnage. The LCIA results for the council are summaries in Figure 13. Wakefield Metropolitan DC collected 2,179 tonnes of plastic waste from 146,000 households covering a land area of 130 mile^2 by unknown vehicle miles. Without the vehicle mileage information the LCIA is incomplete. However, with a highly populated area the energy consumption and carbon emission are expected to be lower than those from other councils such as Hambleton and East Ridings. The collected plastics are sent to a MRF called GRUK in Barnsley for sorting and baling and later sent to a re-processing plant in Derby, Midland at 56 miles away. In average two loads were sent daily leading to 38,080 miles of transport, consuming 67,012 MJ of fuel energy and producing 5,485 kg of CO_2. Based on the same assumptions of Arena *et al.* (2003), the sorting of the 2,179 tonnes of plastic waste consumed 348MJ of electrical energy and produced 96.7kg of CO_2. In summary, the collection, transportation and sorting of 2,179 tonnes of plastic waste in Wakefield Metropolitan DC consumed at least 67,012 MJ of fuel energy, and 348MJ of electrical energy and produced at least 5,581 kg of CO_2. It is noted that the plastics processed in the MRF at Derby could be either sold to sport markets locally, or exported to Europe or other foreign countries.

The major problem facing Wakefield Metropolitan DC is the cost of collection due to the complexity originated from the multi-stream collection schemes and the frequency of collection adopted. Another problem is about the difficulty in encouraging households to participate in plastics recycling. It is hoped that the packaging and retail industries are able to standardize plastic types so public do not have to identify and sort different polymer types. It is currently very confusing and difficult for the DC to disseminate the right information to the households.

3.4.6 North Lincolnshire council case study

North Lincolnshire Council has approximately 160,000 population and 72,161 households in a land area of 326.7 mile^2, with over 489 people in each mile^2. North Lincolnshire Council provides brings scheme, kerbside scheme, and household waste collection centre (HWRC). Kerbside three two-stream collection scheme is provided to all households in the council area. The two-stream co-mingled kerbside collection operates once every two weeks by eight council owned refuse vehicles. Only plastics bottles are collected.

North Lincolnshire Council collected 3,256 tonnes of plastics in 2008/09 but mileage spent is unknown. Bring sites are another source of recycle materials. Out of the 38 brings sites 22 of them allow disposal of plastic materials. Bring sites are emptied fortnightly. The bring scheme collected only 25.5 tonnes of plastics. There are 8 HWRS systems but no report on plastics collection is available. In total approximately 3,289 tonnes of plastics were collected last year, with 45.5 kg of plastics collected for each household annually, and an overall recycling rate of 49%. The council sent 6% of the collected plastics to landfill due to contamination and other reasons.

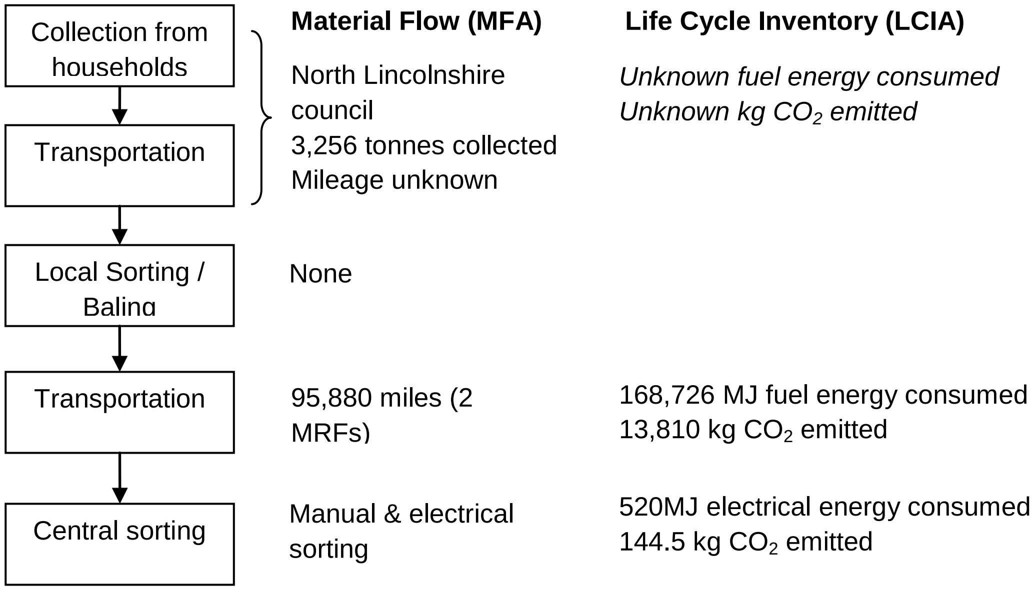

Figure 14 LCIA for North Lincolnshire's plastics recycling

The life cycle inventory analysis (LCIA) results for North Lincolnshire Council reflect its collection scheme and tonnage. The LCIA results for the council are summaries in Figure 14. North Lincolnshire Council collected 3,256 tonnes of plastic waste from 72,161 households covering a land area of 326.7 mile^2 by unknown vehicle miles. Without the vehicle mileage information the LCIA is incomplete. The collected plastics are either sent to a MRF in Rochdale, Lancashire, 107 miles away or another MRF in Caenby Corner, Lincolnshire 34 miles away. In average it is estimated that one load was sent daily to each of the two MRFs 95,880 miles of transport, consuming 168,726 MJ of fuel energy and producing 13,810 kg of CO_2. Based on the same assumptions of Arena *et al.* (2003), the sorting of the 3,256 tonnes of plastic waste consumed 520MJ of electrical energy and produced 144.5kg of CO_2. In summary, the collection, transportation and sorting of 3,256 tonnes of plastic waste in North Lincolnshire Council consumed at least 168,726 MJ of fuel energy, and 520MJ of electrical energy and produced at least 13,955 kg of CO_2. It is noted that the plastics processed in the MRFs could be either sold to sport markets locally, or exported to Europe or other foreign countries.

3.4.7 Greenstar – a single-stream waste management company

Since there is no large single-stream waste management company in the Yorkshire and Humber region, a lot of the post-consumer recyclable materials are sent to waste management companies outside of the region. For example, the single-stream recyclable materials collected by Hull City Council are sent to a MRF at Walsall, West Midland operated by Greenstar even though Greenstar has a MRF in Dewsbury, West Yorkshire and another MRF in Skegness, Lincolnshire. Greenstar operates integrated waste collection, recovery and recycling activities through the operation of a network of state-of-the-art Materials Recovery Facilities (MRFs) around the UK combined with modern fleet logistics, skips and bins. The Greenstar MRF plant built in 2008 at Walsall has an annual capacity of up to 300,000 tonnes of paper, card, glass, aluminium, steel and plastics.

The Greenstar MRF in Walsall is specifically designed to sort and bale single-stream co-mingled materials. The increasing use of single-stream by local authorities is driven by cost pressure. The landfill tax is expected to rise to £72 in three years time, nearly double today's rate. UK's recycling rates are among the worst in the EU and there is a need to increase the recycling rate. Past experience of local authorities which switched to single-stream collection system saw rocketing recycling and composting rates and landfill rates decreasing. Apparently the participation of UK households in kerbside-sort and multiple-stream collection schemes is much lower than the participant of UK households in single-stream collection scheme.

Just like other new nation-wide MRFs in the UK, Greenstar's collection and recycling supply chain relies on hundreds of operational depots and suppliers around the UK. Greenstar attempts to establish long-term relationships with its sub-contractor. There is a 'preferred suppliers' system in Greenstar recycling network. This network of preferred suppliers has taken almost 10 years to develop. To ensure reliable supply of recyclable materials, Greenstar takes a partnership approach, meaning there is much more to the supplier management than just 'brokering services'.

The recycling industry has also moved on to the use of more integrated information and reporting systems. For example, Greenstar has an online management tool for customers to extracts data off from Greenstar information system to produce reports on the up to date scheduled service, all extra and additional collections, detailed breakdown of waste streams showing landfill and recycling figures by customer, and collection service performance report. With these improved information and reporting systems, customers become more aware of the recyclable materials they collected. For example, Hull City Council now realised that about 50% of the materials collected (in tonnage) are mixed paper; roughly 30% are glass, 4% are steel, and only about 7% are plastics (2% mixed plastics, 1.8% PET natural, 1.8% LDPE, 1% HDPE natural, and the rest HDPE Jazz and PET Jazz).

Another Greenstar MRF located at Redcar is one of the MRFs with the latest technology for processing plastics in Europe. The plant hires 70 employees and processes 24,000 tonnes of plastics. Built in 2003, the plant sorts, cleans, processes, and compounds all types of plastic including food grade materials such as milk bottles, food trays and cosmetic bottles. Another

Greenstar's latest attempt is the processing of food grade recycled HDPE (rHPDE). The aim is to sort bales of milk bottles and finish with a food safety quality rHPDE pellet. The key is to clean the milk bottles to avoid any contamination. However, this involves a lot of processes. The first step is material inspection. Baled milk bottles are inspected and hand sorted to remove any metal and separate milk bottles into colour groups. The milk bottles are then shredded, cleaned, and further separated. Next is the granulation process which includes air separation and dry cleaning and further three stages of centrifuge and then optical sorting before going on to the extrusion process to produce food grade pellets. The food grade pellets are inspected and tested in the laboratory. The quality good grade pellets are then transported to the bottle production plants.

3.5 Cross-case analysis

In the following sections comparison of cases are made to highlight similarities and differences across different cases of post-consumer plastics recycling logistics systems especially in terms of collection schemes, the use of MRFs, and LCIA analysis.

3.5.1Collection schemes

Even though all the five local authorities under this research employed kerbside collection schemes, they chose different sorting solutions (see Table 4). Hambleton DC uses kerbside sort meaning households are asked to sort the recyclable materials and the collection vehicles have different compartments for different materials such as glass, fiber/paper, plastic, metal, etc. This is a very inefficient use of transportation capacity but this is a better way to avoid contamination. This method produces an average household plastics recycling rate (8.3kg/household/year).

Other local authorities chose to use single or multiple-stream co-mingled solutions. That means households are given two or more bins for different types of materials and there are two or more different types of collection vehicles. It is typical to have one stream for dry recyclable materials (fiber, paper, glass, and plastic) and another stream for garden or food waste materials (e.g. Hull City). The more different streams involved the more vehicles required and the less efficient it is in term of fuel consumption and the higher GHG emission it emit. Without considering the geographical factor, when we compare the kerbside-sort collection scheme of Hambleton with the single stream co-mingled collection scheme of East Ridings, the mileage and fuel consumption appears to be higher for the kerbside sort solution. With co-mingled materials it is often easier for local authorities to encourage recycling and achieve higher recycling rates, especially for more populated council areas such as Hull City Council (17.9kg/household/year) and Wakefield DC (14.7kg/household/year).

However, this research has not specifically compared the life cycle inventories among single, two or three-stream co-mingled recycling systems because the focus is just plastics not other recyclable materials. However, contamination is the main trouble for co-mingling materials. Many local authorities are tolerable to this problem because contamination level is generally low (below 5%).

3.5.2 MRFs

This research found very few large-scale modern material recovery facilities (MRFs) within the Yorkshire and Humber region. MRFs within this region mainly take care of collection, sorting and baling of plastics from commercial and industry (C&I) and municipal solid waste (MSW) stream. Some MRFs in this region have increased their capacities since a previous similar study (Ray, 0006) in 2006. However, there is no new facility built since. Many of the MRFs available locally are unable to sort co-mingled materials efficiently due to the lack of investment in modern sorting technology.

There are a few plastics recycling and re-processor in the Yorkshire and Humber region, for example linpac and i-plas. However, they do not adequate capacity or contracts from the local authorities from this region. Many of the studied local authorities actually send their recyclable materials to MRFs outside of the region, some as far as 172 miles away. As indicated by Table 8, the additional fuel consumption and GHG emission due to this transportation activity can be staggering. It is estimated that the five local authorities spent about 319,600 miles to transport 8,610 tonnes of plastics to their MRFs annually, consuming 562,425 MJ of fuel energy and emitting 46,037 kg of CO_2.

3.5.3 LCIA analysis

Table 8 compares the life cycle inventory analysis (LCIA) results for the five local authorities. These LCIA results provide the basis for achieving the first objective of the study i.e. to identify and map logistical and ecological flows of plastic waste taking case study of Yorkshire and Humber region.

Local authorities	Hambleton	Hull City	East Ridings	Wakefield	North Lincolnshire
Population density (/mile^2)	171	9031	360	2466	489
Land area (mile^2)	506	27.6	929.9	130.7	326.7
Collection schemes	Bring & Kerbside	Bring & Kerbside	Bring & Kerbside	Bring & Kerbside	Bring & Kerbside
Stream / Sorting for kerbside	Kerbside sort	2-stream co-mingled	1-stream co-mingled	3-stream co-mingled	2-stream co-mingled
Annual plastic recycling rates (kg/household)	8.3	17.9	6.9	14.7	4.6
Plastic collected by kerbside scheme (tonnes)	279	2,000	896	2,179	3,256
Fuel energy consumed (MJ) by kerbside collection	246,400	*unknown*	193,600	*unknown*	*unknown*
CO_2 emission due to kerbside collection (kg)	20,174	*unknown*	20,174	*unknown*	*unknown*
Transportation to MRFs (miles)	53,040	116,960	15,640	38,080	95,880
Fuel energy consumed by transport (MJ)	93,340	205,824	27,523	67,012	168,726
CO_2 emission by transport (kg)	7,642	16,848	2,253	5,484	13,810
Electrical energy consumed in sorting (MJ)	45	319	143	348	520
CO_2 emission by sorting (kg)	1.25	88.8	12.5	96.7	144.5

Table 8 Comparison of LCIA analyses

Overall, Table 8 suggests that transportation activity provides the major environmental impacts to the whole plastics collection and sorting activities. The fuel consumption and GHG emission due to transportation for collection and transportation of waste to MRFs are equally high. The impacts due to the transportation of waste to MRFs could be saved or reduced if there were adequate MRFs within the region. Since individual volumes from each local authority within this region are small a joint authority effort would be needed to justify an investment of a large MRF within this region. It is noted that the recyclable materials are sorted manually and mechanically (electrical) and consumed a less significant amount of energy when compared with transportation.

Next, based on the above LCIA results it is possible to understand if the plastics recycling logistic systems have actually saved any energy and reduce any GHG emission. Based on the above LCIA analyses, we applied the baseline model and recycling model (Table 5) to estimate the savings in input and output due to the recycling of plastics, assuming all the recovered plastics are PET and re-processed locally in the UK (transportation from the central sorting to the re-processing plants are ignored in this study). This analysis is based on the cases of Hambleton and East Riding because there are complete LCIA analyses.

MFA/LCI	**Hambleton**	**East Ridings**
MFA		
Collected plastic	279t	896t
Sorted plastic	268t	860t
Re-processed plastic	114t	366t
LCIA Input		
Energy saving	8,327,635MJ	27,826,980MJ
Water saving	1,658,178kg	12,504,400kg
Savings of other input materials	(1,597kg)	(12,040kg)
LCIA Output		
Reduction of atmospheric emission (CO_2)	285,100kg	915,000kg
Reduction of solid emission	5,109,480kg	16,404,120kg
Reduction of waterborne emission	984,960kg	3,162,240kg

Table 9 Savings in input and reduction of emissions due to local recycling of plastics

As summarised in Table 9, for the case of Hambleton Council, 279 tonnes of collected plastics could produce roughly 114 tonnes worth of recovered plastics (in flake forms, based on a 2.35/1 ratio as suggested by Arena *et al.*, 2003). The collection and sorting of the 279 tonnes consumed 339,785 MJ of energy but the saving in energy due to the reprocessing of the recovered is estimated at 8,667,420 MJ (comparing energy consumed by processing 114 tonnes of virgin PET with 114 tonnes of recovered R-PET). The savings in waters and the reduction of emissions are calculated under the same basis. There was no saving in other input materials because the reproduction of recovered plastic require additional materials including some amount of virgin plastic (not considered by this research), master batch (coloring agents) and fillers. Overall, when the energy consumption, other input and output during the re-processing are taken into account, the recycling of plastics materials at would save enough energy to supply 1% of the annual electrical demand of London City and reduce 285,106 kg of CO_2 emissions. Savings in other input and output are summarised in Table 9.

The above analyses (Table 9) do not actually reflect the actual savings in input and reduction of emission because about 80% of the collected plastics are exported. Thus, considering the emissions impact of exporting plastics waste to China (125 – 200 kg of CO_2 per tonne) then the reduction of atmospheric emission (CO_2) for Hambleton DC and East Ridings will be reduced to 231,500 and 743,000 kg of CO_2. The energy, water, other input materials and labour required to process the recovered is basically shifted from the UK to China.

The results of this LCIA are subjected to several critical assumptions, including fuel efficiency, sorting and reprocessing efficiency, exports of recycled plastic, etc. LCIA is an excellent tool but it involves a massive amount of data collected from many parties as well as skills from experts and scientists. Furthermore, LCIA is only the first step in a complete LCA. LCA should be complemented by economical analysis (Craighill and Powell, 1996). Since the cost of collection exceeded the sale values of the recycled plastic most local authorities chose to use the less effective e.g., co-mingled collection scheme. Most collected plastic wastes were sent to material reclamation facilities (MRFs) in the UK for sorting and baling and then exported. Due to the consolidation of plastic waste and other wastes during the transportation to the MRFs, fossil fuel consumption and environmental release could be minimized. However, only a small amount of the sorted plastic wastes were reprocessed locally and the rest were exported overseas, especially to China. It is estimated one third of the savings in terms of the use of crude oil due to plastics recycling is spent on the exports of plastic waste to China (estimated about 20 tonnes in each container by WRAP, 2008) but for each tonne of plastic waste exported there would be 158-230 kg of CO_2 emitted to the atmosphere. It is suggested to further consider the issues of Global Warming Potential (GMP), e.g., a measure of the possible warming effect on the atmosphere from the emission of each gas, relative to carbon dioxide (CO_2) 100-year GWPs basis (Houghton *et al.*, 1992).

3.5.4 Impacts of plastic recycling transportation activities

Table 10 further compares the impacts of transportation activities on plastic recycling (based on Hambleton's data). The above results are similar to the work of Arena *et al.* (2003) and Craighill and Powell (1996). Even there is a need to transport plastic waste to China there is an obvious reduction of energy consumption and carbon emission when we compare the re-processing of recovered plastic with the production of virgin plastic. There have been a lot of questions about the export of plastic waste to China for re-processing; however, as indicated by this study and the WRAP report (2008), impacts of the transportation require to export plastics waste appear to be insignificant when compared with the production of virgin plastic.

Activities	**Virgin plastic**	**Recycled plastic**
Energy consumption due to production	84MJ/kg	7.97MJ/kg
Energy consumption due to local transportation (recycling)	None	0.849MJ/kg
Energy consumption due to export transportation (recycling)	None	1.53MJ/kg
Atmospheric emission (CO_2) due to production	6kg/kg	3.5kg/kg
Atmospheric emission (CO_2) due to local transportation (recycling)	None	0.10kg/kg
Atmospheric emission (CO_2) due to export transportation (recycling)	None	0.125kg/kg

Table 10 The impacts of transportation activities on plastics recycling

Environmental professionals, policy makers, and the general public are intensively interested in having the means to look holistically at the environmental consequences associated with the life cycle of a process, a product or a service. One procedure for doing this is the LCA. This research represents perhaps the first logistic research which applies life cycle assessment (LCA) method to investigate the environment inventories of plastic recycling. It demonstrates that it is useful for logistics researchers to learn from the literature on resources, conservation, and recycling (e.g., Arena *et al.*, 2003; Craighill and Powell, 1996). Life cycle assessment (LCA) methodology is considered one of the best environmental management tools that can be used to compare alternative eco-performances of recycling or disposal systems (Perugini *et al.*, 2005). LCA is found to be an effective tool for assessing energy consumption and green house gas emission of jeans supply chains (Leonardi and Browne, 2009). Instead of just energy consumption and green house gas emission, this study further demonstrates that it is possible to combine material flow analysis (MFA) with LCA, particularly life cycle inventory analysis

(LCIA) to map out all the input resources and out emissions involved in any logistics or recycling processes.

The LCIA analyses of this research show that, when using a combination of kerbside and bring schemes transportation consumed a considerable amount of fossil fuel (non-renewable) energy and emitted a substantial amount of CO_2. In order to collect plastic waste, a council typically needed 100,000 – 140,000 miles of transport (4500 – 7700 gallons of diesel) and emitted at least 28 metric tonnes of CO_2. However, when compared with the production of virgin plastics, the study found that the energy consumption and green house gas emission due to transportation for collection and sorting become insignificant, similar to another study carried in Italy (Arena *et al.*, 2003). Furthermore, the LCIA asserts that recycling of plastics can further save a significant amount of water and reduce atmospheric, waterborne and solid emissions when compared with the production of virgin plastics.

4. Recommendation & conclusion

This research project has identified and mapped logistical and ecological flows of post-consumer plastic waste in the Yorkshire and Humber region. Based on a comprehensive life-cycle inventory analysis (LICA) of plastics recycling supply chains from some selected local authorities it is clear that the recycling of post-consumer plastics is generated less environmental impacts than the use of crude oil to produce virgin plastics, even if we had to export the collected plastics to China for re-processing. Furthermore, the research has also identified several problems and opportunities within the studied plastics recycling supply chains, which will be addressed by the following recommendations.

4.1 Recommendation for municipal waste management industry

The municipal waste management industry in the UK consists of mainly local authorities, MRFs, traders, re-processors. This research is valuable for specifically local authorities. Even though most local authorities have learned to use various life cycle assessment (LCA) tools to assess their waste collection schemes and MRF contracts, this research provides further insights by expanding the LCA assessment to the upstream oil production and downstream re-processors as far as in China. The analysis of environmental impacts based on LCA allows local authorities to understand the impacts of not just the waste collection scheme, but also the wider issues related to the design of a recycling logistics system. The following are some recommendations for the local authorities:

Even though most the local authorities studied by this research have demonstrated improvement in recycling rates and provided both bring and kerbside collection schemes the recycling of plastics still has a lot of room for improvement. Some local authorities collected only PET and HDPE bottles using bring scheme. This is an efficient collection method because there is less chance of contamination and less investment in fuel. However, the recycling rate for such collection scheme will be very low in this country. Many local authorities collect plastics bottles and mixed plastics together with other recyclable materials such as glass, fibre and paper to reduce collection cost and to increase recycling rate but contamination will increase.

Local authorities should be aware of the implications of the collection schemes they choose to employ on the recycling rates and the environments. Recycling of metal, paper, wood, glass, and plastic is generally perceived as an environmental-friendly but the collection, sorting, baling, transportation activities do contribute to the carbon footprint. Even though the transportation of a truck load of glass is heavier than a truck load of plastic but the reduction in GHG due to the re-processing of recovered glass and plastics will not be the same.

Furthermore, plastics contain energy and should be used for at least energy recovery instead of landfill. It is recommended to employ the “cradle-to-grave” approach called life cycle assessment (LCA) to assess environmental impacts of the recycling of all these materials, based on the methods employed by this research.

Especially when each local authority is given a budget to manage and the recycling target to meet it is very hard to achieve economy of scale. The highest tonnage of plastics (slightly over 3,000 tonnes per annum) collected from one of the local authorities in the Yorkshire and Humber region is simply inadequate to justify for the investment for a large (>100,000 tonnes), modern and yet viable MRFs within the region. It is recommended for all local authorities within this region, and even other nearby region to work together to build several large MRFs to reduce use of fuel and GHG emission due to the current transportation need.

Without understanding of the environmental impacts of recycling logistics systems, local authority managers will not be able to make better decisions on the design of recycling logistics systems. In a council with less-populated and large land area the use of kerbside sort scheme will decrease transport (collection) efficiency but the use of co-mingled collection will increase collection efficiency. In populated area it is actually more effective for local authorities to provide bring site sort schemes along the main streets (similar to “Duales System Deutschland (DSD)” system in German) so that there is less collection points (from every household to several collection points on one main street) and fuel consumption due to collection transportation can be reduced. Such a system is proven to consume the least energy while achieve the highest recycling rates and recover rates due to the lack of contamination problem. The current co-mingled kerbside collection scheme provided by most local authorities is a compromise to the difficulty in encouraging people to sort and bring their waste to the nearest walking-distance recycling bins.

Much of the risk due to the volatility in the spot markets of recovered plastics is put under the shoulders of the MRFs, traders and re-processors. Even though it is important to consider life-cycle environmental impacts of a product, it is also essential to ensure a product and the associated businesses are profitable. The sorting and baling of recycled plastics by MRFs can be a risky business. Instead of managing their businesses independently, it is possible that MRFs and re-processors to collaborate together or to form cooperative together so that they can provide a total and integrated service to several local authorities within and beyond the region.

4.2 Recommendation for policy makers

The UK government has set out to achieve 45% recycling target by 2015; with 36.9% recycling rate overall but still the landfill rate is 50.3% (Defra, 2010a). When a national recycling target is set arbitrary without truly studying the impacts of the recycling of each different material such as plastic, paper, fibre, glass, metal, and food waste, the local authorities will prioritise the heavier materials and invest less in the lighter materials such as plastic. The fact is that UK is throwing away four plastic bottles out of every five (WRAP, 2009c). This research thus provides the following recommendations:

Given the ability to track the recycling tonnage and rates for each type of materials using a nation-wide waste database, it is then possible to set recycling targets for each type of material. The need to have sectoral specific policies has been suggested. However, the setting of targets has to be guided by life-cycle analysis (LCA) for each type of materials (such as this research for plastic recycling supply chain)

Given the importance of understanding environmental impacts of each type of material the government is suggested to commission LCA studies for each type of materials. Organisation such as WRAP has indeed conducted numerous studies of this kind but there is still a need to conduct such studies to establish targets for each type of material

At the moment different local authorities are given the power to choose collection scheme, level of investment, and contracting of MRFs but they have little influence on the export of recovered materials. This research proves that such policy ends up with some local authorities with high but some other authorities with low recycling rates. In some other European countries such as Germany and Sweden, there is a relatively integrated recycling system within the countries so there is opportunity to use economy-of-scale to gain efficiency in collection, sorting and re-processing activities. These countries recover more than 80% of their used plastics. The comparison of plastics recycling rates between the UK and other European countries is a clear evidence of this problem

The Yorkshire and Humber local authorities are spending substantially on fuel and emitting a large amount of GHG to the atmosphere to send the collected post-consumer materials to MRFs outside of the region mainly due to the lack of large-scale, efficient and modern MRFs in the region. All these can be reduced when some new viable MRFs are built in the region. Furthermore, this will create jobs which can be classified as "green" jobs

The sending of post-consumer waste to overseas re-processors further spends more fuel and emits more GHG to the atmosphere. Even though it is not possible to block the international trade of recycled materials for re-processing but the government is suggested to consider to not only committing to a recycling rate but also a local re-processing rate.

4.3 Recommendation for logistics research

The logistics research has increased its efforts to study GHG emission due to transportation activities while the life-cycle assessment, chemical and cleaner-production literature have started to widen the scope of their studies to examine the life-cycle impacts of a product or process. This research concludes that, transportation is only part of the many activities contributing to carbon footprint but it is time for the logistics research to consider the "cradle-to-grave" approach by utilising life cycle assessment (LCA) and working together with other disciplines. This research employs life cycle inventory (LCIA) analysis and material flow analysis (MFA) to examine the recycling of post-consumer plastics in Yorkshire and Humber region. The approach not only provides insights to the impacts of transportation activities on plastics recycling but also helps to provide insights into the environmental impacts of other activities required to recycling plastics. Even though there are some logistics studies into the supply chain of various products using "LCA" but the study appears to be limited in scope due to the lack of knowledge in chemistry, production process, energy and atmospheric emission covering all activities from material extraction to end-of-life recycling/disposal. Only with a true life-cycle LCA we can provide accurate recommendations to managers in making an informed decision in the design of any logistics system.

This research also provides insights into the current and future states of plastics recycling industry so that supply chain research community can review the product and supply design research. While the research on "design for supply chain" (DFSC) is still new it is now time to consider "design for environment" (DFE) or "environmental conscious design for life-cycle" (ECDLC) which considers design of materials extraction, production, logistics, product use, re-use and recycling. Even though consideration has been made to make plastics packaging materials well labelled and as thin as possible not all plastics packaging materials are recyclable due to the limitations of the current recycling collection and re-processing facilities. That means it is recommended to conduct research together with packaging and retail companies to develop more environmental friendly packaging materials / solutions.

4.4 Conclusion

Plastics are being increasingly used to make packaging, automotive, building, electronic and electrical products. The replace of plastics with other materials in many of the above applications have no doubt largely led to the reduction in logistics costs and environmental impacts. However, recycling of plastic, though saves energy, reduces raw material extraction and combats climate change, some previous studies discovered that plastic recycling supply chains are logistically inefficient, expansive, fragile, and even environmentally harmful.

This research project identified and mapped logistical and ecological flows of plastic waste within the Yorkshire and Humber region. Even though the results of this research have indicate various improvement and efforts in the region plastics recycling supply chain, many rooms for improvement have been identified. The results provide insights to the atmospheric intake and emission due to the collecting, sorting, transportation and re-processing activities involved in the recycling of plastics arising from the local authorities from the region. By employing a "cradle-to-grave" approach called life cycle assessment (LCA) to assess environmental impacts of a plastic throughout its end-of-life cycle, this research is able to examine comprehensively the environmental inventories of each of the collection, sorting, transportation and re-processing activity, including the export of recovered plastics to China for re-processing. The research confirms that the use of different collection schemes will have an impact on recycling rates, contamination rate, and GHG emission.

This research is valuable for specifically local authorities because the LCA analyses of environmental impacts allows local authorities to understand the impacts of not just the waste collection scheme, but also the wider issues related to the design of a recycling logistics system. The research also answers the question about the environmental impacts of exporting plastic waste to other countries. It provides logistics and transport research communities with further understanding of the use of LCA methods and recycling logistics systems in general. Above all, this research provides insights to retailers and packaging companies on the choices of packaging materials and the environmental impacts of their decisions given particular recycling logistics systems in particular countries.

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