Systems Thinking and System Dynamics to Support Policy Making in Defra – Project Final Report

Prepared for the Department for Environment, Food and Rural Affairs

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Disclaimer Page

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Accompanying Documents

- *Review of Literature on Systems Thinking and System Dynamics for Policy Making* (12/8/2013)
- Waste Prevention Model: Vensim model
- Plastics Packaging Recycling Model: Vensim model, supporting historical data, scenario script, data set for the model containing all the inputs for variables, technical document containing detailed descriptions of all the variables and mathematical relationships between them.

Glossary

C&D	Construction and Demolition
C&I	Commercial and Industrial
CLD	Causal Loop Diagram
DMC	Direct Material Consumption
DMI	Domestic Material Input
GHG	Greenhouse Gases
GVA	Gross Value Add
MRF	Materials Recovery Facility
MSW	Municipal Solid Waste
OEM	Original Equipment Manufacturer
PRN	Packaging Recovery Note
PERN	Packaging Export Recovery Note
PPR	Plastics Packaging Recycling
PRF	Plastics Reprocessing Facility
RAO	Relative Attractiveness Of
RMC	Raw Material Consumption
RME	Raw Material Equivalent
SFD	Stock and Flow Diagram
SD	System Dynamics
ST	Systems Thinking
WP	Waste Prevention

1.0 Executive Summary

This report presents the results of the project titled: *Systems thinking and system dynamics modelling to support policy development using waste prevention and recycling as case studies.* The project was conceived as a research project to evaluate the use of Systems Thinking (ST) and System Dynamics (SD) to support policy making at Defra, whilst building internal capability in these techniques. The project introduced these methods to a group of Defra staff, and produced systems models of two of Defra's policy making areas: plastics packaging recycling and waste prevention.

The project delivered five key outputs:

- **Literature Review:** A literature review of the field of ST, SD and their application to policy development, and a review of SD case studies on the subject of waste management.
- **Training:** Three training days in ST, SD, and model validation; training in SD included the use of Vensim software (a software package used to create, run and calibrate Causal Loop Diagrams and SD models[1]).
- **Plastics Packaging Recycling Model:** A SD model of plastics packaging recycling which simulates the dynamics of the plastics packaging recycling industry, including imports and exports and the relationship between waste arisings, collections, recovery and reprocessing. The model is parameterised and calibrated to historical data, and includes a baseline scenario, projected to 2017, and four "what if" scenarios reflecting possible changes in recycling market conditions and policies.
- **Waste Prevention Model:** A SD model that represents waste prevention practices and the causes of waste, related to the use of products throughout the economy. The model is not parameterised but can be run to explore basic dependencies and dynamics. The model includes a Material Flows Map and seven sub-models that are the key drivers of materials and products as they flow through the system.
- **Systems Insights and Knowledge Consolidation:** Development of a common language and understanding about important interactions and causal effects between system elements through the sharing of mental models. Insights about what the endogenous sources of system behaviour are. Structured consolidation of a large body of knowledge and data about the systems under study.

The application of systems methods to the two chosen policy areas provided the opportunity to evaluate their usefulness and validity in supporting evidence building and policy making. The project revealed that the methods are certainly useful and appropriate as problem structuring techniques, drawing together evidence and expert opinion to build a high level, comprehensive model of the problems of interest. The models allowed policy experts to view an external representation of the knowledge they and others hold about the system in one connected piece. The waste prevention model was particularly useful in this sense, as waste prevention occurs in every sector of the economy and circularity between different sectors is central to these practices – which is difficult to depict with words. The recycling model covered an area with a more well-defined boundary, which is better known to Defra, and for which there are more policies in place. This parameterised and calibrated model was used to understand the dynamics of the recycling industry better, and to estimate the effects of changes in key inputs in the future. It also helped policy makers to think of their policy area more as a system.

[1] www.ventanasystems.co.uk/services/software/vensim/

Neither model has been developed well enough yet to be reliable as a policy testing tool. Even for the more developed recycling model, much more work is needed to develop confidence in the model's ability to represent the real world. To achieve this, further model development should be done through several rounds of testing, reviews by experts, and updating and expanding the data that populates it. This is normal practice for system modelling, and in fact this iterative development is one of the strengths of the approach; regular engagement with the model by a range of users and regular comparison with real-world data brings more accuracy and more confidence in what the model tells the users. The effort needed to update models is far less than that needed to build them, so ideally this practice could become part of existing workstreams.

The waste prevention model will likely not be fully parameterised as it stands because it contains hundreds of variables and the effort needed to find data and fully calibrate the model may not be worth it. In its current form it provides a valuable framework to work within that relates the many known issues related to waste prevention, such as how products and materials move around the economy and the decision making of different actors in the system that affect these movements. This structure can be used to answer questions such as which areas would or would not benefit from government intervention to enable waste prevention, or if there are current policies impeding waste prevention. We recommend that going forward Defra staff select several sub-models that are of particular interest, extract them from the main model, then parameterise, calibrate, and expert review them. They could then be used to test possible effectiveness of different interventions to support waste prevention practices such as repair or remanufacture. However, splitting up the full model in this way would not allow for the identification of unintended consequences of policies on other parts of the economy.

To get the most value from the project, we recommend Defra continue to update the models developed during this project, and include these systems methods in their work in other policy areas. Ideally, over the long term systems thinking and System Dynamics will prove their worth as valuable tools for Defra to perform evidence building and policy making in complex policy areas.

2.0 Introduction

The project "*systems thinking and system dynamics modelling to support policy development using waste prevention and recycling as case studies* "was conceived by Maria E. Angulo of the Climate, Waste and Atmosphere Evidence and Analysis team in Defra as a research project with two aims: to develop Defra's capability in the use of systems thinking and System Dynamics as problem structuring and modelling techniques, and to apply these techniques to support the development of the Waste Prevention Programme for England and enhance the evidence base of packaging waste recycling.

This report serves three purposes:

1. It provides a detailed account of the work carried out during the project and key results.
2. It summarises the key principles of systems thinking and System Dynamics, and how they have been applied during the project.
3. It documents the two system models developed during the project.

The policy areas of waste prevention and plastics packaging recycling were selected as case studies partly because of the interest expressed by the relevant policy teams in trying new approaches to support policy making, and partly because of the complementary nature of the two areas in terms of where they are in the policy cycle[2]. Waste prevention policy is in the early stages of the policy cycle, thus required emphasis on problem structuring and qualitative model building; while the plastics packaging waste system has been the subject of a number of policies for some time and thus required emphasis on mathematical modelling, data gathering, calibration, scenario development, and sensitivity analysis. The two case studies are complementary in several senses:

- They belong to different stages of the waste hierarchy; materials not prevented from becoming waste end up in the waste management system, part of which is plastics packaging.
- They represent different stages of the policy development cycle; waste prevention is an area for which policy is being developed for the first time in England, whereas Defra has been developing policy to increase the rate of plastics packaging recycling since 1994 following the EU Directive on packaging and packaging waste[3].
- There are different amounts of evidence and historical data available; data sources for packaging waste are generally well established, unlike for waste prevention where there is much less data available and many more industries are involved.

The methodologies used in the project – Systems Thinking (ST) and System Dynamics (SD) – provide a framework for structuring complex problems and facilitating shared learning about the system for which policy is being developed. SD had not been used at Defra in this way before. Policy appraisal and evidence building is usually carried out using more traditional economic approaches such as cost benefit analysis – which are valid when dealing with systems in equilibrium. SD can complement this economic view by providing additional insight into dynamic system behaviour over time, especially during transition phases and in the context where systems are performing sub-optimally. SD is particularly powerful when trying to understand systems in which feedbacks

[2] See *The Green Book: Appraisal and Evaluation in Central Government*, HM Treasury, 2011 for a description of the policy cycle.

[3] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:1994L0062:20050405:EN:PDF

and delays exist, which can lead to dynamic complexity such as rebound effects and non-linearity. Delay in a system can occur when, for example, there is a time gap between information feedback about system performance and appropriate decision-making, or between decision making and the provision of infrastructure capacity.

Waste Prevention Model: During the project, the basic structure of a SD model of Waste Prevention (WP) over the lifetime of products in the economy was developed. The model consists of a stock and flow diagram that represents the flow of materials and products, the Material Flows Map, and seven dynamic sub-models that drive the rates of flows into and out of the stocks. Each sub-model has a dynamic hypothesis that explains the modelling team's understanding of its dynamical behaviour over time. The WP model was initially developed based on Causal Loop Diagrams created during two model building workshops attended by experts from government, industry and academia. The models created at the workshops represented the participants' combined mental models of the causes of waste, WP practices, and associated issues. These models were combined into a single SD model and then refined through a series of workshops by an expert modelling team. The dynamic hypotheses for the sub-models were compared to evidence derived from data from ONS, HMRC, WRAP, and the literature. The model is designed to represent trends from the last 15 years (1997 to 2012) and includes the majority of everyday products that could be acquired by both organisations and households. The metric of flow of materials is tonnes per year, used principally because of the availability of data; however, this metric does not fully reflect the full intention of WP which is to reduce the total environmental impact of waste. Further development of the WP model could include the tracking of carbon emissions associated with waste, the value of different types of waste materials, and the hazardousness of waste. The model is currently runnable but not parameterised. It shows the direction of influence between variables but not the magnitude of change; therefore it cannot be used for scenario testing.

Plastics Packaging Recycling Model: During the project, a full SD model of Plastics Packaging Recycling (PPR) was built, parameterised, and calibrated. The PPR model helped to structure current knowledge of the system, bringing together different individuals' understanding of parts of the system and creating a wider consensus of how the parts interact. The visual capability of the SD model played a crucial role in facilitating the communication between policy experts, and other stakeholders, with the modelling team. Given that enough information and data about the system was available, we were able to parameterise the model to run a series of test policy scenarios and learn how to use the model as a tool for policy appraisal. The modelling process was used as a framework to gather and document data from a wide range of sources in a structured and unambiguous manner. The process helped to identify gaps and inconsistencies in the data. The evidence and analysis team considers this to be an important, although unexpected, benefit of the model, and they are considering applying a similar approach in other areas. Although the model was parameterised, it needs to undergo further calibration, testing and interrogation of the results. In terms of new understandings gained from the model, it appears that the main demand shifter in the system is potential shocks to the price of virgin materials. There is currently insufficient information to determine the barriers to expansion of the reprocessing industry and the long term competitiveness of domestic operators. However, innovation to reduce costs of sorting and treatment could increase the quality and value of recovered material, helping to reduce international cost differentials and helping growth in the domestic industry. It is currently unclear whether scale is a significant factor affecting growth of the reprocessing sector.

2.1 Reader's Guide

This report may be useful for several types of audiences with different interests. Because all sections of this report may not be relevant for all types of readers, we recommend that readers with specific interests start with the relevant sections listed in Table 1.

Table 1: Recommended Sections for Readers with Specific Interests

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The remainder of this report is organised as follows:

1) Section 3.0 provides background to the project and a description of the tasks done, including: goals of the project, the policy context, and methods used in the project.
2) Section 4.0 describes the waste prevention model, the methods used to develop it, its structure, the dynamic hypotheses of the model and supporting evidence.
3) Section 5.0 describes the plastics packaging model, its structure, its calibration to historical data, the baseline scenario to 2017, and four "what if" scenarios.
4) Section 6.0 provides a summary of modelling results, insights gained from the modelling process, and plans for future work.
5) Appendices A to D provide literature references, a brief guide to SD theory and conventions, supplementary ST literature, and further details on the models.

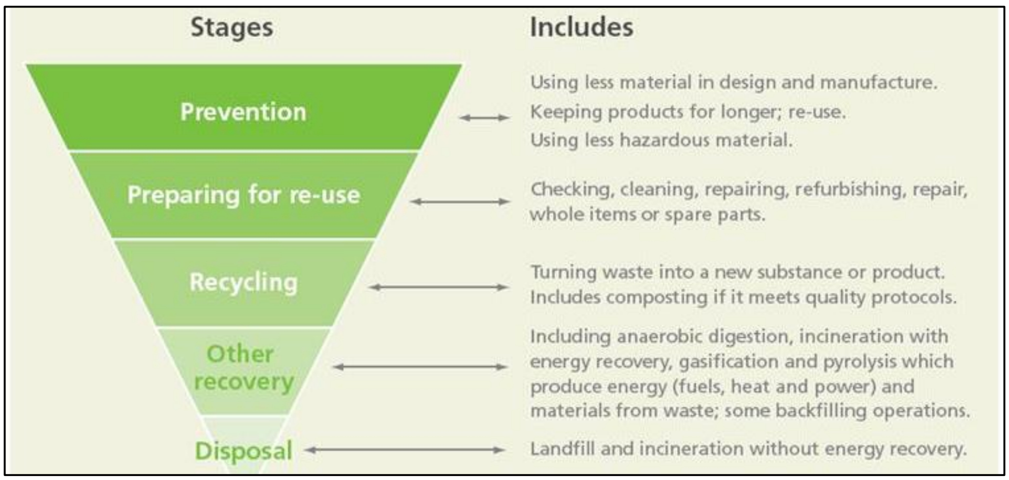
3.0 Background

This section provides background to the work carried out during the project, including the policy context, and theory on systems methodologies.

3.1 The Policy Context

The EU's waste hierarchy (Figure 3-1), as defined in the Waste Framework Directive[4], shows the relative merits of different actions that can be taken within the waste generation and management systems. Waste prevention sits at the top of the hierarchy, followed by preparing for re-use, recycling, recovery, and disposal. Materials are defined as non-waste during the waste prevention phase and then become waste in the following phases; however, this line between prevention and management is not always clearly defined in reality, and activities defined as preparing for re-use could be considered to be waste prevention in some cases. The UK consumes *'approximately 470 million tonnes (Mt) material resources each year, with over 250Mt of resources becoming waste'* (DEFRA 2013c). The impacts of this waste of resources include increased costs to organisations from purchase of materials not used, the cost of disposing of waste, and *'the loss of large quantities of valuable materials*' (ibid) – despite around half of this waste being recovered for recycling.

Figure 3-1: EU's Waste Hierarchy



Source: (DEFRA 2013c)

3.1.1 Waste Prevention Policy Context

At the time that this project was being done, Defra was building the evidence base to support policy making for the first Waste Prevention Programme for England (published in December 2013). The programme was developed in response to the revised EU Waste Framework Directive, which requires member states to develop a WP Programme with the aim to break *'the link between economic growth and the environmental impacts associated with the generation of waste'*[5] , known as decoupling. The WP Programme will aim to enable businesses, Local Authorities, and civil society to maximize opportunities and benefits from reducing waste arisings. Benefits could include reduced costs of resource input, waste management and disposal, and a reduction in the environmental impacts of waste. All of these benefits indicate why the EU has put WP at the top of its waste

[4] http://ec.europa.eu/environment/waste/framework/index.htm

[5] Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives Text with EEA relevance, http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:312:0003:01:EN:HTML

hierarchy, stating that it *'represents the most efficient and sustainable use of resources'* (European Commission 2012).

3.1.1.1 Waste Prevention Practices

The concept of Waste Prevention (WP) encompasses a wide range of actions, or practices, which result in an increase in the efficiency with which materials are used within the supply chain (production and distribution), and an increase in the utility, or useful lifetime, of materials in products while in use. WP practices can involve multiple actors – for example, manufacturers, trade organisations, individuals and families, social enterprises, and central and local government – at every stage along the lifetime of a product.

WP practices are an important part of efforts to achieve higher levels of sustainability in the use of resources, a vision often referred to as the "circular economy." The circular economy differs from an open, linear economy in which *'natural resources are mined and extracted, turned into products and finally discarded'* (Preston 2012). Instead, the circular economy envisages the use of resources occurring within a closed loop, meaning that finite resources such as metals and minerals are captured and reused instead of going into the waste system. Methods for increasing the "circularity" of resource flows can include WP practices in the form of '*switching to longer-lasting products, modularization and remanufacturing, component reuse, and designing products with less material'* (ibid).

There is a wide range of WP practices in use, or that could be introduced, throughout the economy – performed by different stakeholders at different times in the lifecycle of a product. For the purpose of developing the WP model, we selected a subset of practices which are the ones currently best understood and which represent a large proportion of WP practices in use.

- **Material Efficiency of Production:** More efficient use of materials in the process of manufacturing of products, leading to less material waste being generated by producers per product – this could include use of the waste from one process to feed into another, or better designed production processes that use less material to make the same product.
- **Material Design Efficiency:** More efficient material design of products so that smaller amounts of, lighter, less hazardous, or more recoverable materials/components are used to make and distribute products.
- **Distribution Efficiency:** More efficient distribution and retailing of products through the supply chain so a higher percentage of materials in products end up being used by end users.
- **Alternative Consumption Models:** Business models for supplying products other than via direct sales, such as: leasing or renting; car share schemes; Product Service Systems ('*providing a service based upon delivering performance outputs'*[6]) such as copier services in offices. All of these could reduce the total number of products in use.
- **Product Design Lifetime:** Design of products so they are more robust and have a longer expected lifetime, so products can stay functional for longer and are more easily resold or repaired.
- **Repair:** Repair of products or products parts, when broken or in some way not functional – ('*the correction of specified faults in a product'* (Parker 2007)). This can be done by a 3rd party repair service, by the owner, or by friends and family. Repair leads to products staying in use for longer.

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[6] http://www.wrap.org.uk/node/13052/#a

- **Reuse:** Reuse of useable unwanted products, or components of products, by gifting or selling to a new owner. There are several routes this can happen:
    - Selling a product directly from person to person (via classifieds, internet sites, word of mouth, etc.);
    - Donating products to 3rd party non-profit organisations (via charity shops, jumble sales, etc.) which then sell them on within the UK or export them;
    - Donating products directly from person to person (via classifieds, freecycle[7], friends and family networks, leaving things on private property but in view of the street and with a note indicating they are being given away, etc.).
- **Remanufacture:** Remanufacture (*'a series of manufacturing steps acting on an end-of- use part or product in order to return it to like-new or better performance'* (Parker 2007)) to extend the useful life of products or product parts. Remanufactured products are sent back to the manufacturer and acquired by new users in two principal ways:
    - Owners bring or send the broken item to the retailer/distributor, who provides a remanufactured version of the product as an immediate replacement under warranty, and then sends the faulty product back to the manufacturer for remanufacture; or
    - Consumers are offered a remanufactured product instead of new at a discount at the point of purchase.
    - Consumers under a service contract are provided a remanufactured product as part of the provision of service.

3.1.1.2 Barriers to Waste Prevention

The barriers to WP are varied and sometimes have complex causes. Some examples identified in the literature and by government are presented here.

(Brook Lyndhurst 2009) identified two overarching barriers to WP in a literature review for Defra:

- The idea of consumerism, which encourages people to buy more of everything – food, clothes, household items – and to replace items while they are still useable; and
- Long-established personal beliefs and values provide the grounding for many of our waste generation and waste prevention behaviours, meaning that it is extremely difficult for politics to intervene.

Defra (DEFRA 2013c) has identified five key barriers to WP, or market failures, which are principally economic or informational in nature:

- Environmental Externalities: the decision making that leads to more waste does not consider the environmental damage caused by waste, partly because decision makers do not have to directly pay appropriate and full costs of the effects of waste.
- Split Incentives: The beneficiaries of WP actions may not be the same as those who incur the cost of those actions. For example, an extended product lifetime will benefit the consumer and Local Authority that has to manage waste, but not necessarily the producer who has invested in it.
- Informational: Consumers and businesses may not be aware of the full costs of waste (e.g. wasted raw materials and labour costs embedded in products) or preventative actions they could take to reduce it.

[7] http://www.uk.freecycle.org/ The website states *'Freecycle groups match people who have things they want to get rid of with people who can use them. Our goal is to keep usable items out of landfills.'*

- Behavioural Short-termism: Decision makers in organisations often underestimate the value of long-term benefits versus short-term costs and/or overestimate the risks associated with such investments.
- Financial: WP actions may require initial investments before benefits can be realised, which can be affected by reduced access to credit.

(Wilson et al. 2012) identified several barriers to WP specific to businesses:

- Lack of customer demand: consumers rarely make specific demands for WP from businesses, although their interest is starting to encourage businesses to improve general environmental performance; for example, consumers have shown interest in businesses reducing the hazardousness of waste.
- Corporate culture: Business cultures are sometimes unsupportive of WP efforts, with a lack of leadership commitment and a failure to integrate WP activities across the business.
- Competing Goals: The widespread practices of recycling and landfill diversion can act as barriers to preventing waste at source. For example, crushing hard-core and using it as backfill or aggregate on construction sites leads to a significant reduction in waste generation, but at the expense of more sustainable practices such as reducing wastage of unused construction materials and preparing reclaimed materials for reuse.

3.1.1.3 Waste Prevention Policy

An EU guidance document on preparing a WP programme advises that because WP is a cross-cutting area of policymaking it has *'direct relevance to a considerable number of already established policy areas*' (European Commission 2012). The document describes the need to pay special attention to the questions of policy integration and policy coherence and defines three types of integration:

- Horizontal integration is the integration of environmental aspects into other policy areas. WP policy must consider policies with close relevance to WP but in primarily non-environmental domains, including policies that define the structure of the economy, the directions of economic and social progress, and the development of infrastructure.
- Vertical integration is integration amongst the different levels of governance, such as EU, national, regional, and local levels (e.g. Local Authorities, county councils). How policies at different levels of governance can mutually reinforce each other to promote WP is the challenge.
- Lifecycle integration is the integration of policies along the life-cycle stages of production and consumption. This would create better links between supply-side and demand side policies – for example, the EU Ecolabel and Green Public Procurement.

The document states that one challenge of creating WP policy is that these three dimensions of integration need to be considered at the same time: *'Policy needs to identify opportunities to create synergies and improve policy coherence, but also consider trade-offs.'* (ibid) One of the intentions in developing the WP model in this project was to provide policy makers with a tool that represents the dynamics of the whole system, enabling them to test potential policies for their policy coherence, trade-offs, and synergies.

Regarding evidence of existing WP efforts, a 2007 study into household WP policy options for Defra (Eunomia Research and Consulting 2007) revealed that, at that time, there were few policies in place in the UK or any of the other countries they surveyed that have been primarily aimed at reducing waste. The authors found that WP policy *'does not appear anywhere to have been developed and implemented in a strategic manner that addresses the key facets of product design and delivery through the supply chain to consumer and householder behaviour in an integrated way'*. (ibid)

However, since 2007 there has been increasing action taken in the UK in specific sectors and for prevention of specific types of waste that have achieved notable results, for example:

- Results from an evaluation of the Courtauld Agreement[8], managed by the Waste and Resource Action Programme (WRAP), show an 8.8% drop in supply chain packaging and product waste for the participating food retailers and producers between 2009 and 2011.
- WRAP's "Love Food Hate Waste" scheme aims to reduce food waste from households through improving purchasing, storage and consumption practices. WRAP's website states that between 2006 and 2010 food waste fell by around 13%, although the reasons for this are not given[9].
- The Community RePaint scheme, which estimates that around 15% of paint bought in the UK is not used, collects reusable unwanted paint and redistributes it to a variety of stakeholders who can make use of it. In 2012, the network saved over 380,000 litres of paint going to waste and redistributed over 218,000 litres of paint to individuals, families, community groups, charities, voluntary organisations, and people in social need.[10]

A more comprehensive list of WP actions carried out is provided in (DEFRA 2013c). These successes within specifically targeted sectors and for particular product types indicate a need for WP policy to be responsive to a highly heterogeneous set of causes of waste.

3.1.2 Plastics Packaging Recycling Policy Context

Recycling plays a crucial role in the management of waste, delivering a wide range of environmental and economic benefits to society; turning waste into useful materials reduces the dependency on virgin materials and is more energy efficient. The recycling industry contributes a significant amount to the UK economy, with estimates of its worth between £12bn (KMatrix for BIS 2010) and £23bn[11]. In March 2012 new packaging recycling targets for 2013-17 were announced[12] that will increase the plastics recycling target from 32% in 2012 to 57% by 2017. The 57% target applies only to businesses obligated by the Producer Responsibility Obligations, which equates to a national average of 42.3%. Plastic is one of the most energy intensive packaging materials, so these new targets are expected to deliver considerable environmental benefits; additionally, recycled materials should be less expensive and their prices less volatile. Recent projections (WRAP & Valpak 2013) for the rate of Plastics Packaging Recycling (PPR) suggest that additional measures to those currently in place will be required to meet the new target.

3.1.2.1 Packaging Producer Responsibility

The UK has had a statutory producer responsibility regime for packaging in place since 2008. This places a legal obligation on businesses which make or use packaging (raw materials manufacturers, converters, packer/fillers and sellers) to ensure that a proportion of the packaging they place on the market is recovered and recycled. Although overall packaging recycling rates have increased considerably since 2008, PPR rates have not followed the same pace. f the estimated 5 million tonnes of plastics consumed in the UK every year, about 40% is used in packaging. Currently, only around 26% of plastics packaging waste is recycled in the UK overall and represents a 5% increase from 2008.

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[8] www.wrap.org.uk/content/new-courtauld-figures-show-grocery-sector-track

[9] http://england.lovefoodhatewaste.com/content/facts-about-food-waste-0

[10] www.communityrepaint.org.uk

[11] www.mrw.co.uk/recycling-industry-now-worth-23bn-in-uk/8625475.article

[12] www.defra.gov.uk/environment/waste/business/packaging-producer/

3.1.2.2 Quality Action Plan and MRF Code of Practice

The revised Waste Framework Directive requires Defra to take measures to promote high quality recycling. In February 2013 Defra published the Quality Action Plan (DEFRA 2013a), setting out the range of actions that will be taken over the next few years to improve the quality of recycling of dry recyclates (paper, glass, metal and plastic). The expected benefits of higher quality recyclates include:

- Higher income levels from their sale;
- Reduced pressure on Local Authorities' budgets;
- Increased confidence amongst UK reprocessors, encouraging them to invest and expand, rather than tying up their energy and resource in dealing with low quality material;
- Improved resilience of the waste management industry to fluctuations in demand.

Some evidence suggests that the quality of recyclates currently coming out from Material Recovery Facilities (MRFs) that sort materials collected via co-mingled collection systems does not always meet the required quality standards of the recycling sector. Contamination rates for plastics post-MRF sorting vary widely by type of plastic, and averages range from 4.5% for HDPE natural plastic bottles to 18.2% for mixed plastics. A significant number of MRFs do not assess the quality of the recyclable material they produce. Consequently, there is a lack of robust and consistent information on quality of outputs which undermines the ability of reprocessors to confidently identify MRFs that meet quality specifications.

To date the majority of Local Authorities (LAs) have been primarily concerned with maximising landfill diversion and minimising the costs of collecting and disposing of waste, and have therefore been attracted by MRFs offering low gate fees. However, there are some examples of LAs negotiating revenue shares from the sale of recyclates, which drives improvements in quality and means LAs get feedback from MRFs about reject rates and contamination levels. This leads to improvements by the LAs in collection rounds and providing feedback to householders. As part of Defra's Quality Action Plan, MRFs will need to comply with a code of practice, and publish information on the quality of their input and output materials. This could lead to higher gate fees to cover increased sorting costs and quality assurance processes.

3.1.2.3 Waste Exports

Although exports of recyclates should happen only in response to overseas demand or lack of domestic capacity, MRFs sometimes find markets for poor quality outputs through exports of paper and plastic mainly to Asia. The EU Waste Shipments Regulation prohibits the export of waste for disposal from the EU and the export of waste that is contaminated to such an extent that it could not be recovered in an environmentally sound manner. However, the regulation does not set a limit for the level of contamination that is acceptable, with much depending on what is acceptable in the receiving country. Better information on MRF output quality will help the Environment Agency with its enforcement on the Waste Shipments Regulations and help authorities within importing countries to identify and stop low quality consignments.

3.1.2.4 PRNs and PERNs

The Packaging Waste Recovery Note (PRN) and Packaging Export Recovery Note (PERN) system is designed to incentivise the growth of the recycling and recovery industry. The system works as follows:

- PRNs are certificates/notes generated by accredited reprocessors when packaging waste is recycled or recovered. Obligated companies (those with a turnover above £2m and who handle more than 50 tonnes of packaging per annum) fund packaging recovery and recycling costs by purchasing a proportional number of PRNs. This money is then reinvested in the recycling system to help increase collection and recycling capacity.

- PERNs are issued by exporters as evidence of the amount of packaging waste recovered/recycled when the waste is exported rather than reprocessed in the UK.
- The obligations for PRNs and PERNs are calculated at the start of each year, based on the projection of packaging handled by those businesses and the prevailing UK targets. PRNs and PERNs are then bought and sold throughout the year.
- Recycling companies can produce a PRN for each tonne of recycling they produce and then sell it. This is additional income for the company for each tonne of material recycled.
- Registering for the scheme by recycling companies involves an accreditation fee paid to the Environment Agency plus administrative costs. When administration costs and/or accreditation fees are greater than the PRN value, or the PRN revenue is small relatively to the material value (e.g. aluminium) there will be little incentive for the company to register their PRNs.
- There are two ways to acquire PRNs: contract or spot market. Many buyers and sellers are signed up to long term contracts for PRNs, either on an individual basis (if the company is large enough) or through a compliance scheme (e.g. Valpak). The other mechanism is the spot market, where they buy and sell depending on the price at the time.
- PRN and PERN prices are affected by supply and demand, and PRN prices are likely to increase when there is a perception that there is not enough evidence in the market to meet targets. However, often prices fluctuate for other reasons which are often unknown.

3.1.2.5 End of Waste Regulations

In July 2012 the Environment Agency updated guidance on applying for accreditation to reprocess and export UK waste packaging. The guidance allows plastics to cease to be waste post sorting and cleaning (at 'flake' stake), rather than after they have been through a re-melt process. A PRN can now be raised prior to re-melt as long as companies adhere to quality assurance protocols for non-packaging plastics. This change could lead to an increase in the number of PRNs being raised, and facilities producing plastic 'flake' could register for accreditation. However, if the material goes on to be melted in the UK by an accredited reprocessor, the number of PRNs will remain unchanged but they will be raised earlier in the supply chain.

3.1.2.6 Landfill tax

The landfill tax is designed to reflect the environmental externality of disposing of waste into landfill by increasing its cost. It achieves this to a limited degree but does not reflect other externalities involved in waste treatment such as incineration, recycling or material re-use. Increasing the cost of land-filling increases the overall cost of managing a tonne of waste, and therefore should lead to a reduction in waste arisings, but the extent to which this occurs is likely to differ in different sectors and for different materials. Where the cost of having waste collected and disposed of is very small relative to the cost of the resource inputs, one might expect a landfill tax to have little effect, but where the cost of collection and disposal is a significant part of the costs then it could make a difference. Landfill taxes have risen consistently since being introduced, starting at around £11/tonne in 2000 and rising to around £64/tonne in 2012. They will increase by £8 per annum going forward

Evidence on the effectiveness of landfill tax mostly indicates that it does drive down waste to landfill. A study by (Bartelings et al. 2005) on the effectiveness of landfill tax in The Netherlands to reduce waste to landfill modelled the impacts of a range of landfill tax rates. The study found that:

- Landfill tax has a significant effect on the amount of waste landfilled. The higher the landfill tax the more waste will be recycled or incinerated.
- Municipalities will start to incinerate all their waste if the landfill tax becomes too high.
- Only in municipalities that charge a unit-based price for waste collection will the behaviour of households be influenced; household recycling efforts are low regardless of the pricing system for waste collection.

A review of the relationship between landfill tax and percentage of Municipal Solid Waste (MSW) landfilled across the EU found a *'general negative relation between tax rate and the percentage of MSW landfilled'* (Chapter 15 from (Kreiser 2012) (Bassi and Watkins)). The exception to this is Germany, which has achieved an almost total diversion of waste from landfill without the use of landfill taxes; instead measures were introduced that amounted to an *'effective total ban on landfilling of untreated MSW'* (ibid). Bassi and Watkins found that in the UK, the percentage of MSW landfilled initially remained high after the introduction of a landfill tax (above 80%); however, since 2000 gradual yearly increases in tax have been associated with a consistent decrease in landfilled waste, with the rate being about 49% in 2009.

3.2 Methodologies Used in the Project

This sub-section introduces the key concepts of the methods used in this study – systems thinking and System Dynamics. This is intended as a brief guide to help readers understand the rest of this report, rather than as a comprehensive guide to the methods. The literature review accompanying this report gives an overview of SD theory, several case studies in its application to the waste industry, and its use in government policy making.

3.2.1 Systems Thinking

The term "systems thinking" has been defined in different ways by many different authors, their understanding influenced by their use of ST in their professional field. Presented below are four of these definitions which reflect the authors' perspectives; common to all are the concepts of dealing with complexity, seeing interconnectedness, identifying emergence, and working in an interdisciplinary way.

- Open University: *'Systems thinking enables you to grasp and manage situations of complexity and uncertainty in which there are no simple answers. It's a way of "learning your way towards effective action" by looking at connected wholes rather than separate parts'* (Open University 2012).
- Richardson*: 'Systems thinking is the mental effort to uncover endogenous sources of system behavior'* (Richardson 2011)*.*
- Senge*: 'Systems thinking is a framework for seeing interrelationships rather than things, for seeing patterns rather than static snapshots. It is a set of general principles spanning fields as diverse as physical and social sciences, engineering and management'* (Senge 1990).
- International Council on Systems Engineering: *'Systems thinking is a way of thinking used to address complex and uncertain real world problems. It recognises that the world is a set of highly interconnected technical and social entities which are hierarchically organised producing emergent behaviour'* (INCOSE UK 2010).

Within the ST field there is a range of formally defined methodologies, each with its own methods and tools for working with real world systems. Systems methodologies are generally oriented more towards soft (i.e. people) or hard (i.e. physical) systems, and they can be applied at any level, from a single case (e.g. a particular organisation or piece of equipment) up to the global (e.g. climate science models of the Earth). System modelling is the primary tool of systems thinkers. Models are *'the means by which a systems thinker comes to terms with complex real-world problems'* (Godfrey 2010).

3.2.2 Problem Structuring and Causal Loop Diagramming

When the problem to be modelled is not clearly defined, and there are stakeholder *'groups of diverse composition'* (Mingers & White 2010) that need to work with and solve complex, problematic situations, then Problem Structuring Methods can be used to frame and define the issues that are contributing to the problem. Methods of system modelling and group facilitation can provide the support needed to stimulate dialogue about the problem space and help stakeholders reach a shared understanding and joint agreement with respect to the problem.

One tool commonly used for problem structuring is Causal Loop Diagramming. Causal Loop Diagrams (CLDs) are *'visual representations of the dynamic influences and inter-relationships that exist among a collection of variables'* (Spector et al. 2001). (Sterman 2000) states that CLDs can help by:

1) Quickly capturing hypotheses about the causes of system dynamics;
2) Eliciting and capturing the mental models of individuals or teams about the system; and
3) Communicating important feedbacks believed to be responsible for a problem.

CLDs cannot be parameterised or simulated, and they don't communicate levels of change in stocks and flows of things such as equipment, information and people. The fundamental limitations of CLDs were identified by (Schaffernicht 2010):

1) *'They cannot express the causal effects of the absolute values of variables.*
2) *They draw attention to events rather than to behaviour.*
3) *They represent only structure and leave the behavioural aspects to the user.'*

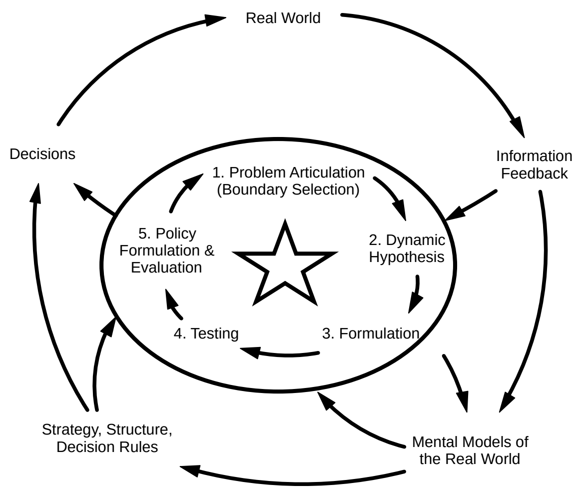
Despite these limitations, CLDs are a good way to represent key system elements, the causation between them, and important feedback loops that drive system behaviour. CLDs are often used at the beginning of a study in order to conceptualise a problem (Lane 2008), so that problem owners can begin to think through their mental models of the dynamic system under study. Section 8.2 introduces the conventions for creating and interpreting CLDs.

3.2.3 System Dynamics

SD is a methodology for the elicitation and formulation of system models with a view to gaining insight into dynamical behaviour – both historical behaviour and possible future behaviour – to inform possible interventions. It can thus be viewed as a Problem Structuring Method ((Ackermann 2012), (Mingers & Rosenhead 2004), (Rosenhead 1996), (White 2009)) – although it is not usually viewed as such by the Soft Operational Research community.

Its ontological basis relies on the concept that socio-technical systems can be modelled and studied as "information feedback control systems". These are systems in which the environment affects decisions made by human actors, whose actions, in turn, affect the environment – and so on. Dynamic behaviour in a complex socio-technical system arises endogenously, as a consequence of system structure and information feedbacks. According to (Sterman 2000) all dynamics within a system arise from feedback loops, of which there are two types – positive loops reinforce or amplify whatever is happening in the system, and negative, or balancing loops, counteract and oppose change.

Figure 3-2: Sterman's Double Loop Learning



Source: adapted from (Sterman 2000)

Double Loop Learning: The SD methodology is based on "double loop learning", which describes how mental models of the world are updated in the light of experiences arising from the effects of previous decisions. The actual process of modelling using SD thus becomes the mechanism that enables double loop learning to take place, as represented in Figure 3-2.

Use of Diagrams: In discussing the use of diagrams in SD, (Lane 2008) states that they are used to represent a set of causal assumptions. This representation allows the existence of these assumptions to be communicated and then discussed, options for change to be discussed, and the policy consequences of the assumptions to be debated.

Communication can come in two forms:

- A diagram can be used for "model conceptualization," in which case it is an evolving *'thinking tool'.* It represents the current understanding of a problem by individuals or a team, communicates their assumptions back to them, and then leads to them framing '*a fully formulated simulation model'.* (ibid)
- A diagram can be used for "model exposition," in which it represents the assumptions of an underlying mathematical model. In this case, the aim of the diagram development is to communicate what the main features of a model are, so that it is possible to explain *'why different behaviour modes arise and why certain policy levers are effective'.* (ibid)

There are three types of variables in SD models:

1) "stocks" or "levels" are changed by the accumulation into them, or draining out of them, of some quantity and are integration formulas;
2) "rates" or "flows" are the quantities of those accumulating or draining processes and can be simple arithmetic formulas or differential equations; and
3) auxiliary variables can be constants or formulas, can influence flows, but do not directly influence stocks. (from (Lane 2008))

Simulation Modelling: Essential in the practice of SD is the use of simulation modelling. (Sterman 2000) says that although mapping participants' mental models is necessary, the temporal and spatial boundaries of our mental models are dynamically deficient, omitting feedbacks, time delays, accumulations, and nonlinearities; thus, parameters and functional forms are needed to fully specify and test a model. Computer simulation is the only practical way to test a conceptual model, and without simulation even the best model can only be tested and improved by learning through the real world – a slow and ineffective process.

(Luna-Reyes & Andersen 2003) describe the full SD modelling process as involving four stages:

1) Conceptualization (problem definition and system conceptualisation);
2) Formulation (positing a detailed structure and selecting the parameter values);
3) Testing (model behaviour and model evaluation); and
4) Implementation (policy analysis and use).

Dynamic Hypothesis: (Coyle & Exelby 1999) discuss the need, in some cases, to hypothesise a structure for the model being developed within commercial SD projects. They quote (Richardson & Pugh 1981)'s definition of a dynamic hypothesis: *'The dynamic hypothesis in a system dynamics study is a statement of system structure that appears to have the potential to generate the problem behaviour'*. Coyle and Exelby's approach starts with identifying the behaviour of the system in the real world then moves to diagramming a model of the chosen structure; however, they state that this use of dynamic hypotheses appears to be problematic when real world behaviour is to be used to validate the structure, since '*the structure was assumed from the behaviour'.* (Saeed 1992) describes a process for developing SD models for policy design, which '*must aim at mobilizing the internal forces of the system to create functional patterns and avoid dysfunctions*'. (ibid)When policy is the concern, Saeed states that understanding the mechanisms of change is the priority, rather than forecasting events. His approach starts with organising historical information into a reference mode and then formulating a dynamic hypothesis. The dynamic hypothesis is expressed in terms of feedback loops between '*the decision elements in the system that create the particular time-variant patterns contained in the reference mode'.* (ibid) This approach of creating dynamic hypotheses was used in the WP model development.

Agency, Structure, and System Behaviour: Part of the practice of SD is to understand the relationships between system structure, system behaviour and the agency of actors within a system. Within the field of SD, system structure is defined, according to (Sterman 2000), as a combination of feedback loops, stocks and flows, and nonlinearities created by the interaction of the physical and institutional structure with the decision-making processes of agents acting within it. System behaviour can be thought of as the long-term trends within the system that drive the metrics of interest (for example, GDP for a country or profit for a corporation). System behaviour can also be thought of as the aggregate of the behaviours of all the decision-making actors within a system. From the point of view of actors, they make decisions based partly on the system structure and partly on their own sense of agency, or choice. Taking account of agency, *'an individual's sense that they can carry out an action successfully, and that that action will help bring about the expected outcome'* (Darnton 2008), is crucial when it comes to determining how much effort individuals will make towards a desired change in behaviour.

(Lane, 2001b) suggests that SD should be positioned within the social theory of Gidden's structuration theory (Giddens, 1984). The essence of this theory is that structure and agency are not a dualism, but are in fact a constantly co-created duality. Instead of viewing structure as a "patterning" of social relations, structure as *'external to human action, as a source of constraint on the free initiative of the independently constituted subject* (ibid), "structuration" is the *'dynamic interplay between the acts of human agents and the effects of social structures'* (Lane & Husemann 2008). In other words, it describes how structure and agents co-evolve the system over time.

As an example of agency, structure and behaviour, we can look at the long-term trends in household recycling.

- Recycling first started with the provision of “bottle banks”, which attracted a small percentage of householders to carry their empty glass bottles and newspapers for recycling. There was little recycling structure available; recycling practices were mostly due to individual agency; and there was a very small system behaviour change (recycling rate of around 1% in 1983 (DEFRA 2012)).
- As the need to reduce waste to landfill grew, government introduced a landfill tax (high-level structural change) which influenced councils to increase their efforts for recycling. Councils increased the range of recyclables that could be deposited at recycling centres, and some introduced kerb-side recycling pickups. There was more recycling structure available; recycling was still done largely due to individual agency but was more encouraged and more convenient; and there was a slightly larger system behaviour change (recycling rate of 11% in 2000 (ibid)).
- Currently, most LAs provide kerb-side recycling pick-ups and some have reduced the size of bins going to landfill; some LAs have established higher recycling targets (influenced by higher landfill taxes). Recycling has become the norm (part of structure) for households and recycling structure is now fully integrated into the waste system. There has been a significant change in system behaviour, with household recycling rates increasing from 11% in 2000 to 43% in 2011 (ibid).

The subject of agency and structure is explored in more detail in Section 6.1 in relation to WP.

3.2.3.1 System Dynamics and Policy

SD has been recommended as a method to improve the robustness of policy making. For example, Lane et al. recommend that *‘whether considering a new pay scheme or negotiating a global trade agreement, policy makers need to think about the possible existence of reinforcing feedback as well as balancing feedback’* (Lane & Husemann 2008), with computer simulation an essential tool for the difficult task of developing effective interventions for complex systems. The use of SD modelling to support policy development allows the development of user-friendly interfaces that can be used to communicate and reach consensus about the system or problem in hand, and “policy laboratories” which enable the testing of possible policy options and their consequences.

(Wheat 2010) describes the process of SD modelling for policy as having two high-level stages:

1) Problem explanation (explaining the reasons for the problematic dynamic behaviour of the system by building an explanatory model); and
2) Policy design (designing and testing policies that could improve the dynamic performance of the system by building a policy structure and integrating it with the base model).

Policy design structure is described by Wheat as a *‘stock-and-flow feedback structure that implements decision rules specifying when the new policy will become operational, how it will work, and what will happen over time to improve the performance of the system’;* however, he warns that if the assumptions made when developing the model’s new decision rules are too naive then the results from model simulations can provide unrealistic expectations about how effective policies can be.

Policy makers often think in terms of “policy levers” that can be pulled to try to affect policy outcomes (for example, success rates of operations or percentage reduction in tonnes of waste generated per year) within the system of interest (for example, the health service or the economy). Whether or not these are the most effective levers, and whether there is a risk that pulling a lever will create unintended consequences is not always fully understood. This can be due to high levels of dynamic complexity in the system, caused when many positive and negative feedback loops interact between the agents in a system, and uncertainty about what drives the decision making of those agents. Along these lines, Sterman describes the phenomenon of “policy resistance” –

unexpected effects of policy interventions, which are the unanticipated "side effects" of well-intentioned interventions. He states that *'our decisions provoke reactions we did not foresee. Today's solutions become tomorrow's problems. The result is policy resistance, the tendency for interventions to be defeated by the response of the system to the intervention itself'* (Sterman 2002). Sterman cites examples of this in road building programs that eventually lead to increased traffic congestion and the evolution of antibiotic-resistant pathogens, saying that it occurs partly due to the worldview that many people live by, a narrow thinking style that is event-oriented and reductionist.

The structures within which policies are implemented are both physical and social. While physical flows are relatively easy to identify and model, and for which there is usually some data available, social structures are far more "messy." SD has been recommended by Lane and Husemann as a suitable tool for modelling social structures, which evolve *'in forms such as laws, customs and resource allocations'* (Lane & Husemann 2008). They describe the way these structures are encountered by individuals in their daily lives, how they discourage or encourage certain acts, and the ongoing feedback between individuals and social systems: *'Human agents interpret such influences in terms of attitudes, values and roles which become part of the mental models informing their behaviour. Such mental models are expressed as social actions, which then create new structural effects, or replicate existing ones'.* (ibid)

Meadows (Meadows & Wright 2009) has described twelve leverage points, or places to intervene, that are typically found in existing systems. These leverage points can be used to influence one or more behaviours of the system to change in a particular direction, and they are often not understood intuitively. Meadows' categories are focused on *where* in a system the intervention is introduced, rather than the type of intervention. The relative merits, applicability, and strength of impact for each of these places to intervene are described in detail in Appendix B. A summarised version follows here, with the intervention points presented in increasing order of effectiveness:

1) Numbers: constants and parameters such as subsidies, taxes, standards
2) Buffers: the sizes of stabilising stocks relative to their flows
3) Stocks and Flow Structures: physical systems and their nodes of intersection
4) Delays: the lengths of time relative to the rates of system changes
5) Balancing Feedback Loops: the strength of the feedbacks relative to the impacts they are trying to correct
6) Reinforcing Feedback Loops – the strength of the gain of driving loops
7) Information Flows: the structure of who does and does not have access to information
8) Rules: Incentives, punishments, constraints
9) Self-Organisation: the power to add, change or evolve system structure
10) Goals – the purpose or function of the system
11) Paradigms: the mind-set out of which the system – its goals, structure, rules, delays, parameters – arises
12) Transcending Paradigms

Appendix A provides an introduction to the basic tools of SD.

4.0 Waste Prevention Model

The aim of the WP modelling stream was to explore the subject of WP in quite a broad sense. The team's approach was to model the key dynamic connections between people, products, and the economy that drive waste generation and identify where WP practices exist and could be expanded, or where new practices could be introduced.

4.1 Model Development Method

4.1.1 Problem Structuring and Purpose

The first task was to agree a reasonable working boundary for the system of interest. The problem, waste generation from economic activity, can be categorised in several ways:

- By the sector which produces it: household, mining and quarrying, construction, or commercial and industrial;
- By the activity which produces it: product-related (producing, distributing, acquiring and using all types of products); large industrial-related (e.g. mining and construction); or government-related (e.g. the military);
- By WP activity/practice, such as remanufacturing, re-claiming of construction waste on site, efficient material design, design for repair, etc.

The project team chose to focus the model only on products, and to use an approach that is generic to product types (e.g. electrical, food, textiles), sectors (households, commercial businesses, industry), and types of WP practices, with the intention that the model could be adapted to be more specific if required. Heavy industry (including the power sector, construction, mining and quarrying, agriculture and forestry, fishing and aquaculture) and government (including military) were excluded from the model. This was partly due to the lack of publically available data for these sectors, and partly because the weight of waste from those sectors is far higher than from other sectors (on average twice that of manufacturing, household and services combined) and generally of less material value, and so including it when using tonnes as the metric would have skewed the data towards those sectors.

Two initial model building days were held, two weeks apart, for problem structuring and to develop Causal Loop Diagrams (CLDs) of the system of interest[13]. Participants were a mixture of academics, government policy makers and evidence analysts, and experts from industry, trade bodies, research institutes, and local government. The approach taken on the two days was based broadly on the work of (Andersen et al. 2007) and (Andersen & Richardson 1997). Based on the schema on p103 of Vennix's Group Model Building (Vennix 1996) and an understanding of (Parsons 2002) and (Cartwright & Hardie 2012), the decision was made not to present a "straw man" model, but to ask participants to start a model from scratch.

The first workshop started with a general discussion on modelling purpose, what the participants' understanding of WP is, and what WP policy should be designed to achieve. Then participants were put into four groups and asked to identify key factors related to WP. In the next session they clustered similar factors into themes, pulled out the most important ones, and then connected them as CLDs. The groups worked undirected and they ended up modelling slightly different areas of the system, such as the repair industry, the design of products in industry, and types of business models that promote "fast fashion" – with some overlap of subject matter between the groups.

[13] Prior to the group model building days, three training days had been run at Defra by staff from Ventana Systems UK in the use of systems thinking, causal loop diagramming and system dynamics modelling with Vensim software; however, not all workshop participants had attended these trainings.

While participants were building the CLDs the project team went round to try to ensure the teams were modelling the system "as is" rather than their policy wishes. When challenged on this, several participants agreed that they had at least partially modelled the system as they would like to see it. The day finished with a plenary session in which each group explained their CLDs to the other groups.

After the first workshop, the project team transferred the hand-drawn CLDs into Vensim[14]. We also reviewed the plenary session discussions and supporting literature to come up with a working definition of model purpose and system boundary:

- The purpose of the model is to understand the dynamics of the flow of materials in products, from cradle to discard, in the domestic and commercial and industrial sectors – identifying the drivers of waste-intensity of activities and associated carbon emissions, in England/ UK, and how these drivers interact.
- The system of interest lies between the producer and the point at which products/materials enter the waste system.

The second workshop started with a plenary session in which the suggested purpose and boundary definitions were presented to the group for their review, prompting some stimulating discussions on WP in general and the role of central and local government policy. The initial CLDs had been printed out on A0 paper, and the participants were split into four teams and asked to review the models (everyone worked on a model they had not built in the first workshop). They marked the models, changing some of the connections and adding variables as they saw fit. The CLD review session led to quite a few changes and additions to the first CLDs, but few major changes to the basic structure of the models. At the end of the day each team again presented their models to the other teams.

4.1.2 Model Building

A review of the workshop CLDs found that four main themes had emerged: consumption, re-use of products, repair of products, and business models. The next step was for the project team to consolidate the many workshop CLDs which was done by creating four complex summary CLDs on each of the themes identified. The summary CLDs captured the causal connections from all of the sessions on a similar theme and also included ideas from the group discussions that had not made it onto the sheets of paper.

It then became apparent that a Stock and Flow Map of material flows through the system was going to be necessary to move model development further. This map, named the Material Flows Map, was built based on literature reviews, the workshops, and talking with experts. It represents the main routes through which materials and products flow through the economy. The map was then combined with the four summary CLDs through several workdays with the project team to create a SD model structure, with material flows in the Material Flows Map driven by the causality from sub-models. The number of sub-models in the model rose to seven in the final model, because the four summary CLDs produced from the first two workshops had not covered all of the dynamics needed to drive materials around the system.

The draft model was presented to a smaller group of WP policy makers and experts at a subsequent workshop. The reviewers gave feedback on how well they felt the elements in the model, the connections, and the expected behaviour of the model fit with their knowledge about the system. Informed by the feedback, the model was further revised.

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[14] http://vensim.com/

The next step was to document the dynamic hypotheses for each of the sub-models and to produce relevant evidence. The dynamic hypotheses were based on discussions from all of the workshops and evidence from the literature. Evidence on system-wide, macroeconomic trends for key variables over the last 15 years was based on data gathered from government data sources, academic, and trade literature. The dynamic hypotheses and the evidence were compared and this comparison confirmed, in whole or part, some of the hypotheses and revealed the need to further investigate where there was ambiguity on trends.

4.2 Model Structure

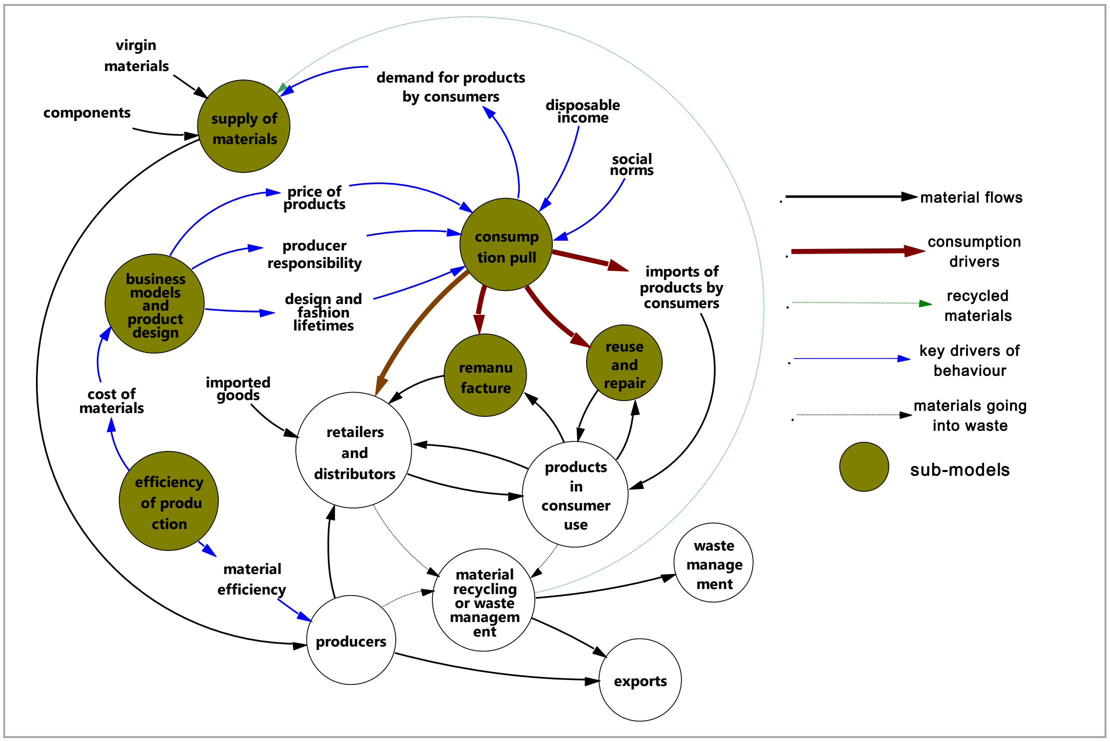
The WP model's structure combines a Material Flows Map (stock and flow diagram) and seven dynamic sub-models which drive the flows of materials through the system. The names and descriptions of the "views" (i.e. sub-models) in Vensim are listed in Table 4-1. Sub-models are classed under "supply of products" or "use of products".

Table 4-1: Views in the Waste Prevention Model

Grouping	View Name	Description
Physical Flows	Material flows Map	A map of the flow of different types of materials – virgin, recycled, as parts of products, or as finished products – through the economy, from their point of delivery to producers or importers, to their entry into the waste management system
Supply of Products	Supply of Raw Materials	Models the ratio of virgin to recovered materials, the price of materials in products, and the cost of new products
	Efficiency of Production	Models the level of efficiency with which materials are used in production, which affects waste generation by producers
	Business Models and Design	Models the price of new products to consumers, producer product lifetime stewardship, and the design and fashion lifetime of products
Use of Products	Consumption Pull	Models the total amount of goods demanded by consumers, and the relative attractiveness of different options for acquiring new goods
	Repair	Models the third party repair industry and the relative attractiveness of choosing to repair a product compared to other options
	Remanufacture	Models the flow of broken goods sent for remanufacture, and the demand for remanufactured products as replacements or discount products
	Reuse	Models the flow of second hand goods offered for resale or gift and the demand for second hand goods bought from a person or a shop, or accepted as gifts

A high-level diagram of these views and how they relate to each other and to the material flows is shown in Figure 4-1. To keep it simple, this diagram does not include all of the connections between modules and includes only a few of the key exogenous variables.

Figure 4-1: Model Structure Diagram



4.3 The Material Flows Map

The Material Flows Map represents the movement of materials through the economy. This includes virgin materials, materials in component parts of products, materials in finished products, materials in packaging for shipping and product sale, and materials entering the waste stream.

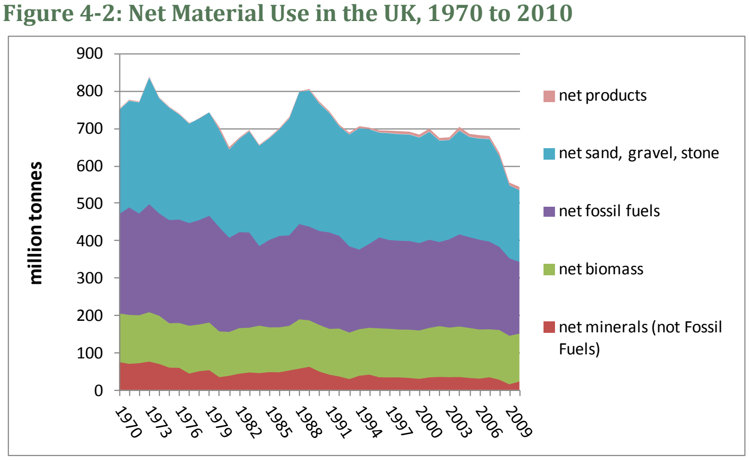
4.3.1 Evidence

This section provides an overview of evidence about the different flows represented in the map.

4.3.1.1 Net Material Use

Net total material use in the UK, in tonnes, has decreased since 1970 by 28%, as shown in Figure 4-2 (domestic extraction plus imports minus exports). Categories showing a strong decline include non-fossil-fuel minerals and sand, gravel and stone. Although some use of these materials are not directly related to the production, distribution, and use of products (materials may be used in construction for example) these trends are an indicator of the material intensity of the economy. Net products are a small percentage of raw materials in terms of weight.

Figure 4-2: Net Material Use in the UK, 1970 to 2010

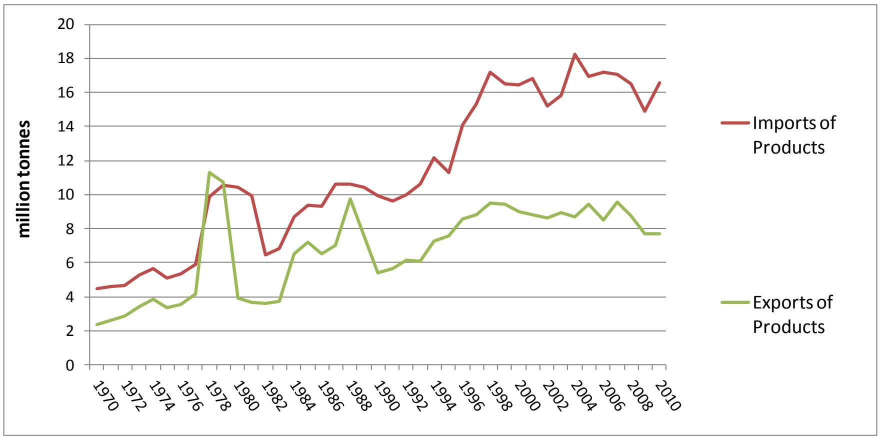


Source: (ONS 2012f)

4.3.1.2 Materials in Products

Figure 4-3 presents data on flows of materials in products into and out of the UK (i.e. materials embedded in finished products). The ratio between imports of products to exports, in tonnes, in the UK has been approximately 2 to 1 since the 70's, rising slightly in recent years. Net imports of products (imports minus exports) have risen steadily since the 1970's to around three times more in 2010. Per capita net imports of products (not shown) also increased over the period.

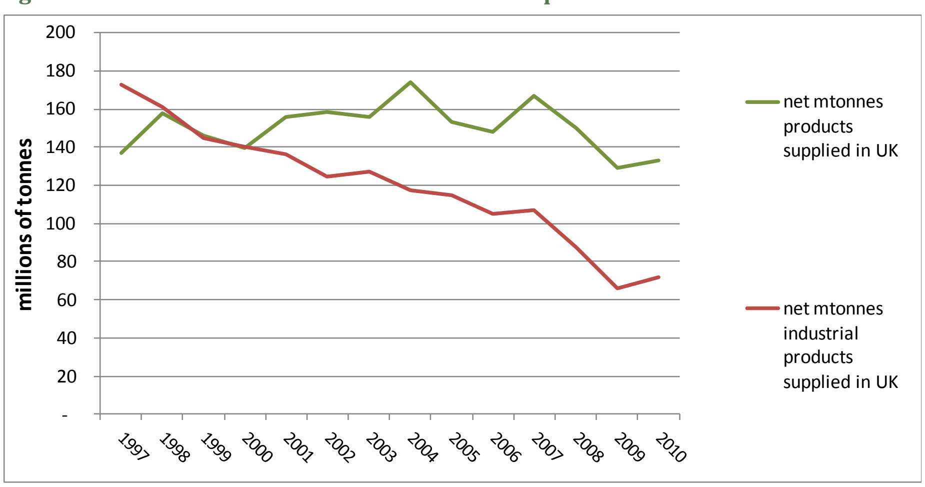
Figure 4-3: Imports and Exports of Products, 1970 to 2010



Source: (ONS 2012f)

Figure 4-4 shows a very high-level estimate of the consumption of all products supplied in the UK, including domestically produced, for the period 1997 to 2010. The estimate was calculated by combining data on the weight of imports of products and materials from HMRC and data on the supply of products (in £) from ONS. Over the period, the amount of non-industrial products supplied first rose and then after 2007 fell by 20%. The amount in 2010 was about the same as in 1997. Net industrial products show a steady decline, and decreased by almost 60% over the whole period.

Figure 4-4: Tonnes of Products and Industrial Output in the UK

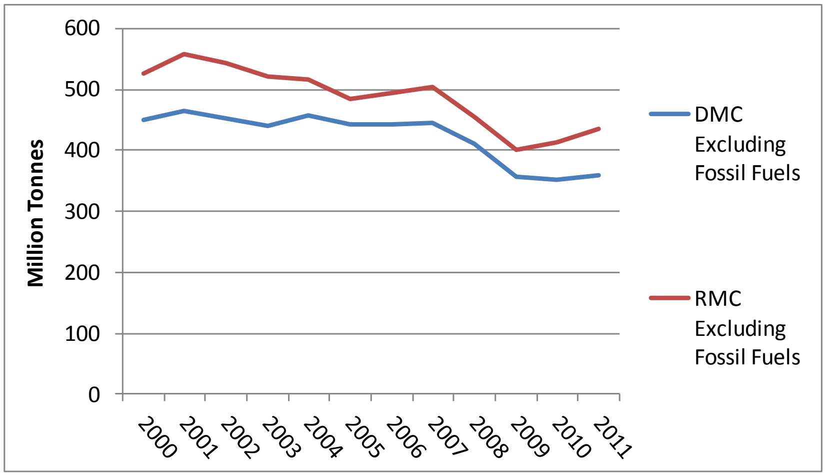


Source: (HMRC 2013) *and* (ONS 2012g)

4.3.1.3 Embedded Materials and Imports

The long-term trend of rising imports of products, shown in Figure 4-3, indicates that some portion of the reduction in UK material consumption may have been transferred to the countries manufacturing products the UK imports. Defra's experimental data on Raw Material Consumption (RMC), which accounts for raw materials used to produce imported goods (excluding fossil fuels and energy carriers) show RMC averaging 15% higher than Direct Material Consumption (DMC). Figure 4-5 shows that RMC values have been tracking DMC fairly closely since 2000, apart from between 2009 and 2011 when they increased by 8% (while DMC increased 0.3%), mostly due to an increased in RMC mineral use.

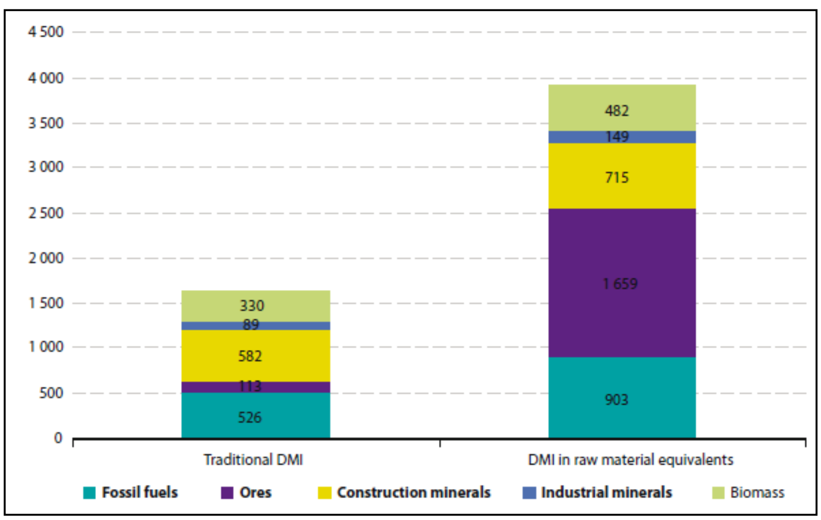
Figure 4-5: UK Raw Material Consumption



Source: (DEFRA 2013b)

Another view on the difference between virgin and product accounts comes from the Federal Statistical Office in Germany ((Buyny et al. 2009)cited in (Eurostat 2010)). Their indicator converts imports into their associated Raw Material Equivalents (RME). The Domestic Material Input (DMI)) in Raw Material Equivalents for Germany in 2005 was about 2.4 times higher than the DMI value derived using the traditional approach. This difference in DMI and RME varies by material type, with the RME significantly higher for ores, minerals, and fossil fuels (Figure 4-6).

Figure 4-6: Traditional versus Raw Material Equivalent values of DMI, Germany, 2005 (million tonnes)



Source: (Eurostat 2010)

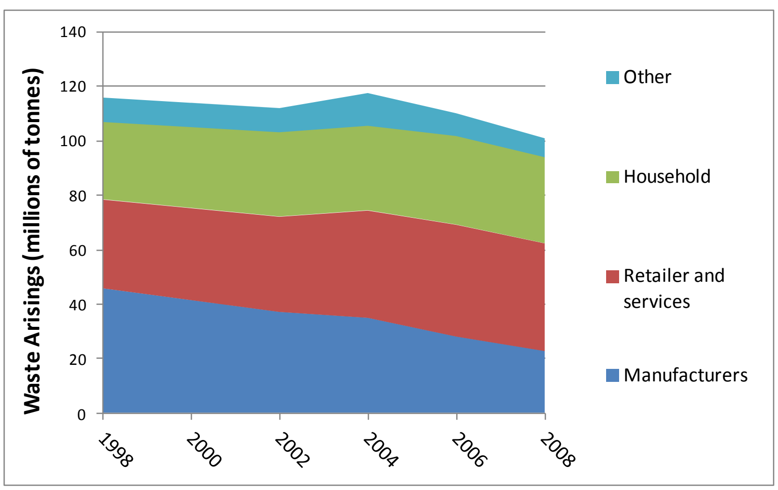
Regarding embedded emissions, a report from the (House of Commons Committee on Energy and Climate Change 2012) on consumption-based carbon emissions, which take into account what emissions occurred as a result of the manufacture of goods or services overseas that are eventually consumed in the UK, states that the although the UK's territorial emissions have been decreasing, consumption-based emissions have been increasing, meaning that the UK is contributing to a net increase in global GHG emissions. The CCC confirmed this in April 2013, finding that *the UK's carbon footprint has increased (by an estimated 10% over the past two decades), as growth in imported emissions has more than offset reductions in production emissions. The increase in imported emissions is largely a result of rising incomes which has increased demand for manufactured goods... now mostly produced elsewhere'.* (CCC 2013)

The difference in trends for embedded carbon emissions (upwards) and Defra's estimates for RME in imports (downwards) is a complex problem that has not yet been fully explored or explained. Embodied carbon and RME have not been included in the first draft of the WP model, but they would need to be if the model is to become a useful tool for working to reduce the UK's carbon footprint.

4.3.1.4 Waste Arisings

Data on waste arisings in the UK between 1998 and 2008 (Figure 4-7) show the total amount of waste falling by around 12% over the period, after reaching a peak in 2004. Generation of waste from manufacturing decreased and generation of waste from the retailer and services sectors increased. Household waste rose by 29% between 1984 and 2005 but then decreased by 16% between 2005 and 2011. The services sector is combined of transport, local government, and retail and wholesale, and for those years in which detailed data on waste from the services sub-sector was given, around 40% of services waste came from retail and wholesale. These waste trends reflect broadly the macroeconomic picture of the percentage of turnover in different sectors, with economic activity partially shifting into services and away from manufacturing. Note: values shown in Figure 4-7 represent total waste arisings, before materials are sent to recycling or other forms of waste management.

Figure 4-7: Waste Arisings by Sector



Source: (ONS 2011) *and* (DEFRA 2011)

4.3.1.5 Waste Decoupling

Waste decoupling is one of the goals of WP, as defined by the EU: '*Decoupling economic growth from the environmental impacts associated with waste generation is a key objective of the EU's revised*

Waste Framework Directive... waste growth in the EU must now reverse' (European Commission 2012). A similar objective, but with a different emphasis, is to improve "resource efficiency", which is described on the EU's Online Resource Efficiency Platform as '*using the Earth's limited resources in a sustainable manner'*.[15] The platform describes natural resources such as metals, minerals, fuels, water, land, timber, fertile soil, clean air and biodiversity as vital inputs to the economy, and the potential for resource efficiency to reduce the need for these inputs, minimise waste, and improve management of resource stocks.

In this report we have taken a material-neutral and nation-wide view of material flows and waste, while acknowledging that there is considerable heterogeneity within the full range of types of goods and materials we are modelling. We acknowledge that there is likely to have been more decoupling in some sectors compared to others, and for different types of products; however, time and resources have not allowed us to investigate these differences within the project timeframe.

A variety of opinion and evidence on the potential for and achievements of waste decoupling exists. A 2009 literature review for Defra by (Brook Lyndhurst 2009) found that some authors questioned whether economic growth *'is in any way compatible with conserving finite natural resources on the scale that now appears to be required*'; additionally, the review of evidence papers on the effects of decoupling policies showed that *'decoupling appears either to have been extremely weak, non-existent, short-lived or highly ambiguous'.* (ibid)

A more recent study by (WRAP et al. 2012) examined waste decoupling by sector and found that:

- For households, there have been short periods of absolute decoupling of waste generation from economic indicators prior to the economic recession, and relative decoupling across much of the period reviewed (1988 to 2010).
- For the commercial sector, a decoupling relationship between waste arisings and Gross Value Add (GVA) is not clear, and data limitations and quality concerns prevent any firm conclusions from being drawn.
- For the industrial sector, trends show greater falls in waste arisings than industrial GVA over the period, indicating decoupling has taken place.
- For construction and demolition, there are no clear trends in the relationship between waste and GVA, with periods where waste appears decoupled, coupled and negatively coupled.

The WRAP report also presents findings of a regression analysis on household waste, which found that changes in GVA per capita (positive), mean household size (negative), and expenditure on snacks and takeaway food (positive) would all increase household waste arisings.

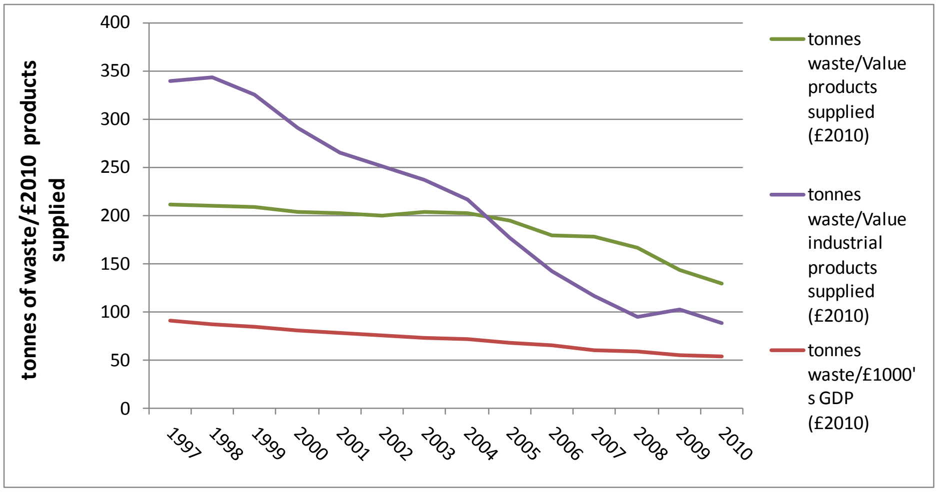
Figure 4-8 shows our estimate of recent trends in the coupling between waste generation, economic activity, and the value of products supplied. For finished products, waste arisings from household and services sectors were compared with the value of products supplied (adjusted for inflation with GDP deflator), and for industrial products waste from manufacturing was compared with value of industrial products supplied (adjusted for inflation with GDP deflator). Real GDP (adjusted for inflation with the GDP deflator) was compared with total waste arisings from households, services, and industry.

These estimates show waste decoupling for industrial products of 70%, waste decoupling for GDP of 41%, and waste decoupling of 29% for the value of products supplied, over the whole period. Because this analysis has been done at a very basic, aggregate level it may mask different underlying trends that go in different directions – e.g. better waste prevention in one area, but

[15] http://ec.europa.eu/environment/resource_efficiency/about/index_en.htm

increased consumption in another. We understand that work on developing more accurate waste decoupling indicators is in progress at Defra. One expert estimate is that the decoupling seen so far is about half due to improved efficiency and half due to recession and changes to the structure of the economy[16]. During this period, the less material-intensive services sector rose from 29% to 35% of UK business turnover (ONS 2010)), and the more material-intensive manufacturing sectors fell from 26% to 19% of UK business turnover (ibid)).

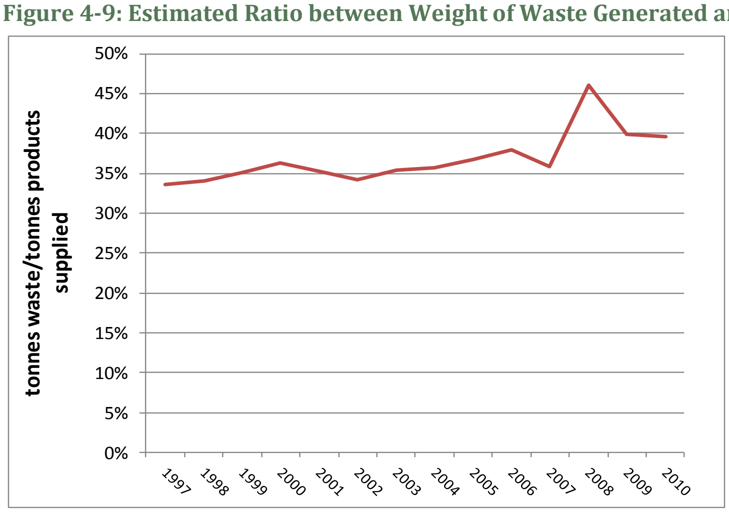
Figure 4-8: Estimates of Coupling between Waste and Value of Products Supplied



Source: (HMRC 2013) (ONS 2012g), (ONS 2011), (ONS 2012d), (The Bank of England 2010)

To examine waste generation trends from a purely materials viewpoint, a comparison was done between materials coming into and going out of the economy – the ratio of (estimated) total tonnes of products supplied in the UK and tonnes of waste generated in all sectors. The ratio increased by 18% between 1997 and 2010, with the highest ratio in 2008 at 45% - most likely due to the drop in the supply of products at that time. We would expect some delay between materials entering and leaving the system for durable products, depending on the rate at which they are replaced, but the effect of this delay is difficult to estimate; it would partly depend on the ratio of durable to non-durable products in the waste stream.

Figure 4-9: Estimated Ratio between Weight of Waste Generated and Products Supplied



Source: (HMRC 2013) (ONS 2012g), (ONS 2011)

[16] Conversation with Rocky Harris, at Defra, 10/10/2013

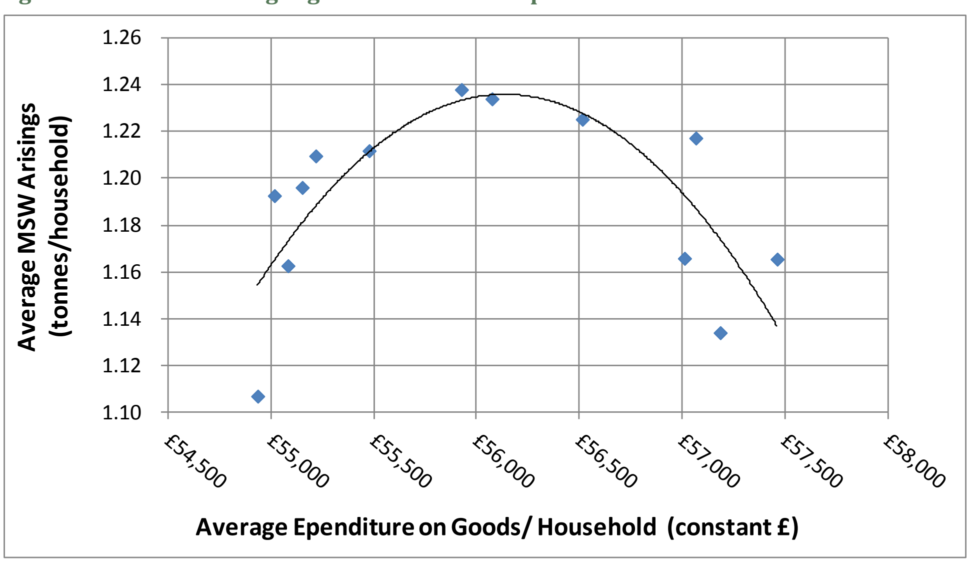
4.3.1.6 Waste Decoupling in Households

One theory on the relationship between household waste generation and income is provided by the Environmental Kuznets Curve (EKC), the hypothesis about which '*claims that some categories of environmental impact, such as water and air pollution, show an inverted U shape with respect to the indicators of economic development.* The EKC assumes that a "negative scale effect" of economic growth on environmental impact exists, and that there are ""positive efficiency effects" associated with economic growth – including technological innovation, environmental policies, and the desire for environmental protection as a kind of luxury good (Mazzanti 2008). The turning point (TP) of the inverted U is of particular interest as this is where household waste decoupling starts to happen. Mazzanti examined trends in MSW generation across the EU, and also across regions of Italy, through two studies.

1) In (Mazzanti 2008) data from 103 provinces in Italy provided evidence in favour of a EKC for waste, *'with rather high TPs but within the observed income range'.* The TP was in the range of €23,000 to €26,000 of value added per capita, when socio-economic drivers and policy factors were considered.
2) In (Mazzanti & Zoboli 2008) data from across the EU showed '*no absolute delinking trend is present, though elasticity to income drivers appears lower than in the past'* (ibid). Regarding policies, the study found that no policies, including landfill tax, appeared to provide enough incentive to get WP practiced. They find that this is '*a result that calls for the introduction of waste policies targeted at the level of the sources of the waste generated'*. (ibid) The authors conclude that '*structural changes in consumption and production'* (ibid) should be considered when developing policies for waste.

The relationship between MSW arisings and average household expenditure on goods between 1997 and 2010 shows some evidence of relative decoupling of waste generation with higher expenditure, as shown in Figure 4-10. The turning point appears to be where total household expenditure is around £56,000 (£2011 constant). This is not a true EKC as it does not compare waste and income within different household sectors, but compares average household expenditure for the whole UK in each year with average household waste arisings. Thus it indicates a trend in social norms rather than the behaviour of households with different incomes.

Figure 4-10: MSW Arisings against Household Expenditure on Goods



Source: (ONS 2012c) *and* (DEFRA 2012)

4.3.1.7 Waste Decoupling in C&I Sectors

Data on waste arisings in the manufacturing and services sectors (the services sector includes retail) show a decoupling of waste generation and economic activity. Table 4-2 shows tonnes of waste from the manufacturing (excluding heavy industry such as mining and construction) and retail/services sectors per £M of GVA for those sectors. This data was calculated from primary data from ONS and Defra. Both sectors decreased their waste intensity by over 30% between 1998 and 2006. Possible causes of this could include: changes in types of manufacturing activities in the UK, the trend for light-weighting of goods, material efficiency improvements, increasing amounts of GVA coming from selling non-material products such as financial, and waste prevention. Interestingly, a converse trend has been seen in Danish industry; an economic analysis of waste trends in non-household sectors in Denmark revealed a 40% increase in the waste intensity of economic activity since 1994 (Brix & Bentzen 2005).

Table 4-2: C&I Waste Intensity, 1998 to 2006 (Tonnes Waste/£M GVA)

Year	Waste Intensity Manufacturing (not heavy industry)	Waste Intensity Retail and Services
1998	348	100
2000	323	92
2002	313	89
2004	291	80
2006	241	49

Source: (ONS 2010), (ONS 2011), (DEFRA 2011), (ONS 2012d)

4.3.1.8 Summary of Material Flows Evidence

The evidence presented in this section indicates that in general, over the period of the model, there has been relative decoupling of both waste and material use from economic activity in all of the sectors examined. For material consumption there has been absolute decoupling, with a drop in the total amount of materials consumed, and there has also been a total drop in waste generation, especially since 2004. Household waste appears to follow a pattern of relative decoupling with increasing expenditure, once past a tipping point.

4.3.2 Details of the Material Flows Map

The Material Flows Map, shown in Figure 4-11, is a SD stock and flow diagram that represents the modelling teams' understanding of the structure of the system of interest "as is". In the map, materials flow into and out of the system of interest, as:

- **Incoming:** Imported virgin materials or components supplied to manufacturers, imported recovered materials, and materials in imported products (green);
- **Outgoing:** Exported products and exported recovered materials (purple); waste materials landfilled, incinerated, or exported by producers, retailers, and consumers (red); and material unaccounted for and that is lost as measurable data to Defra (orange)

There are three categories of actors making decisions that affect flows of materials: producers, retailers and distributors, and consumers (which can be households or organisations). These decisions are influenced by the dynamics of the seven sub-models, described later in this section, and by the structure of the material flows map.

Materials generally flow from left to right, coming into the system as imported or domestic virgin materials, being converted from materials into products by producers, passing through retailers and distributors (who also import finished products), and going into the hands of consumers (who can also import directly from overseas).

The length of time products stay in use by consumers is affected by several factors, including the design life of the product (how robust it is and how upgradeable), the fashion lifetime of the product (how long products stay desirable), and the lifetime of need (how long the user has need for the product).

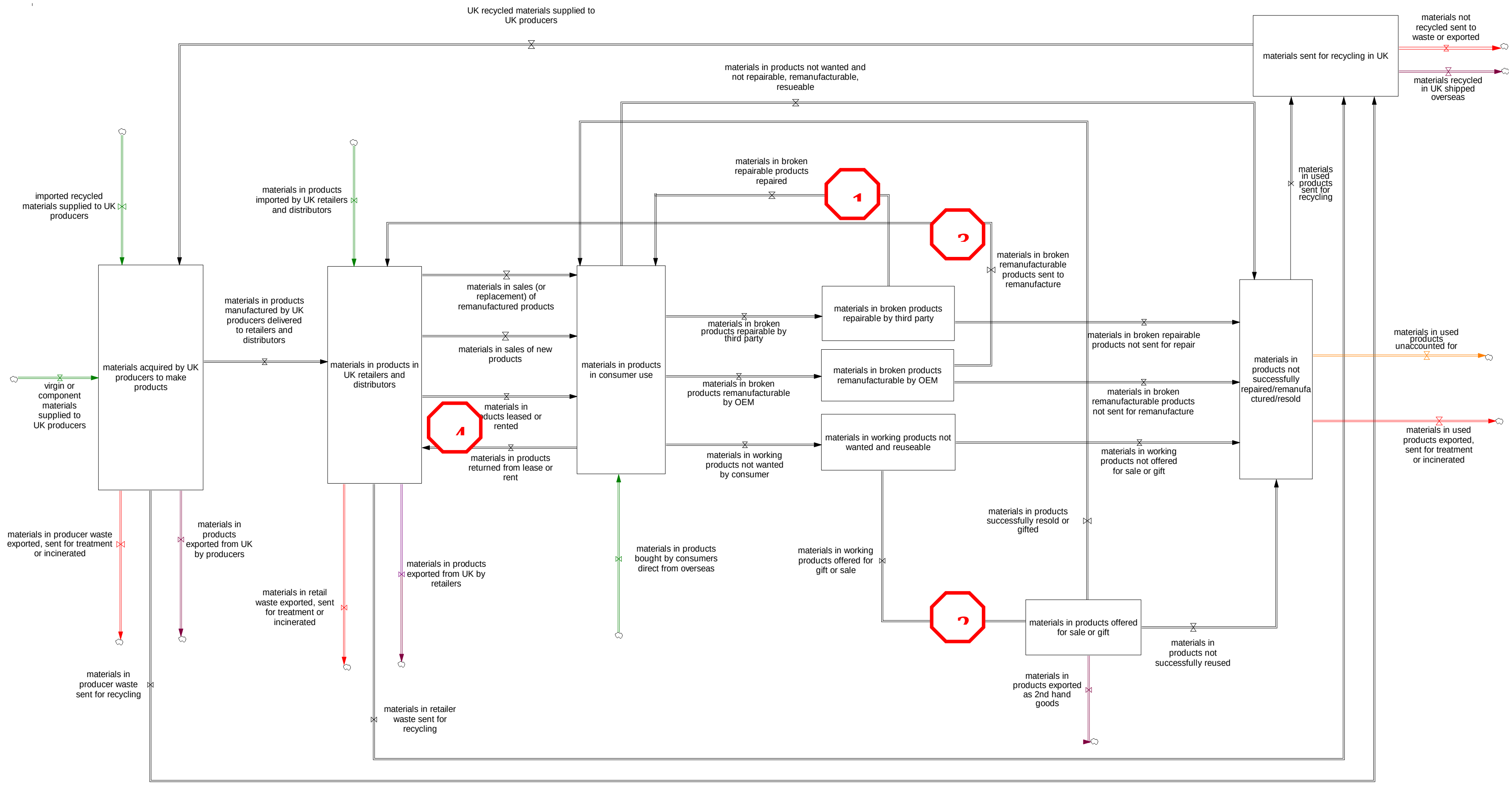
On the left side of the map, within the producer and retailer/distributor sectors, no circularity is shown and business models and commodity markets drive the amount of waste generated. On the right side of the map, once products are in the hands of consumers, materials in products can "circulate" by flowing through four WP "pathways", which keep them in use for longer than if they had a single owner and were thrown into waste when broken or not wanted – although often not in the same users' hands and sometimes not as whole products (e.g. parts may be reused).

The theory of the WP pathways, numbered in red on Figure 4-11 from one to four, is as follows:

1. **Repair:** products that are broken or unusable in some way and repairable by a 3rd party (or by the user him- or her-self) flow into the stock *materials in products repairable by 3rd party*. Those that are repaired return into the stock *materials in products in consumer use*, and those not repaired end up as waste.
2. **Reuse:** products that are usable but not wanted by the consumer flow into the stock *materials in products (working) not wanted and reusable*. Some of these are thrown away and some end up in the stock *materials in products offered for sale or gift*. Those that find a new owner circulate back into consumer use through the flow rate *materials in products (working) successfully resold or gifted* and those that don't end up as waste.
3. **Remanufacture:** products that are broken or unusable in some way and remanufacturable by the original equipment manufacturer (or by a 3rd party) flow into the stock *materials in products remanufacturable by OEMs*. Those sent for remanufacture flow back into the stock *materials in products in UK retailers and distributors* and then back into consumer use via the flow rate *materials in products (remanufactured) as sales or replacements*, and those that don't end up as waste.
4. **Lease or rental:** products can be rented or leased via the flow rate *materials in products leased or rented* which flows from retailers to consumers. Products are returned via the corresponding flow rate *materials in products returned from lease or rent*.

There is one more pathway through which material efficiency can be improved, which is through recycling. This is not strictly a WP pathway, but is included to reflect the overall material efficiency of economic activity. In the material flows map, materials in products sent for recycling that are successfully recycled flow back to UK producers through the flow rate *annual UK recycled materials supplied to UK producers*, and end up flowing into the stock *materials acquired by UK producers to make products* at the left of the map. The total amount of raw materials input into the system is reduced if recycled materials are used in place of raw materials.

Figure 4-11: Material Flows Map



4.3.2.1 Material Flows Map Interpretation

The consumption and use of products can been understood using the conceptual framing created by (Pierce & Paulos 2011) who define material consumption as having four stages – acquisition, possession, dispossession, and reacquisition. Table 4-3 relates these four stages with how they are represented in the material flows map. Note: these categories apply more to durable goods than to non-durable goods such as food.

Table 4-3: Stages of Consumption (from Pierce and Paulos)

Stage	Definition	Representation in the Material Flows Map
Acquisition	purchase of first hand products	The flow rate *materials in sales of new products*
Possession	products that are in consumers' hands (households and organisations)	The stock *materials in products in consumer use*
Dispossession	• giving away or selling products • putting products in for repair • returning products to the manufacturer for remanufacture • returning products that have been leased or rented • throwing away products as waste	The flow rates: • *materials in products (working) offered for gift or sale* • *materials in products (broken) repairable that are repaired* • *materials in products (broken) remanufacturable sent to OEM* • *materials in products returned from lease or rent* • *materials in products not repairable, remanufacturable, reusable; and materials in products repairable, remanufacturable, reusable but not offered for gift or sale, or not sent for repair or remanufacture*
Reacquisition	acquisition of products as second hand, remanufactured or repaired, or leased or rented	The flow rates: • *annual materials in products (working) successfully resold or gifted* • *materials in products (remanufactured) as sales or replacements* • *materials in products leased or rented* • *materials in products (broken) repairable that are repaired*

Another way to interpret the material flows map is to think about times in the past when the flows have been at their minimum or maximum. Theory on two contrasting examples follows.

- **Restrained Flows of Consumer Goods:** During the Second World War and up to 1954 imports of materials were restricted and much of UK manufacturing produced products for the war effort rather than consumer products. The government introduced rationing for clothing, most food items, and petrol, and promoted a culture of "make do and mend". The aim of clothing rationing was to '*ensure fair shares. But it was also intended to reduce consumer spending, to free up valuable factory space and release workers for vital war industries*'.[17] Imports of food were affected by enemy blockades and some imported fruit, such as lemons and bananas became virtually unobtainable.[18]

  In the material flows map, during this period the flow rates between producers and retailers and between importers and retailers would have been very much reduced compared to before the period, reducing the flows into the stock *materials in products in consumer use*. Much of UK production would have flowed directly between producers and the government for the war effort (procurement by government is not shown separately on

[17] http://www.iwm.org.uk/history/clothes-rationing-in-britain-during-the-second-world-war#

[18] http://en.wikipedia.org/wiki/Rationing_in_the_United_Kingdom#cite_note-5

the material flows map and war-related products have not been considered in the model) – a key difference in system structure compared to today. The four WP pathways would have been used more, and much less would have ended up as consumer waste. The useful lifetime of products and materials would have been long compared to their design lifetime (possibly longer), reducing the flow rates out of the stock *materials in products in consumer use* (in fact, flows out would have been restricted by the slower flows into this stock as the stock cannot be negative).

- **Abundant Flows of Consumer Goods:** Between the mid 1990's and the economic downturn starting in 2008 there was high availability of both products and capital for consumers and businesses, driven partly by a boom in the property market and increasingly cheap imports of some types of goods (see Figure 4-17). The culture of "fast fashion" became more prevalent, with more sales of cheaper consumer products with shorter design lifetimes (and shorter "technology chase" cycles for electronic goods). A study on the environmental impacts of consumption of clothing in Denmark by (Jørgensen & Jensen 2012) found that '*increasing clothing consumption is influenced by an interaction between business strategies based on low prices and fast fashion and increasing expectations by colleagues and friends of frequent shifts in clothing'* – in other words, the social norm with regard to clothing became almost opposite to that of WP.

  In the material flows map, the flow rate of new products going into *materials in products in consumer use*, at least for some product categories, would have increased (as indicated in Figure 4-4, tonnes of products supplied per person). Flow rates in the four WP pathways, relative to the total amount of goods being acquired as new, will have decreased as the imperative to use them was reduced. The lower fashion lifetime of many types of products, often lower than the design lifetime, would have led to a faster flow rate out of the stock *materials in products in consumer use.* Tonnes of household waste generated per person rose by 16% between 1995 and 2007 (DEFRA 2012) while the estimated weight of products supplied per person rose 10% during that time (Figure 4-4); in other words, there was a higher rate of increase in waste than in consumption, indicating less use of the WP pathways.

Additional Points of Interest and Model Development Options

- The Material Flows map can be seen through several lenses. The term "consumer" can mean any individual or any organisation that acquires a product, and all types of consumers produce waste streams. There is crossover between different types of consumers – for example, supermarkets are both consumers and suppliers.
- It may be more useful to think of actors in the system playing different roles rather than them being fixed as a producer, supplier or consumer. This can happen on the right hand side of the map also, as consumers who offer second hand goods for sale to others act as suppliers. The key difference is their relationship to the product in each phase of its lifetime.
- It may be useful for analysts to group case studies in terms of where they appear on the map, which would reveal gaps in current understanding and also where there is potential for policies to have a large impact.
- The map could be populated with data that focuses on different metrics: volume of products, value of products, environmental impacts, number of jobs, and specific materials in products, especially scarce ones. This would lead to better articulation of what type of data is needed, and why. Because the dynamics of the system will be significantly different for durable versus non-durable goods, there may need to be two versions of the map to reflect this.

- The boundary has been set around the UK, but the UK is part of a highly interconnected trading world, and so the impact of the red and green flows into and out of the system on WP efforts could be very significant. However, the UK has little influence over production in other countries; multinational companies have their own priorities when it comes to resource efficiency which may or may not be beneficial to the UK's WP efforts. The benefit of the model may be in having a tool with which to view the system through different lenses to understand the impact of UK actions versus international trading impacts.

4.4 Waste Prevention Sub-Models

This section provides details on the sub-models that drive materials around the material flows map, evidence on the dynamics they describe, and the theory behind the sub-model designs.

N.B. All wording in this section describes the modelling team's combined mental model of the real world. We are *not* saying definitively that "this is how the world works", rather we are saying that this model presents our view of how the world works. The optimal way to use this model would be to update it in an iterative way, through several rounds of review and update and comparison with empirical data, with the goal of achieving an improved understanding of the dynamic complexity of the system of interest. The model has not been parameterised yet, and it is likely that when it is parameterised it will go through some significant changes.

4.4.1 Supply of Materials Sub-Model

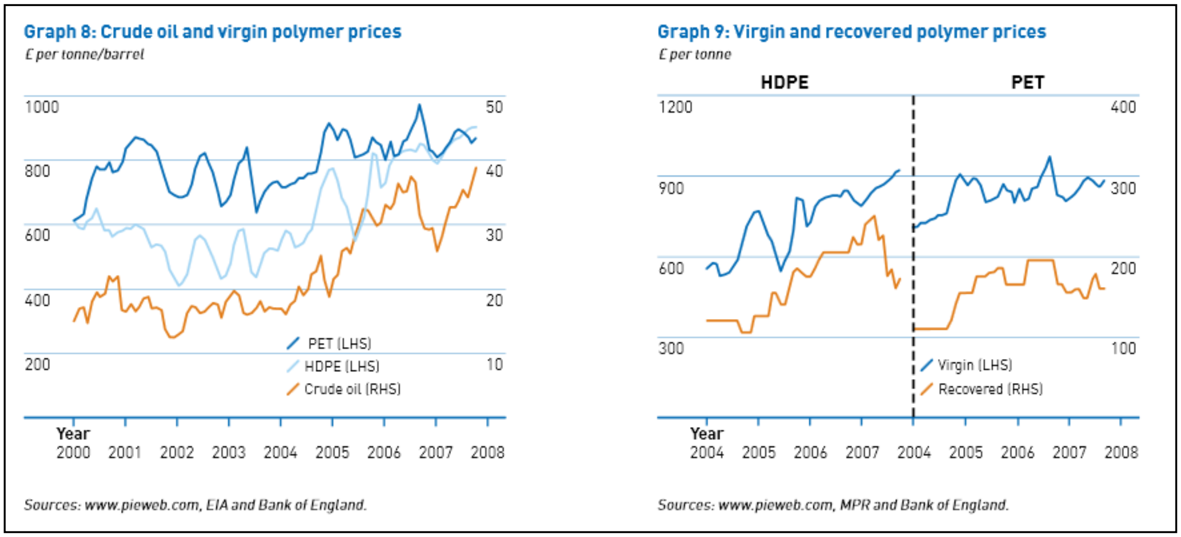
The Supply of Materials sub-model describes the dynamic relationships between the prices of and demand for both virgin and recovered materials. This dynamic influences the mix of materials used by manufacturers – part virgin and part recovered – which in turn influences the price of products.

4.4.1.1 Evidence for Supply of Materials Sub-Model

The relationship between virgin and recovered material prices has been examined by (WRAP 2007) for plastic polymers, one of the most common recovered materials in use in the UK. As shown in Figure 4-12, virgin polymer prices follow oil prices to some extent but not to a high level of correlation; between 2000 and 2008 crude oil prices rose by around 100%, but polymer prices rose only by around a third. The relationship between virgin and recovered polymers is more closely correlated, with recovered prices staying at around just over 50% of virgin prices during this period. Recovered polymers have restricted use (e.g. they cannot be used to make hard plastic goods) and different physical properties to virgin polymers, hence the much lower price.

Further work on this sub-model could evaluate evidence on whether consumer preference for purchasing products that are partly made from recycled materials, if it exists, gives companies that offer these goods a market advantage. This would mean that producers are willing to pay extra for using recycled materials if they are not economic anyway. Additionally there is currently no link between the Business Models sub-model and the Cost of Materials sub-model in terms of business models that support the use of recycled materials in production.

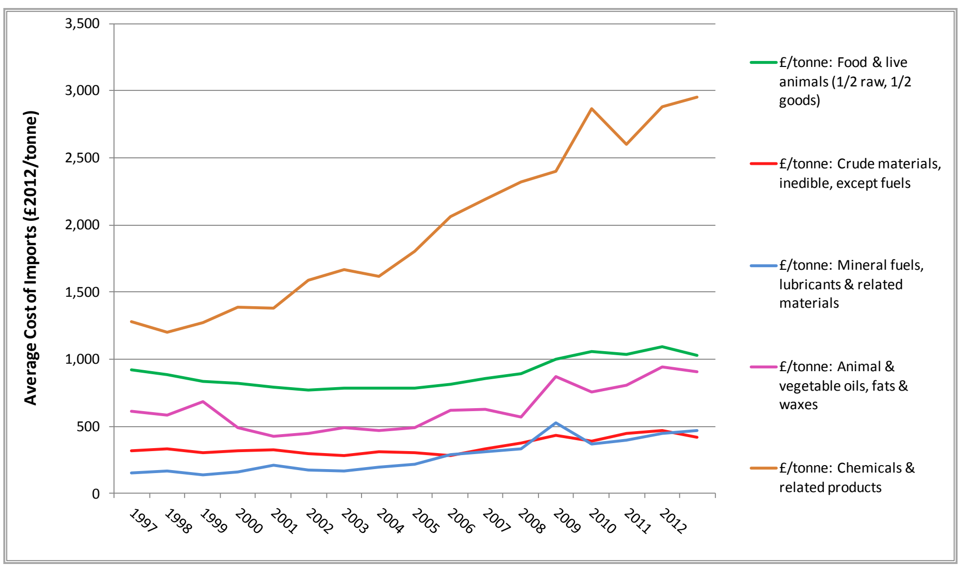
Figure 4-12: Relationship between Crude Oil and Virgin Polymer Prices, and between Virgin and Recovered Polymer Prices



Source: (WRAP 2007)

Trends in the price of raw materials are represented in Figure 4-13 via the price of virgin material imports from HMRC (in £2012, adjusted with the GDP deflator). These prices reflect trends in international commodity markets and therefore prices paid by UK producers – although these will not be exactly the same. Between 1996 and 2012 prices in all categories (except for chemical products) rose by less than 50%.

Figure 4-13: Trends in Raw Material Prices from Imports



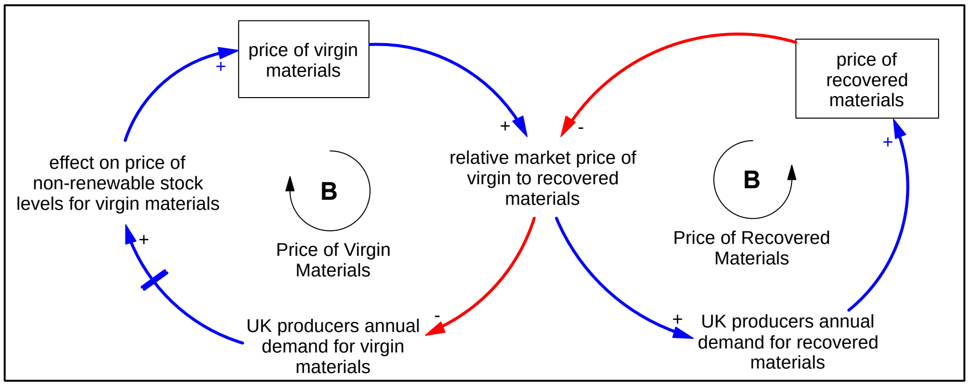
Source: (HMRC 2013)

4.4.1.2 Supply of Materials Sub-Model Dynamic Hypothesis

The dynamic hypothesis about the supply of materials, shown in Figure 4-14, is fairly straightforward. Prices for virgin materials and recovered materials exist in dynamic equilibrium with their demand, as would be expected (the more demand, the higher the price). The prices of virgin materials and recovered materials also exist in dynamic equilibrium with each other, by means of their relative market price. There are several known uncertainties within this sub-model:

- This relationship will not exist for those materials for which no recovered materials market exists;
- The relative effect of UK demand on the price of virgin materials may not be strong or may not even exist – many virgin material prices are highly influenced by global markets;
- The relative effect of UK demand on the price of recovered materials is likely to be stronger than for virgin materials; however, the UK imports and exports both recovered materials to be used in manufacturing, and recyclates intended for recycling, and so this is a complex issue involving international markets.

Figure 4-14: Supply of Materials Sub-Model



4.4.2 Material Efficiency of Production Sub-Model

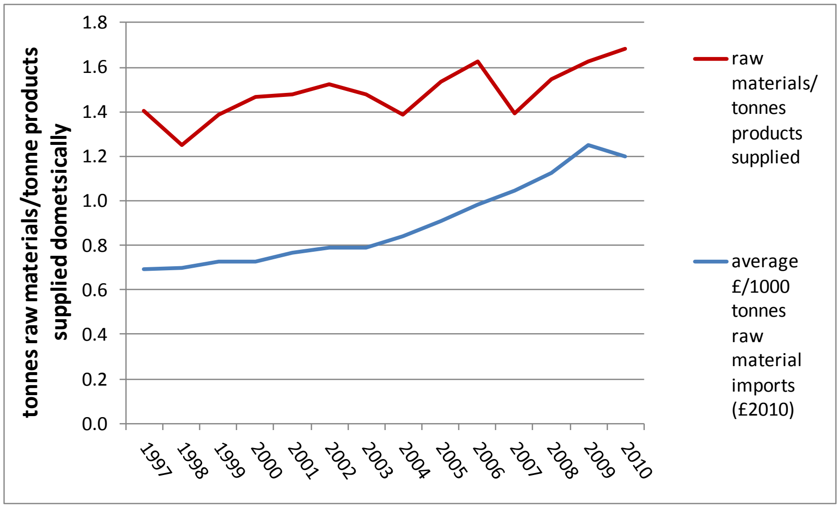
The Material Efficiency of Production sub-model drives the level of efficiency with which materials are used in production, which affects the amount of waste generated by producers and therefore the total amount of waste generated. An improvement in this efficiency level would mean lower waste intensity for the production of products.

4.4.2.1 Evidence for the Material Efficiency of Production Sub-Model

This sub-model is focused on the efficiency with which materials are used in the manufacture of products, and the relationship of this efficiency with the cost of materials. (Allwood et al. 2011) describe material use efficiency as the rate of "yield loss": '*More primary material is made than ends up in final goods, and this loss of material between its liquid form and use in a final product is termed the 'yield loss'... Yield losses can arise from start-up losses, trimming and scalping during processing, subtractive processing, quality problems, high purity requirements, mismatches between batch and order volumes, and over-ordering.'* (ibid) The authors state that there is substantial scope for reducing yield loss but the trade-off between increased manufacturing costs with component specialisation and reduced material costs limits this action, presenting data on the very long-term downward trends in material costs that show worldwide prices in 2000 a fifth of what they were in 1840.

Figure 4-15 shows recent trends for the UK in the relationship between raw materials and products supplied. The ratio between net raw materials used in the UK and an estimate of the tonnes of products supplied domestically (i.e. not imported) rose by 24% over the period shown. At the same time, the average cost of all imported raw materials almost doubled. Despite this recent rise in material costs there are no indications of it having an effect on industry practice, possibly because as (Allwood et al. 2011) state, '*in developed economies, labour costs often dominate material costs, so the incentive to reduce yield losses may be low'*.

Figure 4-15: Raw Materials per Tonne of Products Supplied, and Price of Imported Raw Materials

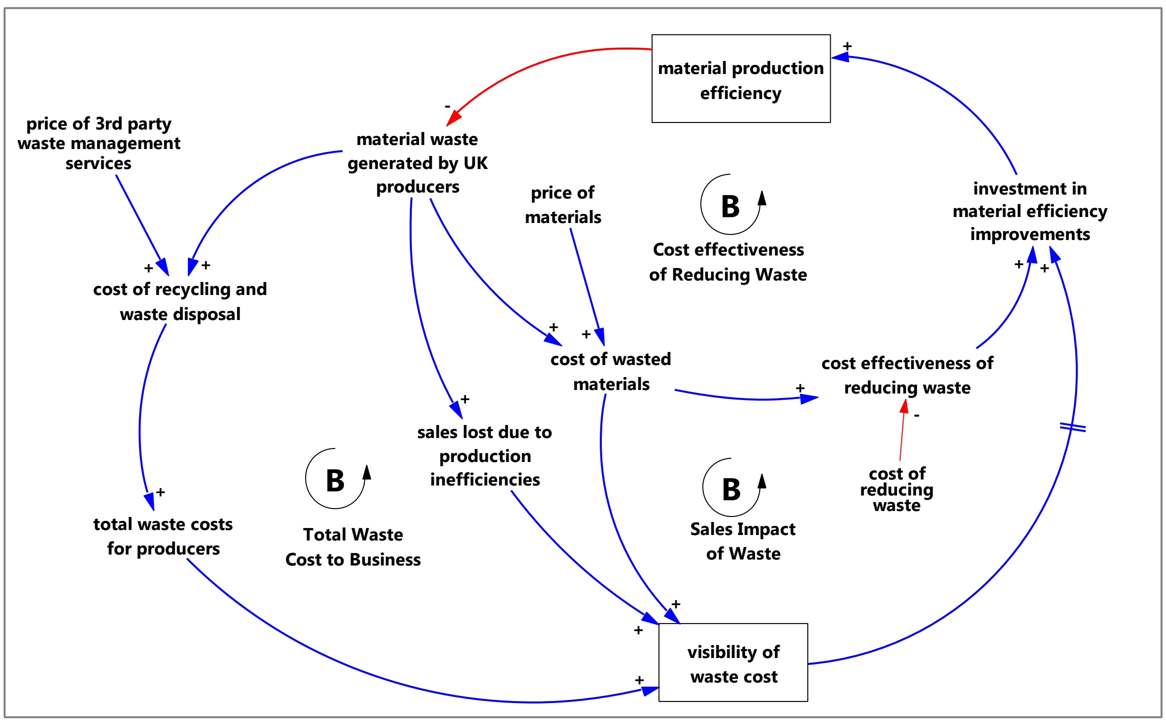


Source: (HMRC 2013), (ONS 2012g), (ONS 2012f)

4.4.2.2 Material Efficiency of Production Sub-Model Dynamic Hypothesis

The material production efficiency sub-model, Figure 4-16, shows the dynamic hypothesis about the efficiency of use of materials by producers.

Figure 4-16: Material Production Efficiency Sub-Model



When the benefits of material efficiency improvements outweigh the costs, there is an increase in investment in practices aimed at improving these efficiencies (for example, lean manufacturing methods such as Muda[19]). Material production efficiencies will not be improved in excess of what is cost effective to achieve, hence this is a balancing feedback loop. The cost effectiveness of reducing

[19] http://www.lean.uky.edu/reference/terminology/

waste is partly driven by the exogenous variables "price of materials" and the price of 3rd party waste management services, and partly by the cost of reducing waste, such as extra labour. Visibility of the costs of waste arises within the organisation from the combined impact of the cost of waste disposal and recycling, the cost of lost sales, and the cost of wasted materials. This visibility drives material efficiency improvements but over a longer timescale and it is more likely to be affected by industry norms.

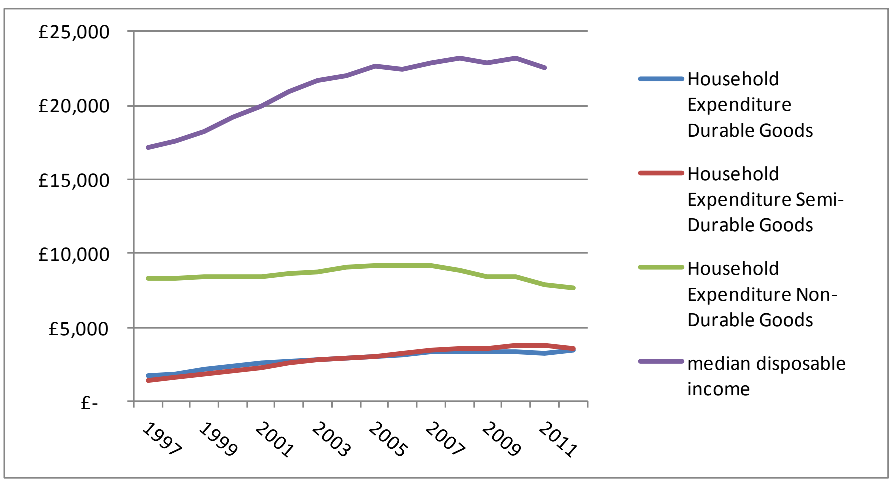
4.4.3 Business Models and Design Sub-Model

The Business Models and Design sub-model drives several factors that affect the lifetime and volume of new products sold: the price of new products to consumers, the level of product lifetime stewardship, and the design and fashion lifetime of products.

4.4.3.1 Evidence for the Business Models and Design Sub-Model

Key drivers within the business model are concerned with the volume of products sold and the cost of products. Figure 4-17 shows changes in the Chained Volume Measure[20] of household expenditure (in constant prices) for durable, semi-durable and non-durable goods between 1997 and 2012. Both durable and semi-durable goods show a consistent trend for increasing expenditure up to 2007, by over 100%. This trend is reversed for non-durable goods, which includes services, which fell by 8%. Also shown is median household disposable income, which rose by 31% over the period. These figures indicate a general rise in purchase of durable and semi-durable products but the relationship between price and volume purchased (i.e. the number of products) will be different for different product types.

Figure 4-17: Trends in Household Expenditure by Category (£2011)



Source: (ONS 2012d), (ONS 2012c) *and* (ONS 2012e)

Looking at two subcategories of household expenditure, the relationship between Consumer Price Index and consumption is, in general, that as CPI rises or falls, consumption falls or rises. For clothing in particular, although prices fell by half, expenditure more than doubled, indicating a larger volume of sales altogether.

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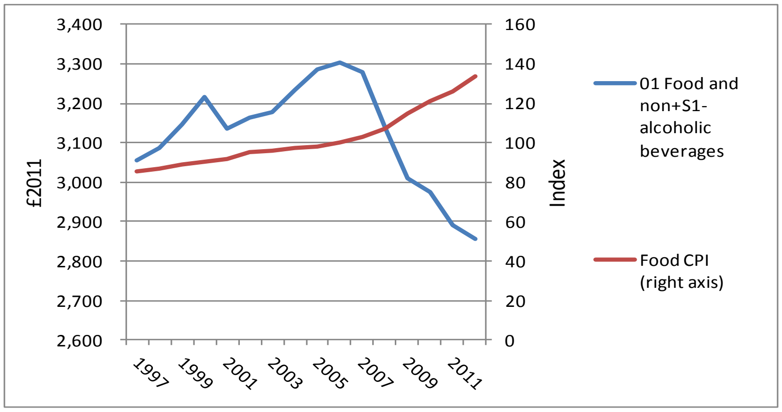
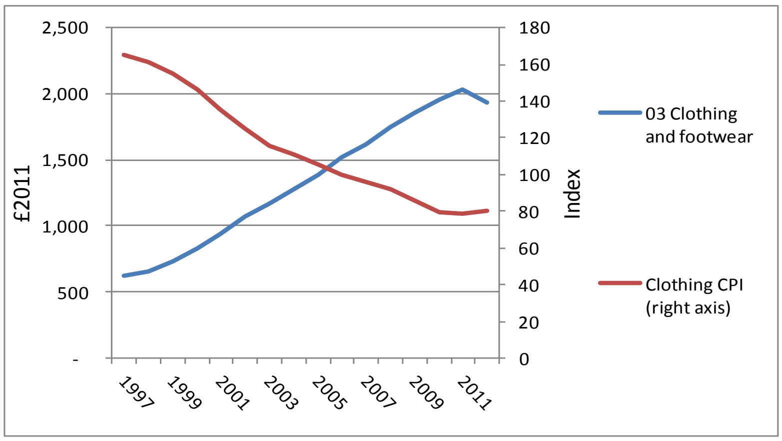
[20] Chained Volume Measures *'allow users to identify changes in expenditure on a good (or service) resulting from a change in the volume, rather than a change in the price of that good (or service)'.* From: ONS Definitions and conventions for Household Final Consumption Expenditure (HHFCE) in Consumer Trends. http://www.ons.gov.uk/ons/guide-method/method-quality/specific/economy/consumer-trends/definitions-and-conventions.pdf

4-18: Trends in CPI and Household Expenditure for Food and Clothing





Source: (ONS 2012d), (ONS 2012c) *and* (ONS 2012e)

4.4.3.2 Business Models and Design Sub-Model Dynamic Hypothesis

The diagram in Figure 4-19 shows the sub-model for business models and product design. The dynamic hypothesis is as follows:

- Businesses can make profits by selling high volumes of relatively cheap goods, small volumes of relatively more expensive goods, or some combination of these two. Profits are affected by production costs, which include material costs and non-material costs such as overheads, capital and labour.
- We use the term "short-term business model" to represent a generic business model that puts the highest priority on short term profits and minimises investment in longer-term goals such as longer-lasting products, customer loyalty, and Corporate Social Responsibility. The shorter-term the business model, the higher the sales volume targets, the lower the expected unit profits, and the higher the planned obsolescence. This can lead to one or more of: lower-quality goods with a shorter design lifetime, a shorter fashion lifetime, or a shorter technology lifetime (e.g. for electronic goods). Shorter lifetimes lead to increased unit sales, as do lower sales prices. Future improved versions of the model will need to consider a more diverse range of business models, and the interaction between them.
- In the main reinforcing loop the proportion of businesses with a short-term business model drives the unit profit and sales volume targets, which eventually lead to achieved overall profits and reinforce the business model. Two balancing loops represent business practices fulfilling the unit profit and sales volume goals.
- The stock *percentage of business models that are short-term,* which represents the mix of business models for all businesses, from retailers to distributors to producers, is so named

because of the predominance of short-term business models within the historical time period for the model.

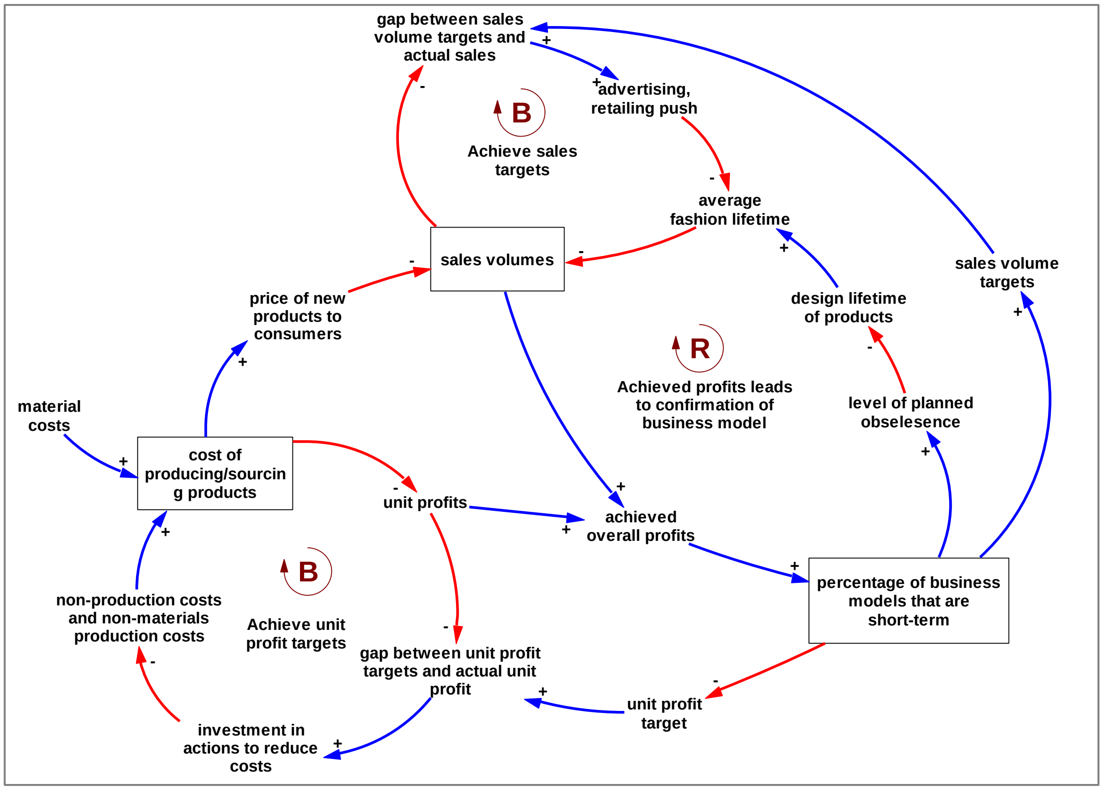
- A small but increasing trend for a more sustainable business model exists, which aims to provide products made with lower environmental impact, and/or lifetime product care through retailer relationships, and/or product stewardship through to the product's end of life. This has been observed in some large retailers who provide product lifetime guarantees and service, which increases consumer loyalty but increases the sale price. If this trend continues then the stock *percentage of business models that are short-term* will decrease, increasing the average design life of products and producer responsibility.
- Exogenous to the sub-model is the cost of materials, generally expected to rise in future, which will eventually lead to increased product prices to consumers (and therefore reduced sales volumes) and/or the use of replacement materials.

Additional Points of Interest and Model Development Options

- There could be a complex link between average fashion lifetime and sales volumes; a decreased lifetime might not necessarily lead to increased sales volumes.
- If a product lasts longer, this could mean higher sales eventually; companies are competing in a large market and they may increase the number of new and repeat customers through increased market share. From the viewpoint of the customer, they may buy more because the product is improved. There is a relation between market share and value, so improving product robustness could be better for some companies compared to others.
- Consumers don't necessarily want long lasting products. Often they want new products and they want to get products more frequently. However, the "newness" may only be in relation to themselves, and so they may be just as content with a second hand product.
- There's a tipping point in people's income where they start valuing aspects other than price more. This elasticity needs to be captured in the model. However, it will be heterogeneous with respect to product types.
- If there is a significant decrease in how much people purchase, it's not clear how this would affect UK Plc. It may depend on whether goods are made in the UK or imported. Some businesses such as remanufacturing might thrive while others such as retail could be negatively affected within their current business model.
- This sub-model works better for some products and not others – toasters versus dishwashers, food versus furniture.
- The sub-model seems to reflect the viewpoint of corporations rather than the whole market. If the lifetimes of products went up in the whole market, overall sales would go down. Sales volumes and targets are defined at the level of individual businesses, but this would affect the whole market depending on the relevant market share for product types.
- There are broader potential benefits in transitioning to business models with a long term focus, but much of the market needs to be working together to do achieve that. Currently there are several barriers to businesses cooperating in this way, which should be reflected in the model.
- A programme currently being run by WRAP called Rebus [21] aims to demonstrate how businesses and their supply chains can implement resource efficient business models, focusing on electrical, clothing, furniture and construction products. This would be good data to feed into the model.

[21] http://www.wrap.org.uk/content/rebus

Figure 4-19: Business Models and Design Sub-model



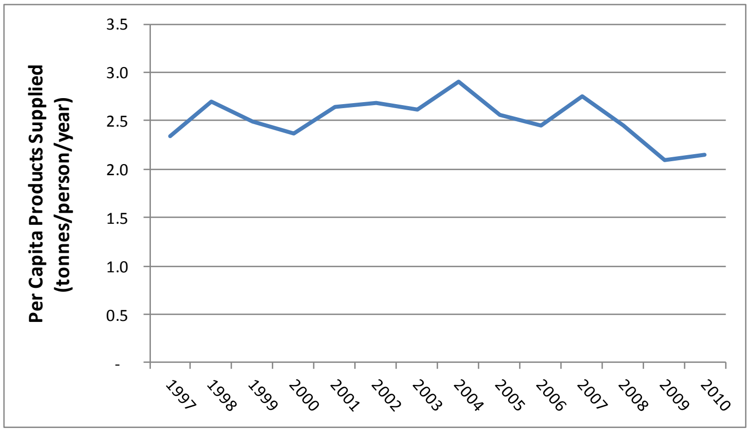
4.4.4 Consumption Pull Sub-Model

The Consumption Pull sub-model drives the total amount of goods demanded by consumers, and is highly interconnected with the Business Models sub-model. It drives the Relative Attractiveness Of (RAO) three of the six options for acquiring goods: (i) buying new from retailers in the UK, (ii) leasing or renting, (iii) buying direct from overseas (e.g. over the internet). The RAO factors for each of these three options reflect the likelihood of consumers choosing that option over the other five options. Note: The RAO's of the repair, remanufacturing and re-use options are driven within their relative sub-models, described later in this section.

4.4.4.1 Evidence for the Consumption Pull Sub-Model

As shown in the evidence provided for the Business Models sub-model in section 4.4.3, consumption has been rising in some categories and not in others, generally in response to changing prices but also to rising disposable incomes. Median household disposable income per person rose by 39% between 1997 and 2011, in constant £2011. Consumption of products, in terms of weight, on a per person basis has been fairly steady over the period considered, but dropping considerably after 2007. This may not reflect the amount of consumption in terms of number of items procured as new products could be lighter.

4-20: Tonnes of Per Capita Products Supplied



Source: (HMRC 2013) (ONS 2012g), (ONS 2011)

Several authors have examined the issues of material consumption and consumerism:

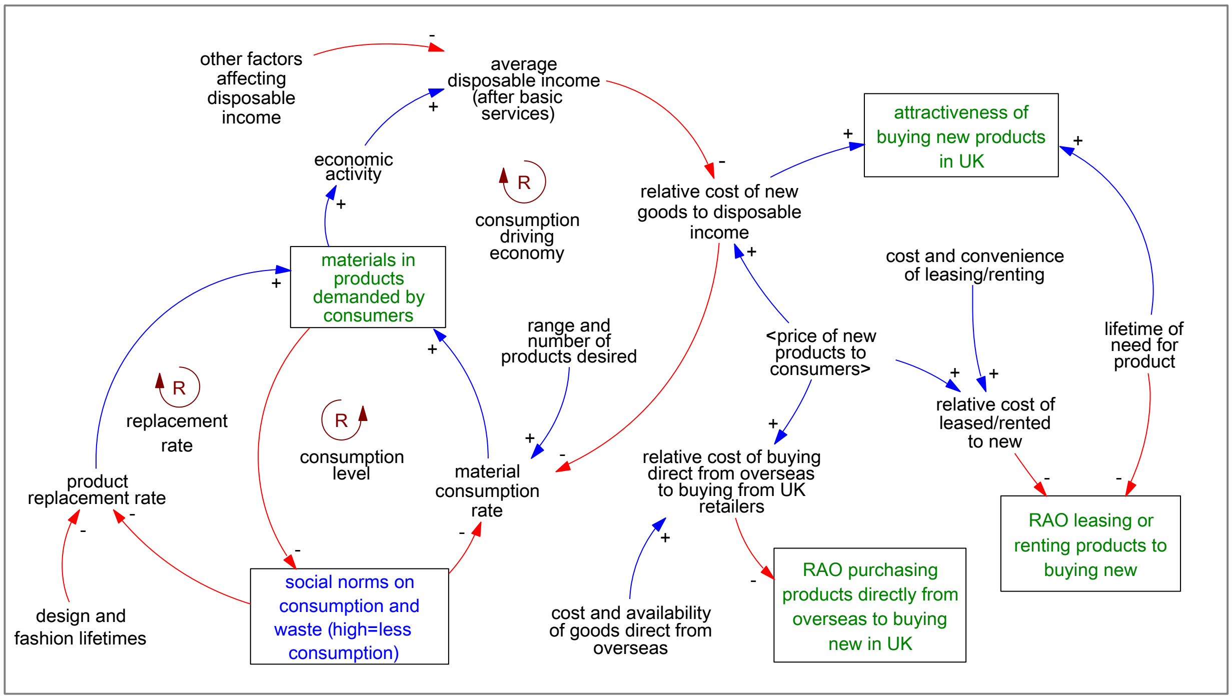
- Ashby describes the lifetime of use of products as the shortest of several lifetime definitions: *the physical life (when the product breaks beyond economic repair); the functional life (the need for the product ceases); the technical life (the product is obsolete); the economical life; the legal life; the life in which the product remains desirable'* ((Ashby 2009) from (Allwood et al. 2011)).
- Sanne, in a paper on policies for sustainable consumption, states that within patterns of consumption in the developed world '*goods and services have become the answer not just to survival needs like food, shelter and security but also to needs for meaning and social order... This trend, sustained in an interplay of business interests and human wishes (which in turn are spurred by business interests), may still not be sustainable'* (Sanne 2002).
- Allwood et al. identified several different aspects of consumerism in developed countries:
    - *'Fashion rather than form or function determines the end of life of many goods*
    - *Focus on "conspicuous consumption" suggests that goods made from re-used material, or designed for future re-use, may be seen as less desirable if they symbolise thrift.*
    - *Convenience has become a major driver of consumption, leading to considerable excess in capacity for service provision.*
    - *Cultural attitudes to waste have moved from moral disapproval to complete acceptance, so the 'throw-away' society treats as normal the discard of materials with re-use value.'* (Allwood et al. 2011)
- De Vries wrote that '*the pervasiveness of marketing and media images of idealised lifestyles ensures that it is the anticipation of consumption that is at the core of today's hedonism, and the fact that the reality cannot live up to the dream drives the immediate craving for further consumption* ((De Vries 2008) from (Allwood et al. 2011)).
- (Wernick et al. 1997) cite data indicating an upward trend in the amount of household goods owned by Americans – the average weight of household goods transferred in intercity moves in the period from 1977 to 1991increased by almost 20 percent to 3,050 kg.

4.4.4.2 Consumption Pull Sub-Model Dynamic Hypothesis

The diagram in Figure 4-21 shows the dynamic hypothesis about consumption pull, as has been happening in the economy in the past 15 years. There are three reinforcing loops in the sub-model driving the dynamics.

1. Consumption driving economy: The higher the household disposable income (after basic services), the lower the relative cost of goods to disposable income (also affected by the price of new products), the higher the material consumption rate, which increases the stock *materials in products demanded by consumers*, which leads to more economic activity, and then to higher average disposable incomes.
2. Consumption level: This is a simple reinforcing loop between social norms and consumer demand – the more products demanded by consumers, the more the social norm on waste declines, the higher the consumption rate, and the more goods demanded by consumers.
3. Replacement rate: This is also a simple reinforcing loop but it drives how often things are replaced rather than how much people want – the lower the social norms on waste, the higher the product replacement rate (also determined by design and fashion lifetimes of products from the business models sub-model), the more products demanded by consumers, leading to reduced social norms on waste.

Figure 4-21: Consumption Pull Sub-Model



Exogenous to this sub-model is the *price of new products to consumers*. As this rises, consumption of new products will be reduced in some non-linear way, affected by price elasticity (not yet included in the model). A similar effect will likely be seen in consumption of used products after some delay. The price of new products, also a proxy for resource scarcity and the cost of waste, puts a brake on the three reinforcing loops which would otherwise keep on increasing total consumption. To the right of the model are the relative attractiveness of three of the options for acquiring goods – buying new from a UK supplier, leasing or renting products, or buying products directly from overseas (e.g. over the internet or importing household belongings). The attractiveness's are affected by the relative cost and availability of goods for each option. Not shown here are connections between the trends for WP practices within the WP pathways and the social norm on consumption and waste. If WP practices were to increase significantly, it could be expected that this would eventually increase the waste social norm and balance the more dominant consumption norm that has been seen in recent years.

Additional Points of Interest and Model Development Options

- One consideration for consumption pull is the importance of income segmentation within the population of consumers. The average disposable income is not always a good representation of buying power; during economic downturns sales of high end luxury goods can actually go up if income inequity grows.
- Decreases in average disposable income may not necessarily lead to decreasing retail sales, at least in the short term, as purchases are enabled more and more through credit.
- The relationship between economics and social norms in driving consumption behaviour has not yet been fully developed in the model. It could be that social norms are more important than relative cost, especially to individuals, which leads to trends that go against economic theory.
- The question of how to define and measure social norms on consumption and waste is another issue, for which there was not enough time in this project to fully explore. They can be thought of as bi-directional, and there are value judgments associated with them. More exploration of what resource efficient actions are, exactly, for different actors in the system would be good.

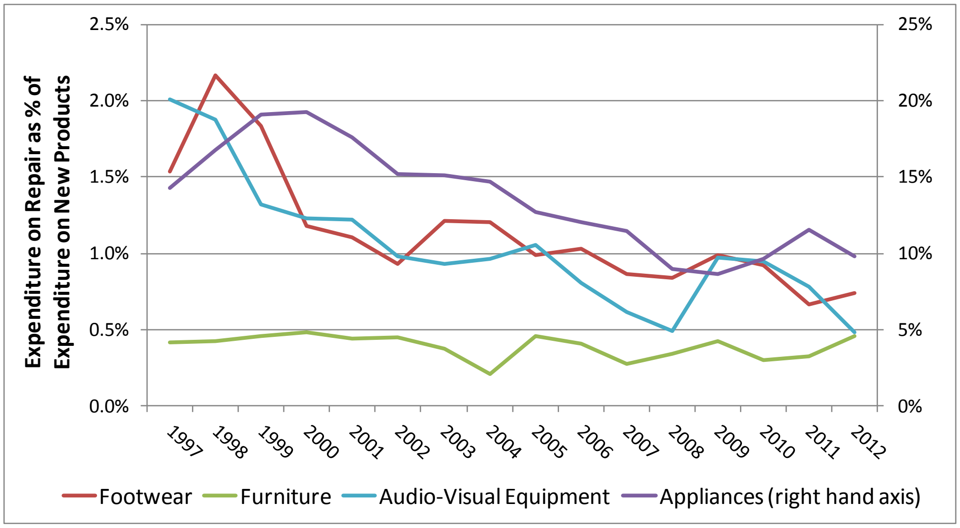
4.4.5 Repair Sub-Model

The Repair sub-model models the third-party repair industry (as opposed to remanufacturing by the original manufacturer). It drives the relative attractiveness of choosing to repair a product compared to other options (throwing it away or giving it away) when a product is no longer functional.

4.4.5.1 Evidence for the Repair Sub-Model

Recent anecdotal history, as expressed by workshop participants when explaining their mental models that fed into the Repair CLD, indicate a decline in the third-party repair industry in the UK. Allwood et al. confirm this, saying that '*the business case for repair, to extend product life, is generally weak in developed economies with high labour costs and where most products are sourced from low labour cost countries with high economies of scale*' (Allwood et al. 2011). Watson's literature review cites two studies on repair practices. In the first, the majority of respondents cited cost as the reason why they didn't get products repaired, and in the second, focused on household appliances, even when respondents wanted to repair goods they were '*defeated by "social systems"* ' (Watson 2008). Data from ONS on household expenditure on repair, as a percentage of expenditure on new goods for several categories of products, does in fact show there has been decline in relative spending on repair over the past 15 years, as shown in Figure 4-22.

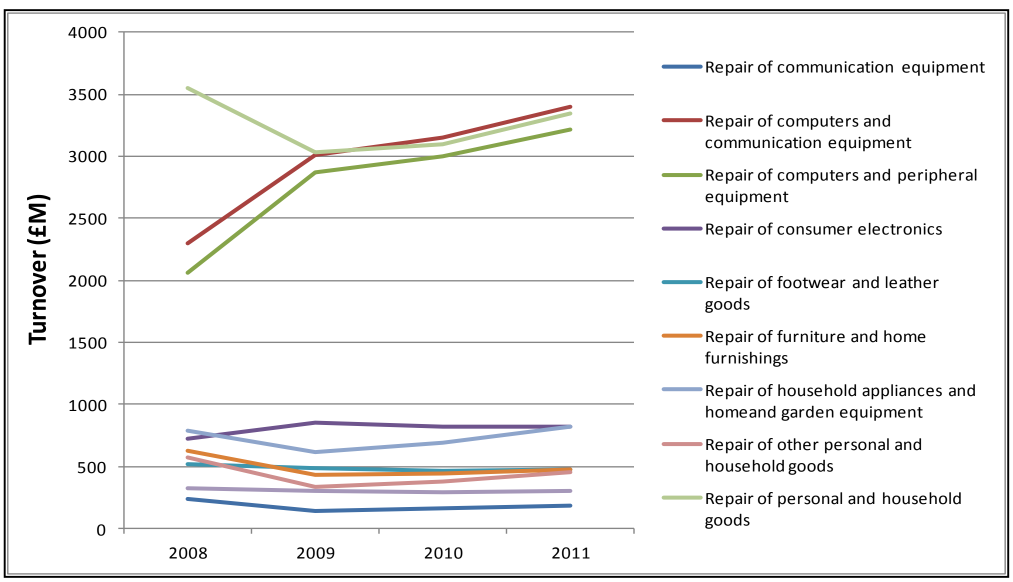
Figure 4-22: Household Expenditure on Repair as a % of Expenditure on New Products



Source: (ONS 2012c)

A closer look at data on the repair industry shows the distribution between different types of repairs. The industry is dominated, in terms of turnover, by repair of computers and peripheral equipment, and personal and household goods, representing around 70% of turnover in the sector. Figure 4-23 shows a significant growth in turnover for repair of computers, peripherals and communication equipment between 2008 and 2011. As this data is from the period starting just after the economic crisis of 2008 it could be that individuals and businesses have had less capital to invest in new products and thus have invested more in repair.

Figure 4-23: Turnover by Sub-Sector in the Repair Industry

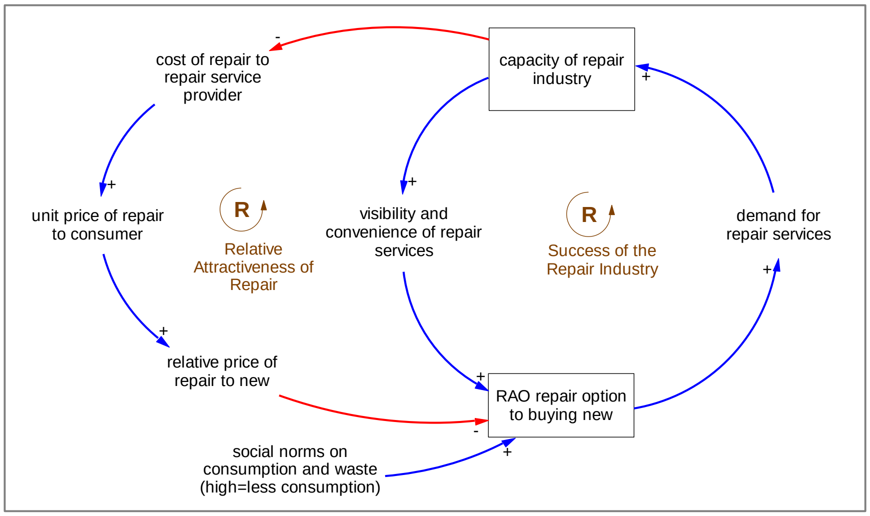


Source: (ONS 2012b)

4.4.5.2 Repair Sub-Model Dynamic Hypothesis

The dynamic hypothesis about the repair industry, shown in Figure 4-24, is that the success of the repair industry depends on the demand for repair, which is driven by the relative attractiveness of repairing products compared to buying new goods (also driven by social norms on consumption and waste), and its convenience and visibility as an option (driven mainly by capacity). A decrease in the capacity of the industry would eventually lead to an increase in the price of repair to the customer due to loss of economies of scale.

Figure 4-24: The Repair Industry Sub-Model



This hypothesis suggests that a drop in the relative price of goods compared to people's incomes, as driven in the Business Models sub-model and which has been seen in some sectors such as apparel, and the promotion of "fast fashion" over the last 15 years (reducing the social norms on consumption and waste), may have influenced the decline of the repair industry.

4.4.6 Remanufacture Sub-Model

The Remanufacture sub-model drives the flow of non-functional products from consumers back to the retailer or distributor and on to OEMs (Note: not all products go this route; some are remanufactured by 3rd party companies and returned directly to the consumer), and also drives the demand for remanufactured products. Remanufactured products are acquired by consumers (either a business or an individual) when they are provided to consumers as an immediate replacement for a returned faulty product, or instead of a new product at a discounted rate. The returned faulty products are sent back to the OEM, remanufactured, and eventually given to a different customer.

4.4.6.1 Evidence for the Remanufacture Sub-Model

The practice of remanufacturing has an estimated value of £5bn and achieves UK-wide savings of 270,000 tonnes of raw materials and 800,000 tonnes of CO_2[22] (Watson 2008). Most remanufacturing takes place between businesses. Key industries for remanufacture are automotive, aerospace, and imaging; some companies use it as a way to achieve ongoing revenue from the same products (e.g. Caterpiller and Xerox remanufacture up to 7 times) (Gray & Charter 2007). Business to consumer remanufacturing is focused on limited product types such as retreaded tyres, ink and toner cartridges, and some electronic goods, with industry facing challenges in *'coping with end-consumers' concerns for fashion and status, and inescapable negative associations of second hand goods for consumers'* (Watson 2008). Many products are not technically remanufacturable.

Design for remanufacture *'optimises remanufacture through consideration of both the business model and the detailed product design'* (Gray & Charter 2007). Grey and Charter's review of design for

[22] We assume this figure is per year, but it is not stated in the report.

remanufacture practices identified six strategies important at different stages in the remanufacture process, shown in Table 4-4, indicating the complicated nature of both design and remanufacture.

Table 4-4: Design Strategies and their Impact on Remanufacturing Process

	Core Collection	Inspection	Disassembly	Cleaning and Storage	Remediation	Reassembly	Testing
Design for Core Collection	x	x					
Eco-Design		x	x	x		x	
Design for Disassembly		x	X	x	x	x	
Design for Multiple Lifecycles				x	X		
Design for Upgrade					x		
Design for Evaluation		x					x

Source: (Gray & Charter 2007)

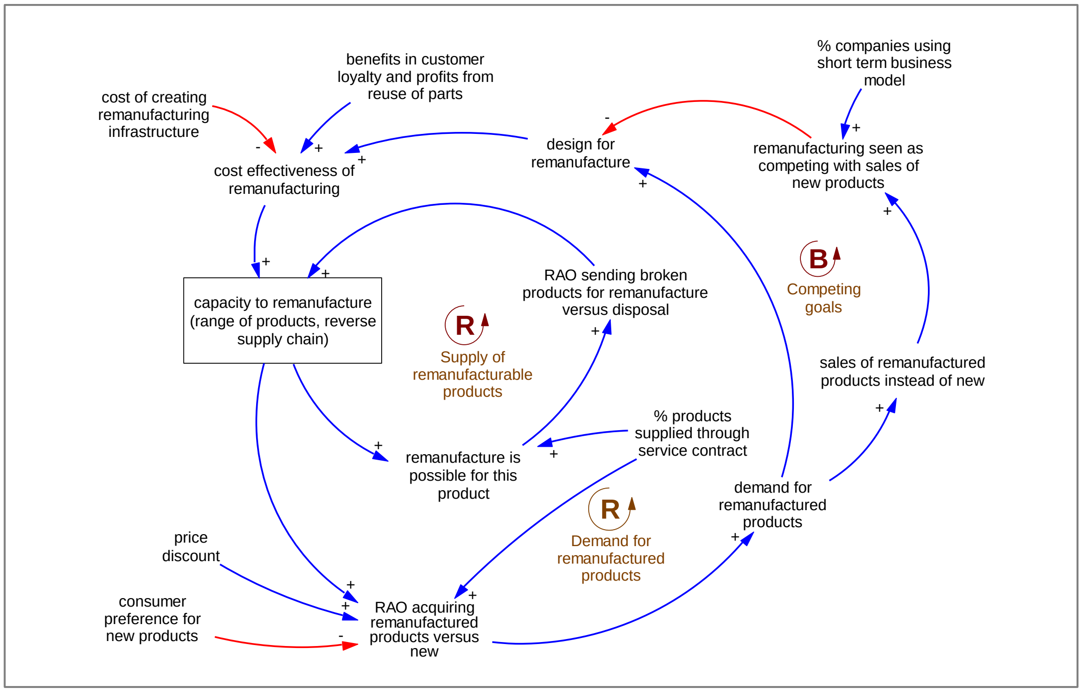
OEMs are key to establishing design for remanufacture, but the '*very small number of OEMs designing their business models and products to take advantage of the opportunities of remanufacture combined with a lack of cross-fertilisation between industry sectors is constraining the take-up of remanufacture.'* (Gray & Charter 2007) Remanufacture is sometimes seen negatively by producers as competing with their own brand new products, and they may update technology to prevent 3rd party remanufacturers from remanufacturing their products. The legislative environment affecting remanufacture (both positively and negatively) includes: Landfill Directive, Waste Electrical and Electronic Equipment Directive, Restriction of Hazardous Substances Directive, End of Life Vehicle Directive, Energy-Using-Products Directive, and the Freedom of Information Act (FoI). (ibid)

4.4.6.2 Remanufacture Sub-Model Dynamic Hypothesis

There are two reinforcing loops in the remanufacture sub-model. One drives the supply of remanufactured goods and is partly driven by the capacity to remanufacture, including the reverse supply chain which takes products from consumers and sends them back to the OEMs. Additionally, the more products in use under a service contract, the more products will be sent for remanufacture as any replacement process will be done by the service company under its contract, and the user will not be required to take action. The demand for remanufactured goods is also driven by discounts offered to consumers to take remanufactured versus new products.

A balancing loop pits the sometimes competing goals of sales of new products with that of long-term customer loyalty and achieving profits from remanufacturing, partly driven by the number of companies pursuing short term business goals (from the Business Models sub-model). Design for remanufacture is driven by the balancing loop and the demand for remanufacturing, and it affects the cost-effectiveness of the remanufacturing process.

Figure 4-25: Remanufacture Sub-Model



Additional Points of Interest and Model Development Options

- There are several possible impacts from making products more suitable for remanufacture. They may need to be designed so they stay fashionable for longer; and a design favouring remanufacture may make it more difficult for products to be reused and repaired.
- In terms of material efficiency it is not clear whether for all types of materials it is better to keep products in use longer versus recovering materials and then using them to make other products.
- A possible benefit for manufacturers is that an increase in remanufacturing could mean less competition between sales of new products and sales of their own products in the second hand market.
- Even if products are made to last longer through design for remanufacture, they still may not be used for their full lifetime.
- Taking this to extremes could lead to a stifling of innovation because of a lack of market for new goods.

4.4.7 Reuse Sub-Model

The Reuse sub-model drives the flow of second hand goods offered for resale or gift (i.e. the supply of second hand goods) and the demand for second hand goods. Second hand goods can be bought from a person or a shop, or accepted as gifts. When donated to 3rd parties such as charity shops and not successfully sold in the UK they are shipped overseas or sent to the waste system. The input to this sub-model, the *supply of products not wanted by consumers*, is driven on the Material Flows Map principally by the fashion lifetime and lifetime of need of products.

4.4.7.1 Evidence for the Reuse Sub-Model

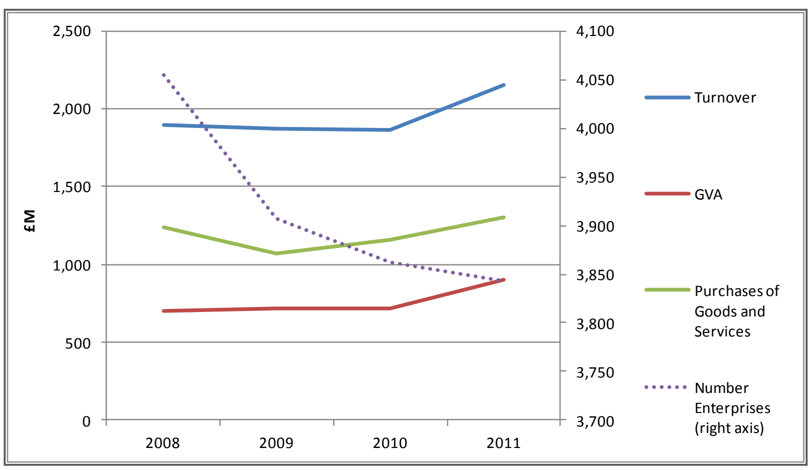
There can be many reasons for acquiring second hand goods. (Pierce & Paulos 2011) define four "reacquisition orientations" covering viewpoints and practices of participants in their field study of reacquisition practices in the USA:

1. **Casual Reacquirers** see reacquisition as a cheaper alternative to the more preferable retail acquisition
2. **Necessary Reacquirers** reacquire out of necessity, as they struggle to get essential goods
3. **Critical Reacquirers** see reacquisition as bound up with their considerations of social, political, economic, ethical and/or environmental concerns
4. **Experiential Reacquirers** appreciate reacquisition for its positive experiential and aesthetic qualities, in terms of the process of reacquisition and the products gained through it.

(Watson 2008), in a literature review, reports on a survey finding that around one in every seven objects in UK homes was reacquired from a second hand source, with family and friends being the most common source, followed by charity shops and car boot sales. Bric-a-brac, ornaments, glassware and crockery, and furniture were found to be the most likely to be second hand, with electrical items, particularly white goods, the least likely. The review finds there is commonly an assumption of social stigma regarding second hand goods, with the size of effect varying by type of product and the social position and attitudes of consumers. Much of the activity in moving products from one user to another, either by gifting or selling, goes through unofficial channels such as car boot sales, person to person sales (e.g. classifieds, ebay, gumtree), market stalls, retail take-back or buy-back schemes (such as M&S's schwopping scheme), leaving products on the street, or gifting of products between friends and relations. There is little data available for these types of trades.

A more official channel is the second hand shop and charity shop sector, for which there is some data on turnover, shown in Figure 4-26, but not on volume of goods traded. Turnover increased in shops in 2011 but the number of shops decreased during the period shown. The increase in turnover could represent an increase in the average sale price of goods and/or an increase in the amount of goods traded. A newspaper article on the charity shop sector reported that '*much of Britain's second hand clothing goes abroad – an estimated 540,000 tonnes a year, or about 70%.*'[23]

Figure 4-26: Recent Trends in the Second Hand Retail Sector



Source: (ONS 2012a)

A report by (Stevenson & Gmitrowicz 2013)examined the issue of displacement for consumer re-use practices for electronics, furniture, and textile products. They define re-use displacement as '*the quantity of second-hand purchases that have replaced what would otherwise have been a purchase of a new item'* (ibid) and the study found that the average re-use displacement rate in Britain is 27%, with it being fairly consistent between the types of products researched. This means that over two

[23] www.guardian.co.uk/uk/2013/jan/11/post-christmas-clear-out-secondhand

thirds of second hand reacquisitions are additional to new goods rather than replacements for new goods. The implication is that if the flows in the re-use loop in the Material Flows Map were to increase, only around a third of that flow would affect the flow of new goods into the stock *materials in products in consumer use.* However, from the perspective of reducing waste, the re-use of products will delay the entry of those products into the waste management system.

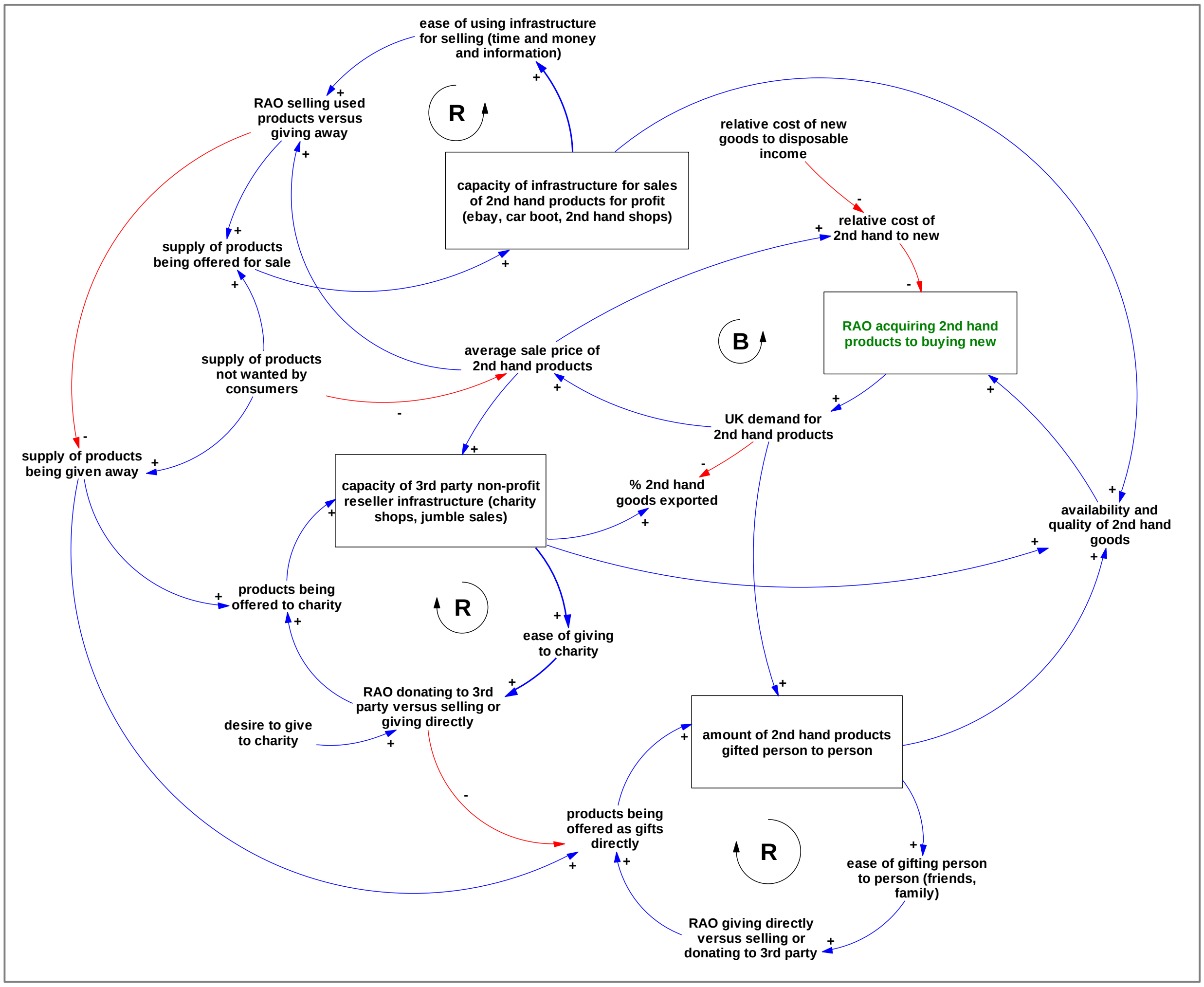
4.4.7.2 Reuse Sub-Model Dynamic Hypothesis

Figure 4-27 shows the sub-model for the sale, gifting and reacquisition of second hand goods.

The dynamic hypothesis is as follows:

- The relative attractiveness of selling products drives the decision of product owners to sell or give away unwanted products. The more products offered for sale person to person, the more infrastructure and practices are developed, increasing the number of products on offer (e.g. the rise of on-line trading such as ebay). The sale price of second hand products is related to the price of new goods in that as the price of new goods rises the achievable sale price of second hand goods will also rise but probably by much less (there are some exceptions to this rule e.g. vintage goods).
- Products being given away are either given to a 3rd party such as a charity shop or given directly to friends and family. There is a reinforcing loop as the more products given to charity, the more trading infrastructure, and the more convenient the practice. There is a third reinforcing loop as the more people gift unwanted products person to person, the more it becomes a social norm.
- The availability of second hand goods from all three pathways (private sales, third party sales, gifting) increases the relative attractiveness of acquiring products as second hand – which is also driven by the relative cost of new products to second hand. The percentage of goods exported is driven by the availability of second hand goods and the demand for them. The relative cost of new goods to disposable income drives a balancing loop – as it goes down, the relative cost of second hand to new goes up, which makes second hand goods less attractive, reduces demand, and thus reduces expected sale prices for second hand goods.
- The demand for second hand goods is driven mainly by the “needs must” purchasers who buy second hand because of financial constraints (comprising casual and necessary reacquirers) and the “unique or vintage” purchasers (comprising critical and experiential reacquirers) of higher socioeconomic status who buy second hand because of its interest. The ratio between these two types of purchases is driven by the social equity of the country and average disposable income (not shown in Figure 3). Different price elasticities will exist for these two types of consumers but this has not yet been put into the model.

Figure 4-27: The Reuse Sub-Model



Additional Points of Interest and Model Development Options

One barrier to the purchase of second hand goods is concern about the reliability of products. This is one area where government could make a difference by, for example, providing standards that can help people trust second hand goods. However, there is conflicting evidence on how well that would work and whether people will trust the standards. For example, when buying a second hand child car seat, there may be concerns about whether the seat has been in an accident. Technology solutions can help with this. For example, mobile phones have an indicator showing whether they have had water damage, some manufacturers offer to replace car seats if they have been in an accident, and one manufacturer is looking into putting a stress indicator on car seats.

5.0 Plastics Packaging Recycling Model

5.1 Modelling Purpose and Method

A prototype SD model of household Plastics Packaging Recycling (PPR) had been developed by Defra before the start of this project, and this was used as a basis for the SD model developed during the project. The original intent of the project was to validate and expand Defra's model and then to build a "policy laboratory" tool. Objectives defined at project initiation included:

1. Validating Defra's prototype model to ensure it reflects the actual system enough to be useful for policy making, including validating the basic structure of the model, the formulas being used, the data sources, and the causation between elements.
2. Expanding the boundary of the model to include C&I PPR and other materials such as paper and glass.
3. Developing a "policy laboratory" that will enable policy leads at Defra to create different scenarios to test the robustness of current and potential future strategies, and to understand the sensitivity of the system to different factors.

The model building process for the PPR model involved several model review sessions with a modelling team looking at model structure, dynamic behaviour, and data; and several model review sessions with recycling policy experts and stakeholders focusing on the high-level behaviour of the recycling sector, the actors in it, the effects of existing policy, and stakeholder concerns..

Despite not having time at the end to include additional materials because expanding, populating and validating the original model took longer than originally planned, the model now covers C&I waste and comprises an interface for policy makers in the form of two interactive dashboards – one for policies and one for financial metrics. The dashboards enable users to change four options: the year which landfill tax is increased until, future annual increases in landfill tax, the year to which the recycling obligation is increased until, and the future annual increase in the recycling obligation. Key metrics are displayed on the dashboard showing the effects of the changes made to inputs.

The model structure was built following the structure of the existing model that had been developed by Defra. Data already available was input into the improved model, and further research was done to identify more data to enable the model to be run and calibrated. This first draft model was then presented to recycling experts from Defra and WRAP, and one industry trade body which was part of the project team. This was done through two full day model review sessions which included in-depth group discussions on the different views of the model while the modelling team took notes. These notes were then used to make changes to the model. In addition to these sessions, Defra's lead analyst on the project met several times with the project team for additional model reviews.

The final version of the model, within the scope of this project, comprises waste generation (both household and commercial), waste collection, waste separation for recycling, the recycling of separated waste, and the entry of recycled materials back into the market. There are three main categories of actors represented in the model:

- Producers of waste (households, or "consumers", and C&I organisations, or "non-consumers")
- Collection agencies (Local Authorities and commercial waste disposal companies)
- The primary recovery sector (MRFs and PRFs), and
- Reprocessors

Interactions between the different sectors and actors in the system are represented in the model through information and material flows. The model's boundary is PPR in the UK but the model takes into account the import and export of feedstock of recovered plastics into and out of the UK, which affect the dynamics of the system. The main sources of data used to populate the model were the PlasFlow 2017 an PackFlow 2017 reports (WRAP & Valpak 2013), market reports ((WRAP 2008), (WRAP 2011), (Valpak 2012)), and input from Defra and WRAP experts. All inputs to the model are documented in the 'Data for Plastics Model' data sheet.

5.2 Model Structure

The Plastics Packaging Recycling Model is a single, connected cause-and-effect model making use of a combination of CLD and SFD representations. Within the model there are several views, comprising specific elements or modules within the whole model. The views are listed in Table 5-1 under six major grouping definitions. A diagram of these modules and how they relate to each other is shown in the format of a CLD in Appendix D.

Table 5-1: Views in the Recycling Model

Grouping	View Name	Description
Physical Flows	• Main System Diagram	Models main physical waste stocks and flows such as waste arisings (both household and commercial); separated vs. co-mingled collections; movement of pre-sorted and post-sorted waste going for primary recovery and/or reprocessing or exports; landfill or other treatment options.
Waste Generation and Collection	• Total Waste Generated • Total Waste Collected • Consumers • Collections • LA Collections • Commercial Collections	Models waste generation and collection subsystems, including physical flows of waste as well as causal drivers and feedback loops
Waste Processing	• MRF Capacity • PRF Capacity • Reprocessing Capacity	Models primary recovery and reprocessing systems, including physical flows of waste as well as causal drivers and feedback loops
Demand	• Global Plastic Demand	Models causal drivers of plastic demand
Policies	• PRN/PERN Price • Plastic Obligation • PRN/PERN Accreditation • Landfill tax	Models causal drivers of PRN/PERN prices and accreditation regime. Landfill tax view calculates cost of landfill tax (allows setting different scenarios). Future obligation view calculates recycling obligated amounts as set by the targets (allows setting different scenarios).
Financial	• Cost as Perceived by Different Stakeholders	This view calculates the costs incurred by the different stakeholders such as local authorities, MRFs, PRFs and reprocessors

In addition to the core model structure, there are additional views for calibration and mass balance checks (LA calibration screen, MRF capacity calibration, and Mass balance checks), and dashboards (Policy Dashboard, Financial Dashboard, Targets Dashboard).

To understand the effects of variation in some of the inputs, four alternative scenarios were developed in addition to the baseline model. The scenarios are run over the entire date range of the simulation (from 2001 to 2018) and examine the model behaviour as it diverges from the known historical trajectory over the historical period and a little into the future.

1. The **baseline scenario** assumes no changes to the current assumptions, including the latest packaging targets to 2017. The behaviour of the following variables was then studied: reported and actual recycling rates; PRN price; cost to Local Authorities; MRF, PRF and reprocessor capacities.

2. **Scenario A** (reduction in overseas demand for UK plastic recyclates) attempts to represent the impact of a sharp reduction, by 50%, in the demand for plastic recyclates from the UK. This could be triggered by either a slowdown of the demand mainly from China or because China shifts to sourcing more of its recovered plastic domestically. The impact of this change on PRN price, PRF and reprocessor imports, MRF capacity, actual recycling rates, and gate fees are examined and compared to the baseline scenario.
3. **Scenario B** looks at the impact on the system of increasing the fraction of plastic packaging material collected by LAs for recycling by 5% annually, without assuming a causal driver for this increase. The impact of this change on actual recycling rates, PRN price, costs to LAs, and MRF and PRF capacities are examined and compared to the baseline scenario.
4. **Scenario C** assumes a 15% annual increase in the plastics packaging recycling targets from 2009. The impact of this change on PRN price, actual and reported recycling rates, MRF and PRF capacity, and LA costs are examined and compared to the baseline scenario.
5. **Scenario D** evaluates the impact of increased prices for reprocessed plastics, probably as a result of an increase in the price of virgin plastics. The impact of this change on PRN price, actual recycling rates, and cost to LAs is examined and compared to the baseline scenario.

In addition to the scenarios, the model was used to carry out sensitivity analyses, in order to test the robustness of the model assumptions (i.e. is the model displaying very different behaviours within the uncertainty range of the input variables?), understand better the relationship between the inputs and outputs of the model, and uncover any possible optimum criteria or tipping points.

Results from the sensitivity tests are covered in section 5.5, mainly to illustrate the process. Most input assumptions (all except those for which sensitivity analysis is meaningless such as unit conversion factors) were subject to a $\pm 20\%$ variation to observe the impact of these individual input variables on the reported recycling rate against the baseline scenario. The top ten variables impacting the reported recycling rate were then subject to multivariate sensitivity analysis, within a $\pm 10\%$ range this time to observe the potential cumulative impact of the uncertainty in the model assumptions.

5.2.1 Subscripts

Subscripts are a particular feature of the Vensim simulation tool enabling repetition of structure. To accomplish this, a subscript range is created, called “stream” for example, and the subscript elements ‘household’ and ‘commercial’ added. If the fraction of plastic packaging waste for collection is then subscripted by the subscript range stream then it will allow for collections in every category in the range. It follows that categories can be changed, added or removed without changing the structure of the model, simply by changing the list of subscript elements. Subscripts that exist in the PPR model are listed in Table 5-2.

Table 5-2: Subscripts in the PPR Model

Name	Description	Elements
Stream	Collection of plastic packaging waste can be through two main channels	• Household • Commercial
MRF Channels	Demand for MRF output from these channels	• MRF Export • MRF to PRF • MRF to Reprocessor
PRF Channels	Demand for PRF output from these channels	• PRF Export • PRF to Reprocessor
PProfile	Used to store settings for the ALLOCATE AVAILABLE function, used in the variables PRF allocation to channel and MRF allocation to channel	• Ptype, • Ppriority • Pwidth • pextra

The remainder of this section presents the variables, assumptions, and structure of the models in each view.

5.2.2 Physical Flow – Main System Diagram

Waste recycling comprises a stream of physical and economic activities involving waste generation, collection, separation, recycling and the entry of the recycled materials back into the market, with each sector in the market interacting with other sectors through information and material flows. The main physical SFM is the largest and most complex diagram in the model. It represents the material flows of waste through the system, and it is described below in text and shown in Figure 5-1.

5.2.2.1 Waste Enters the System

As consumer and non-consumer plastics packaging waste is produced, it is collected via different routes (i.e. black bin bags, co-mingled or separated at kerbside). The separated wastes are then sent to the primary recovery sector.

- In the case of co-mingled waste, it is sent first to a Material Recovery Facility (MRF), which sorts it out into the different types of waste (e.g. plastic bottles) and then sells it to domestic reprocessors, exports it, or sends it to a PRF[24] for further sorting. If the waste has already been sorted at source (i.e. kerbside), then some of the waste is sent directly to domestic reprocessors, some to a PRF for further sorting, and some is exported. The model uses a simple proportion assumption for these allocations at present, but a more sophisticated allocation algorithm may be best and is recommended for future enhancement to the model. The allocations are also different for commercial and non-commercial streams.
- The waste that was collected in black bin bags, and the left-over materials from MRF and PRF sorting or reprocessing that are not suitable for recycling, are disposed of in landfill sites, or sent to other forms of treatment such as incineration.
- The recycling sector produces materials using the recovered wastes. This activity is influenced by the supply of and demand for recovered materials which is affected by several other factors, such as the relative price of recycled materials in comparison with those of virgin materials. The model currently uses a simple assumption on initial demand and demand growth but would benefit from expansion to include the dynamics of the global market for plastics.

[24] Sometimes PRFs have pre-sorting facilities and so MRFs and PRFs reside in the same facility.

In the model, the proportion of co-mingled/sorted waste is represented as an endogenous structure to be calibrated to historical data. The current structure enables an initial proportion and future annual growth in the proportion of waste collected separated, both of which are used in the calibration process to approximate to historical data. (A future version would benefit from a deeper analysis of the drivers influencing the proportion of plastics packaging material collected as separate from the rest of the recycling stream.) Another simplifying assumption in the model is in the split of the sorted material flows between PRFs, reprocessors and exports. The proportion (for commercial and for non-commercial derived flow) has been taken from the Plasflow report (WRAP & Valpak 2013).

5.2.2.2 Co-mingled Material is Sorted

When plastics packaging waste is co-mingled with other waste for recycling (paper, bottles etc.), it is necessary to separate it from the other materials in order to be used as feedstock for reprocessing. This process is performed by Material Recovery Facilities (MRFs) and it is assumed that such facilities will process material at a rate sufficient to draw-down stocks (*plastic packaging waste disposed for recycling (co-mingled)*) and maintain them within sensible limits (*desired plastic packaging stock at MRF*).

As domestic demand for these materials is unlikely to be sufficient to satisfy such a *Desired MRF Push Rate*, it follows that MRFs would need to find markets for sorted materials overseas (*Export demand for UK recovered plastic*). This simple "clearing" assumption has been made with the express assumption that MRFs would not wish to divert surplus stocks to landfill or other treatment. This desired throughput becomes the *Desired MRF Shipment Rate* and, if there is sufficient capacity (*MRF capacity rate*) and stock (*plastic packaging waste disposed for recycling (co-mingled)*), the material is processed (*MRF processing rate*) and becomes available to satisfy the domestic and international demand. The above system structure follows the principles used by Sterman in (Sterman 2001) to describe supply chain systems where production capacity is constantly being adjusted to meet changes in demand.

The value of the stock management input parameters (e.g. *MRF reference inventory coverage*, *minimum MRF processing time* and *MRF order fulfilment*) are arrived at through the calibration process. In future, the process would benefit from additional insight from industry to tailor these assumptions. Often initial conditions (e.g. *initial plastic in MRF*) are set to equal the desired values. This is common practice and generally guarantees that the relevant subsystem is initially in equilibrium relative to its inputs.

5.2.2.3 Sorted Material Allocated from MRF

The output from the MRF processing is allocated to the available demand for each of the "streams" requiring MRF output; domestic PRF, domestic reprocessors and exports. The model makes use of a Vensim allocation function called "Allocate Available". Any time there is a potential mismatch between the amount of something available and the amount that is desired, some sort of allocation needs to be done. Much of the time it is sufficient to just make sure that the amount used never exceeds the amount available, as is commonly done with shipments from an inventory. If there are multiple actors involved, however, this becomes more complicated as it is necessary to decide how much to take from, or give to, each agent[25].

The allocation function requires each demand to be prioritised (*MRF Channel priority*) and this model uses a combination of the price offered for the material (*MRF channel Price*) and a user-

[25] For a detailed description of the Vensim allocation routines, refer to the Vensim user manual 'Allocation Overview' and the Vensim website at http://vensim.com/allocation-by-priority-alloc-p/.

defined (*MRF Channel priority weight*). This latter input represents our views on the priority given by MRFs for supplying each of the demand streams. For example, MRFs may favour to satisfy domestic demand but the prices offered from overseas (including the PERN price) may override such behaviour and lead to more material being exported. An allocation is then made to each of the streams (*MRF allocation to channel*) and it is these allocations that dictate the flow of material from MRFs to PRFs (*MRF sorted plastics to PRF*), reprocessors (*MRF recovery rate sent to domestic reprocessors*) and for exports (*plastic packaging waste exported from MRFs*). Some of the material processed at the MRF cannot be used for recycling and is diverted to landfill or other treatment options (*MRF processing rate to landfill/incineration*). This fraction is a simple assumption in the current model, but could be made dynamic in future versions of the model to enable exploration of policy alternatives.

5.2.2.4 Sorted Material Processed at PRFs

Plastic Recovery Facilities perform the task of sorting plastics by type of polymer or by food/non-food grade etc. They take material from two sources;

- Sorted material from MRFs (*MRF sorted plastics to PRF*)
- Material sorted at kerbside (*separated plastic packaging waste collected to PRF*)

As in the case of the MRF, it is assumed that such facilities will process material at a rate sufficient to draw-down stocks (*plastic packaging waste at PRF*) and maintain them within sensible limits (*desired PRF stock*). As domestic demand for these materials is unlikely to be sufficient to satisfy such a *desired PRF push rate*, it follows that PRFs would need to find markets for sorted materials overseas (*Export demand for UK sorted plastic*). This simple clearing assumption has been made with the express assumption that PRFs would not wish to divert surplus stocks to landfill/other treatment options. This desired throughput becomes the *desired PRF shipment rate* and, if there is sufficient capacity (*PRF capacity rate*) and stock (*plastic packaging waste at PRF*), the material is processed (*PRF processing rate*) and becomes available to satisfy the domestic and international demand.

5.2.2.5 Sorted Material Allocated from PRF

The output from the PRF processing is allocated to the available demand for each of the "streams" requiring PRF output: domestic reprocessors and exports. As described in 5.2.2.3, the model makes use of a Vensim allocation function called Allocate Available. The allocation function requires each demand to be prioritised (*PRF Channel priority*) and this model uses a combination of the price offered for the material (*PRF channel Price*) and a user-defined value called (*PRF Channel priority weight*). This latter input represents our views on the priority given by PRF for supplying each of the demand streams, for example, PRFs may favour to satisfy domestic demand but the prices offered from overseas (including the PERN price) may override such behaviour and lead to more material being exported. An allocation is then made to each of the streams (*PRF allocation to channel*) and it is these allocations that dictate the flow of material from PRFs to reprocessors (*plastic packaging waste from PRF going to domestic reprocessors*) and for exports (*PRF plastic packaging exported*). Some of the material processed at the PRF cannot be used for recycling and is diverted to landfill/incineration (*PRF processing rate to landfill/incineration*). This fraction is a simple assumption in the current model, but could be made dynamic in future versions of the model to enable exploration of policy alternatives.

5.2.2.6 Sorted Material Reprocessed

Material in the reprocessing industry (*plastic packaging waste at domestic reprocessors*) is used to satisfy demand (*total demand for UK reprocessed plastic*) for UK reprocessed plastics (domestic and foreign). This demand (see 5.2.5.1) is for ALL reprocessed plastics and includes non-packaging materials. An adjustment is made to account for this (*plastic packaging reprocessing as fraction of total*) so that the model can handle total reprocessing capacity and throughput together with only plastics packaging throughput. If there is sufficient capacity (*reprocessor capacity rate*) and stock (*plastic packaging waste at domestic reprocessors*), the material is processed (*rate of plastic reprocessing*) and becomes available to satisfy the domestic and international demand. Some of the material processed at the reprocessors cannot be used for recycling and is diverted to landfill or incineration (*rate of plastic packaging waste into landfill/incineration following domestic reprocessing*). This fraction is a simple assumption in the current model, but could be made dynamic in future versions of the model to enable exploration of policy alternatives.

5.2.2.7 Physical Flows Assumptions

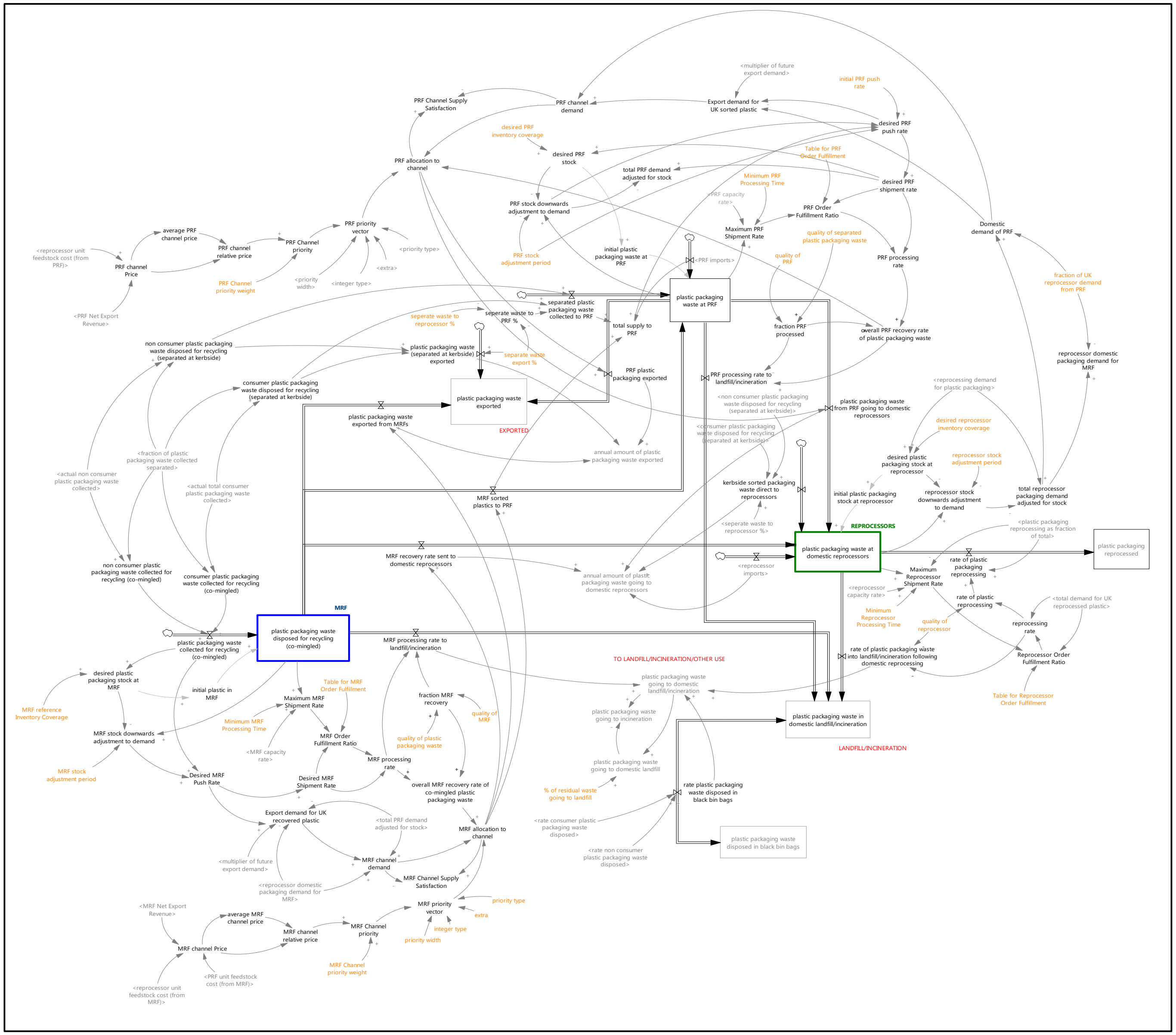
Table 5-3 lists the assumptions made within the physical flow map.

Table 5-3: Definitions for Physical Flows

Name	Description
initial PRF push rate	Used to initialise the desired PRF push rate
quality of separated plastic packaging waste	This will be the amount of plastic which is skimmed off at the front of the PRF, before it enters, but will be included in the overall 'reject rate' for a PRF.
landfill tax experiment time	Time at which data is discarded and future growth/decline assumptions become active. For example, after this date, landfill tax is no longer data-driven but determined by user-assumptions on annual growth.
quality of PRF	Fraction of material making it through the PRF process and not rejected
fraction of UK reprocessor demand from PRF	Proportion of all reprocessor demand obtained from PRF. Determined by calibration.
desired reprocessor inventory coverage	Desired amount of stock in the reprocessing system (years' worth of average demand)
reprocessor stock adjustment period	Period over which the reprocessing industry would like to adjust stock levels to desired level
quality of reprocessor	Fraction of reprocessed material becoming reprocessed plastic, the remainder is disposed of
Table for Reprocessor Order Fulfilment	The ability to ship is constrained by inventory availability. As the inventory level drops, the fraction of customer orders that can be filled decreases. When inventory is zero, shipments cease. Unfilled customer orders are lost.
Minimum Reprocessor Processing Time	The minimum time required to process at Reprocessor
% of residual waste going to landfill	Fraction of disposed plastic packaging going to landfill as opposed to incineration or other treatment options
MRF stock adjustment period	Period over which the MRF industry would like to adjust stock levels to a desired level
Minimum MRF Processing Time	The minimum time required to process at MRF
Table for MRF Order Fulfilment	The ability to ship is constrained by inventory availability. As the inventory level drops, the fraction of customer orders that can be filled decreases. When inventory is zero, shipments cease. Unfilled customer orders are lost.
quality of MRF	Fraction of input to MRF becoming sorted plastic, the remainder is disposed of
quality of plastic packaging waste	This will be the amount of plastic which is skimmed off at the front of the MRF, before it enters, but will be included in the overall 'reject rate' for an MRF
MRF Channel priority weight	Priority for each of the market channels from the MRF
priority width	Specifies how big a gap in priority is required to have the allocation go first to higher priority with only leftovers going to lower priority. When the distance between any two priorities exceeds width and the higher priority does not receive its full request the lower priority will receive nothing.
integer type	Set to 10 for integer allocations; otherwise 0

extra	Extra parameter - used for elasticity when allocation is CES (ptype=5)
Priority type	The type of curve used in the allocation routine. The types are: • ptype 0 – Fixed Quantity • ptype 1 – Rectangular The curve will be shaped as the integral of a rectangle. The ppriority element specifies the midpoint of the curve and the pwidth element determines the speed with which the curve goes from 0 to the specified quantity. pextra is ignored. Use 11 to allocate integer amounts with ALLOCATE AVAILABLE only. • ptype 2 – Triangular • ptype 3 – Normal • ptype 4 – Exponential • ptype 5 – Constant Elasticity
PRF Channel priority weight	Priority for each of the market channels from the MRF
desired PRF inventory coverage	Desired amount of stock in the PRF system (years' worth of average demand)
PRF stock adjustment period	Period over which the PRF industry would like to adjust stock levels to desired level
Table for PRF Order Fulfilment	The ability to ship is constrained by inventory availability. As the inventory level drops, the fraction of customer orders that can be filled decreases. When inventory is zero, shipments cease. Unfilled customer orders are lost.
Minimum PRF Processing Time	The minimum time required to process at Reprocessor

Figure 5-1: Main System Diagram



5.2.3 Waste Generation and Collection

5.2.3.1 Total Waste Generated

This view takes input assumptions for the generation of plastics packaging waste from three distinct sources: commercial (or non-consumer), household, and consumer away-from-home.

Non-Consumer Waste: The non-consumer stock and flow structure takes an initial annual waste generated (*initial non consumer plastic packaging waste*) and an annual rate of growth (*annual change in non consumer plastic packaging waste*) to determine the year-by-year volume of *non consumer plastic packaging waste*. The values chosen were determined from calibration to historical data for *non consumer plastic packaging waste.*

Consumer Waste: Consumer waste generation combines the size of the population (*total number of households*) with an assumption about the average waste arisings per household (*plastic packaging per household*) to determine the total consumer waste, and allocates this to waste generated at home (*consumer household plastic packaging waste*) and waste generated by consumers while away from home (*consumer away from home plastic packaging waste*). Assumptions were determined through a process of calibrating to historical data for each of the three streams of waste.

Figure 5-2 and Table 5-4 show the model structure and definitions of the assumptions used to calculate total waste generated.

Figure 5-2: Total Waste Generated View

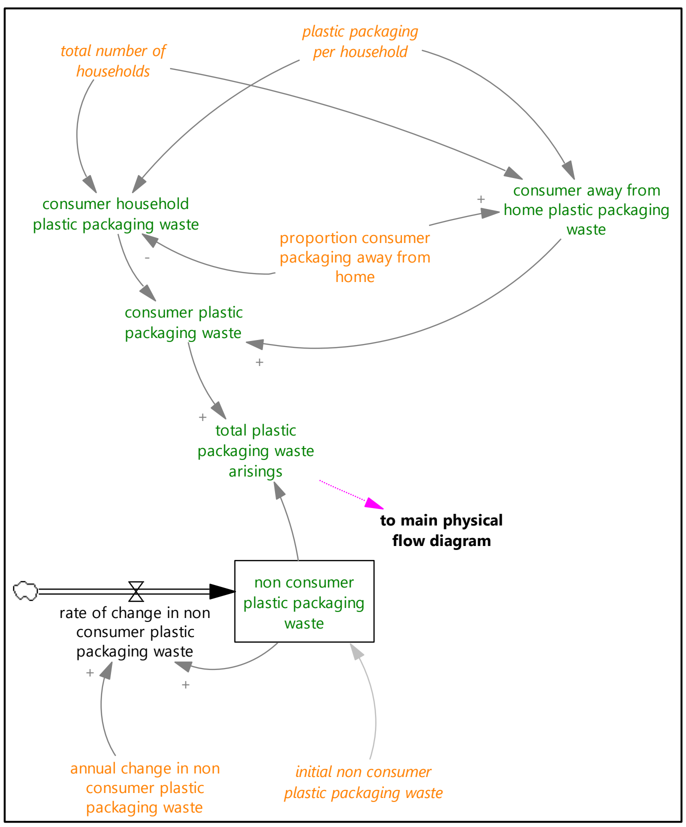


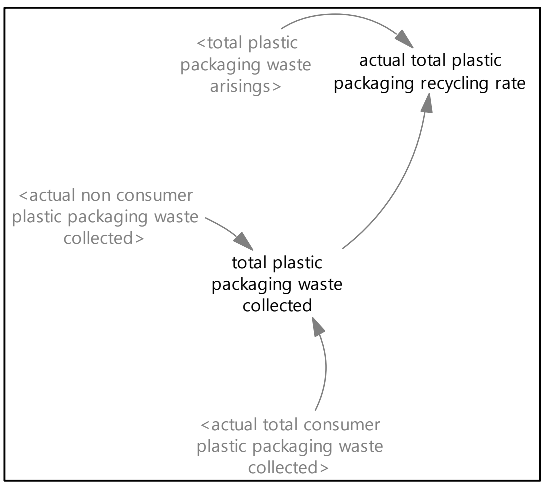
Table 5-4: Assumptions for *Total Waste Generated*

Name	Description
total number of households	Number of households in the UK. The data combines historical values until the present day, and enables the user to set annual growth rates to generate future values
plastic packaging per household	Annual plastic packaging waste generated per household in the UK. The data combines historical values until the present day, and enables the user to set annual growth rates to generate future values – within the source spread sheet
proportion consumer packaging away from home	Splits consumer waste generated into household and away-from-home. Determined trough calibration.
initial non consumer plastic packaging waste	Annual volume of non-consumer waste generated at the start of the simulated period. Determined through calibration.
annual change in non consumer plastic packaging waste	Fractional annual change in the volume of non-consumer plastic packaging waste generated.

5.2.3.2 Total Waste Collected

The total waste collected structure adds together all the waste collected from commercial and non-commercial sources (*total plastic packaging waste collected*), as shown in Figure 5-3.

Figure 5-3: Total Waste Collected View



5.2.3.3 Consumers

Consumer behaviour is captured as a simple proportion of household plastics packaging waste deposited for collection (*recycling participation*). An initial value is estimated during the calibration process (*initial recycling participation*) and this participation may grow at an annual rate of *growth rate in recycling participation*. Participation is used in conjunction with the *fraction of plastic packaging waste for collection* in determining the volume of plastics packaging waste collected for recycling.

Figure 5-4 and Table 5-5 show the model structure and assumptions used for consumer behaviour.

Figure 5-4: Consumer Behaviour View

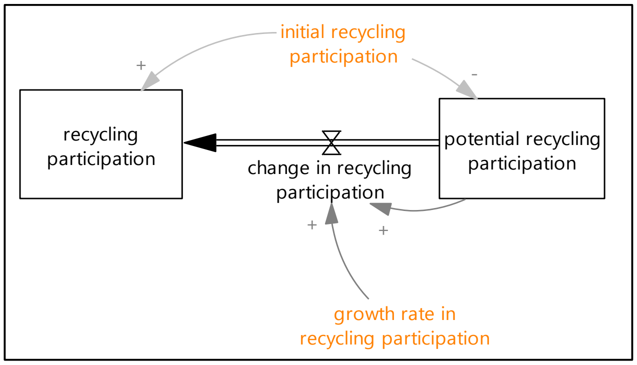


Table 5-5: Assumptions for *Consumer Behaviour*

Name	Description
initial recycling participation	Proportion of potential plastic packaging waste deposited for collection by households. Determined through calibration.
growth rate in recycling participation Are there behavioural limitations to this?	Annual growth in plastic packaging recycling participation by households in the UK. Determined through calibration.

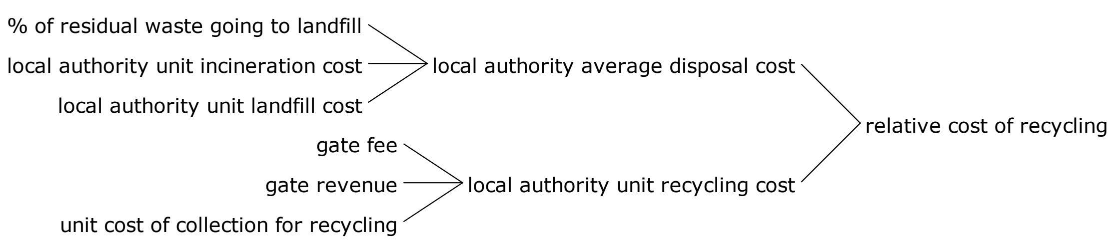
5.2.3.4 Collections

Collection of waste is determined separately for each of the two main streams, commercial and household. Subscripts are used to repeat the structure for each stream; the calibration process selects parameter values to enable close calibration with historical data on the *fraction of plastic packaging waste for collection*, as follows:

fraction of plastic packaging waste for collection[Stream]=INTEG(net change in recycling collection fraction[Stream],initial fraction of plastic packaging waste sent for recycling[Stream])

The main determinant of the fraction of waste collected for recycling is assumed to be financial – the *relative cost of recycling*. This value is computed from a series of assumptions about the cost of recycling (*local authority unit recycling cost*) and the cost of disposal in landfill and incineration (*local authority average disposal cost*), as shown in the casual tree in Figure 5-5.

Figure 5-5 - Relative Cost of Recycling Causal Tree



As described at the end of section 8.5, the relationship between this relative cost and the resulting *fraction of plastic packaging waste for collection* is determined through an elasticity index *sensitivity of collection to relative recycling cost.* At the reference relative cost (*reference relative cost of recycling*) the equation outputs the *reference fraction of plastic packaging waste sent for recycling*. Should the relative cost be greater than the reference value, then the fraction sent for recycling will be lower – how much lower is determined by the magnitude of *sensitivity of collection to relative recycling cost.* (The sensitivity value is negative, indicating that recycling increases if costs fall relative to landfill/incineration). As relative costs change, however, there is no immediate response in terms of a change in the fraction of waste collected for recycling as the system takes time to react to these changes (*collection policy change period*). Eventually, these influences filter through to a change in the *fraction of plastic packaging waste for collection.*

Figure 5-6 and Table 5-6 show the model structure and assumptions used to calculate rates of collections.

Figure 5-6: Collections View

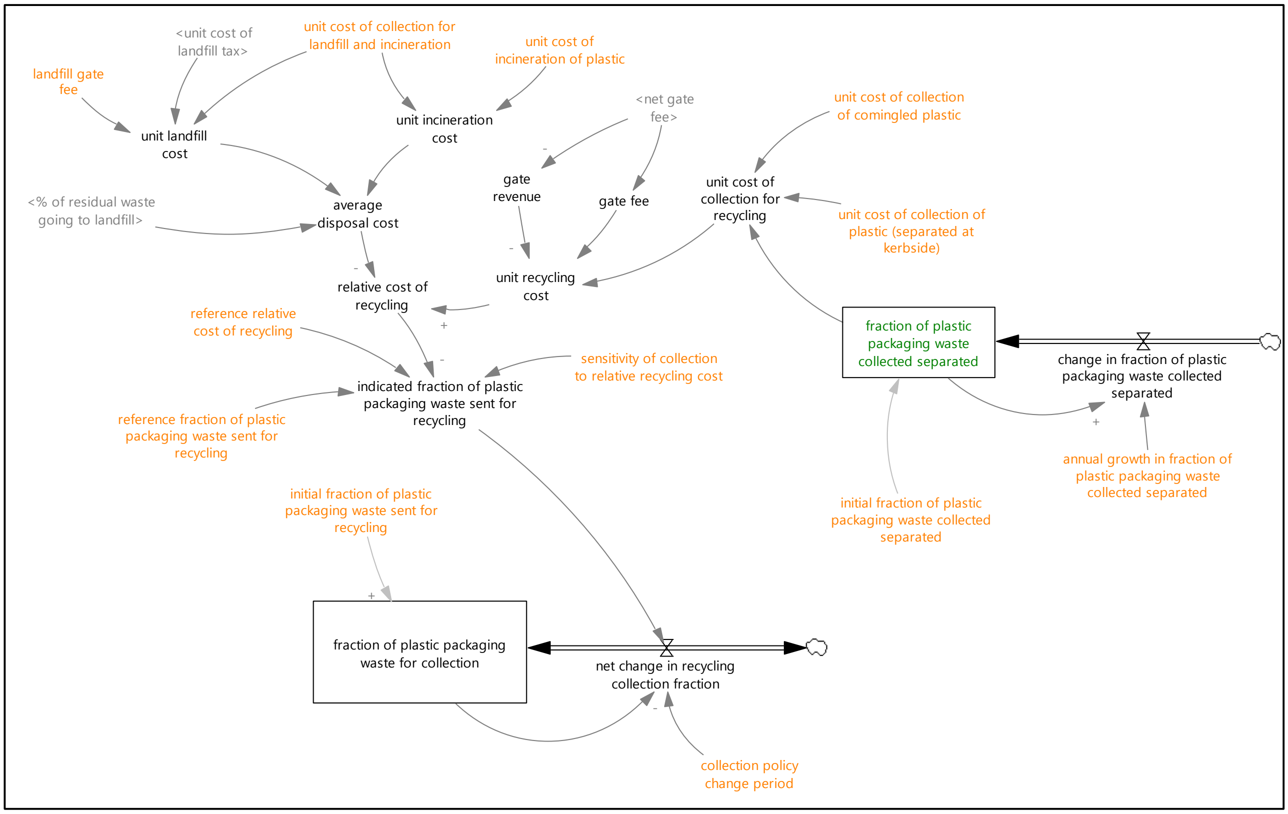


Table 5-6: Assumptions for Collections

Name	Description
unit cost of collection of comingled plastic	Cost to collect co-mingled plastics
unit cost of collection of plastic (separated at kerbside)	Cost to collect plastics sorted at kerbside
unit cost of collection for landfill and incineration	Cost to collect plastic for landfill or incineration
unit cost of incineration of plastic	Cost to incinerate plastic packaging waste
reference relative cost of recycling	Reference relative cost of recycling at which the reference fraction of plastic packaging waste sent for recycling would result. Determined through calibration.
reference fraction of plastic packaging waste sent for recycling	Reference fraction of recycling if relative costs were at the reference relative cost of recycling. Determined through calibration.
initial fraction of plastic packaging waste sent for recycling	Fraction of plastic packaging sent for recycling at the start of the simulation. Determined through calibration.
collection policy change period	Period over which the fraction of waste collected for recycling responds to changes in the relative cost of recycling.
landfill gate fee	Current landfill gate fee

5.2.3.5 Local Authority Collections

This view collates the total collections from consumers – that is, by LAs. It takes the *fraction of plastic packaging waste for collection* and *recycling participation* calculated previously, and determines the *fraction of household plastic packaging waste sent for recycling (all types).* The historical data available for the volume of material collected for recycling only includes material reported in the PRN system and so an additional volume needs to be estimated to account for losses (at MRF/PRF) and for collections not reported (*multiplier of collection data to account for losses and non PRN/PERN*). The resulting *total consumer plastic packaging waste collected* is used in the main physical flow model to generate the flow of material into the recycling system.

In addition to the calculation of recycling material flow, this view estimates the *fraction of consumer plastic packaging waste collected separated* through a simple assumption of an *initial fraction of consumer plastic packaging waste collected separated* and an annual growth in this fraction (*annual growth in fraction of consumer plastic packaging waste collected separated*), both of which are estimates via the calibration process.

The structure called *scenario multiplier of fraction of household plastic packaging waste sent for recycling (all types)* allows the user to manipulate the endogenously calculated fraction by increasing or decreasing the value during a specified period of time.

Figure 5-7 - Scenario Modifier of Waste Collection for Recycling Causal Tree

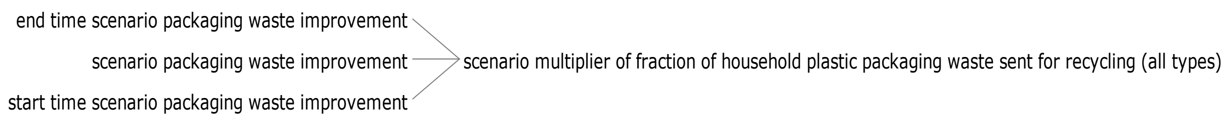


Figure 5-8 and Table 5-7 show the model structure and assumptions used for local authority collections.

Figure 5-8: Local Authority Collections View

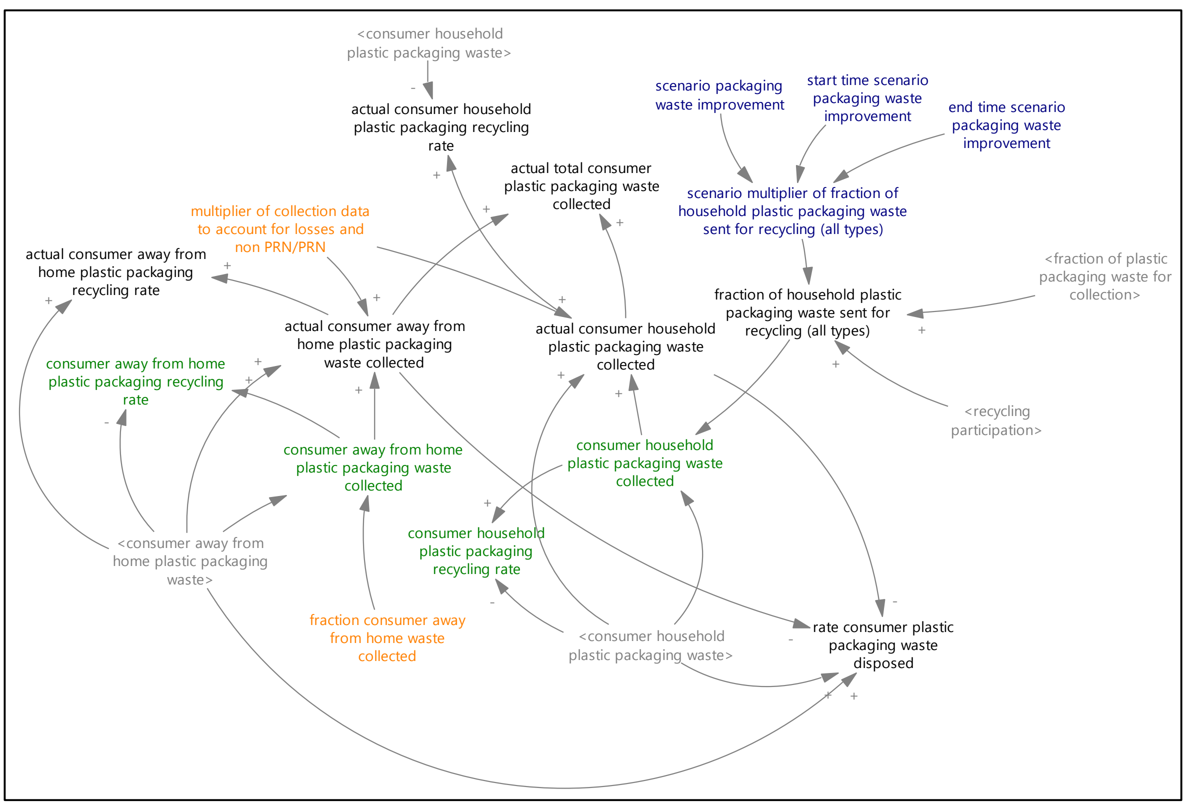


Table 5-7: Assumptions for Local Authority Collections

Name	Description
initial fraction of consumer plastic packaging waste collected separated	Fraction of all plastics collected, separated at kerbside, at the start of the simulated period. Determined through calibration.
annual growth in fraction of consumer plastic packaging waste collected separated	Annual growth in plastic packaging collected separated at kerbside. Determined through calibration.
fraction consumer away from home waste collected	Estimated fraction of away-from-home consumer plastic packaging waste collected for recycling. Determined through calibration.
multiplier of collection data to account for losses and non PRN/PERN	Since the calibration routine ensures close of waste collection volumes to only that waste reported under the PRN system, there is a need to account for material outside the system and for any losses as the material is processed. Determined through calibration.

5.2.3.6 Commercial Collections

This view takes the *fraction of plastic packaging waste for collection* previously calculated for the commercial stream (using subscripts) to produce an *actual non consumer plastic packaging waste collected.* As with the non-commercial stream, a *multiplier of collection data to account for losses and non PRN/PERN* is estimated in order to account for collections outside the reported PRN system and the resulting *actual non consumer plastic packaging waste collected* forms part of the flow of material into the physical flow model.

In addition to the calculation of recycling material flow, this view estimates the *fraction of non consumer plastic packaging waste collected separated* through a simple assumption of an *initial fraction of non consumer plastic packaging waste collected separated* and an annual growth in this fraction (*annual growth in fraction of non consumer plastic packaging waste collected separated*), in the same way as estimated for consumer waste, both of which are estimates via the calibration process. Figure 5-9 and Table 5-8 show the model structure and assumptions used to calculate commercial collections.

Figure 5-9: Commercial Collections View

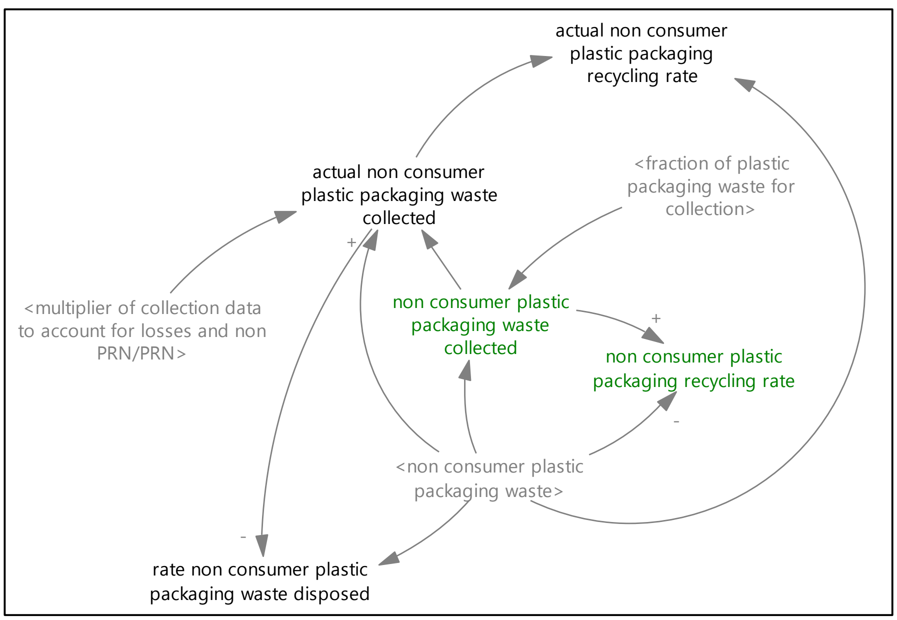


Table 5-8: Assumptions for Commercial Collections

Name	Description
initial fraction of non consumer plastic packaging waste collected separated	Fraction of all plastics collected, separated at kerbside, at the start of the simulated period. Determined through calibration.
annual growth in fraction of non consumer plastic packaging waste collected separated	Annual growth in plastic packaging collected separated at kerbside. Determined through calibration.

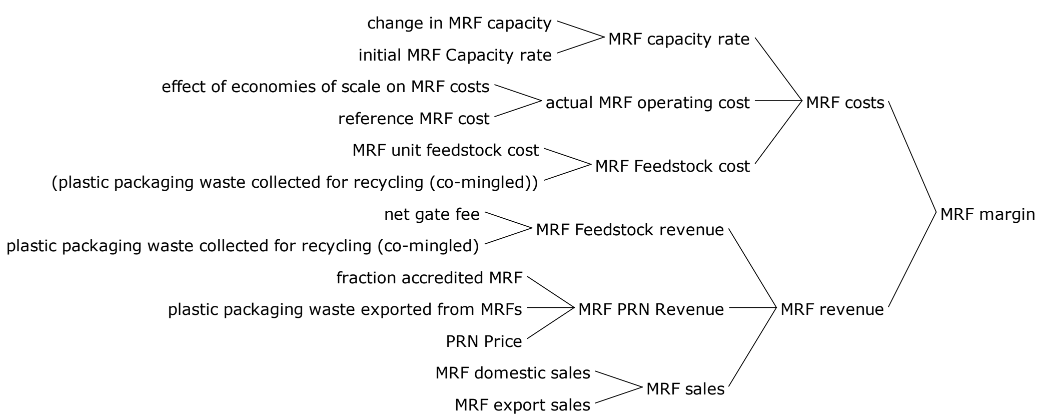
5.2.4 Waste Processing

5.2.4.1 MRF Capacity

This view represents the expansion or contraction of the Material Recovery Facility (MRF) industry. It uses a modified version of Sterman's commodity cycle model (Sterman 2000). In essence, the structure assumes the industry will expand if future profitability is beyond some threshold and will expand more quickly as profitability increases. The degree to which the industry will invest and expand is governed by the *sensitivity MRF investment to projected profitability,* which translates *Expected MRF margin* into a *desired MRF capacity*. Any capacity change will be acted upon over an industry *MRF investment period,* representing the speed at which the industry is able to finance and produce new capacity. If profitability falls, of course, the industry may contract.

Margins are determined from revenues (*MRF revenue*) and costs (*MRF costs*). The former is derived from sales to domestic and export customers in addition to any revenues from LAs required to make a *net gate fee,* and the latter from revenues from the export of sorted materials via the PERN scheme. Figure 5-10 shows the causal tree for MRF margin values.

Figure 5-10 - MRF Margin Causal Tree

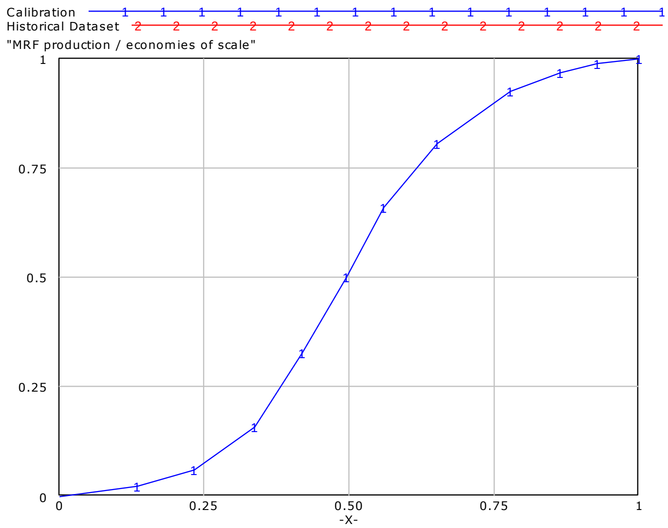


MRF costs are composed of: feedstock costs (if MRFs pay LAs for their waste) and *actual MRF operating cost.* The dynamics of these costs are as follows:

- The price MRFs are willing to pay for material (or, more likely, to charge for material) is determined by the price they receive for sorted material (*MRF price adjusted for PERN Price*), their operating costs (*actual MRF operating cost*) and their desired profits (*actual MRF markup*). This is further complicated by the presence of PERN revenue and it is assumed that some portion of that revenue (*fraction of PERN income passed on*) is used to offset the fees charged to LAs (*MRF unit feedstock cost*). This unit feedstock cost, if negative, means a positive charge to LAs while if it is positive, LAs would be paid for the material they collected.
- *The actual MRF operating cost* accounts for a base *reference MRF cost* modified by any economies of scale. Economies of scale are determined from the lookup table *MRF*

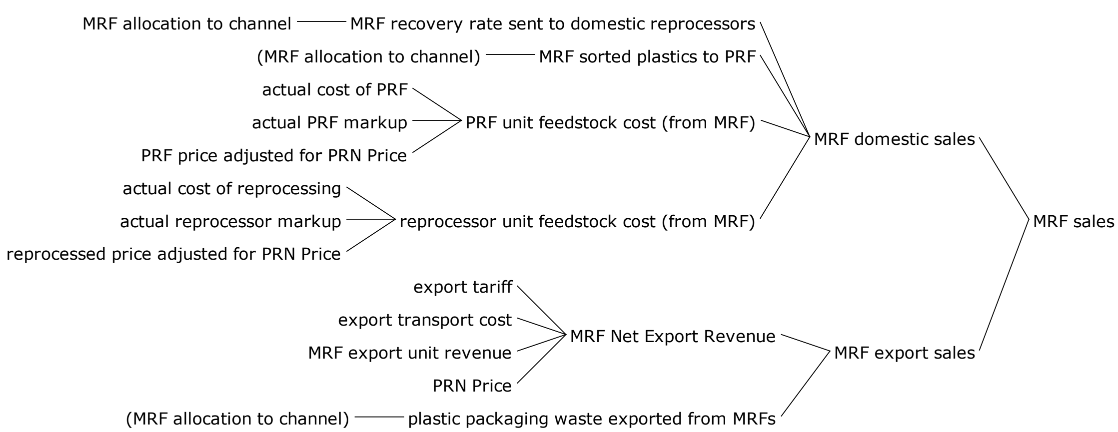
production / economies of scale, which takes the *MRF capacity rate* as its input (normalised using the *base MRF production capacity for economies of scale*) with the multiplier *effect of economies of scale on MRF costs* as the resulting output. As MRF industry size increases, so does this multiplier of the *max MRF economies of scale effect on costs*.

Figure 5-11 - MRF Economies of Scale Lookup Table



<u>MRF sales</u> revenue is determined by the volume of the material sold and the price attained per tonne. Sales can be to Plastics Recovery Facilities (PRF) in the UK, direct to reprocessors in the UK, or to overseas, each will have their own volume and price elements. Figure 5-12 presents a causal tree for MRF sales.

Figure 5-12 - MRF Sales Causal Tree

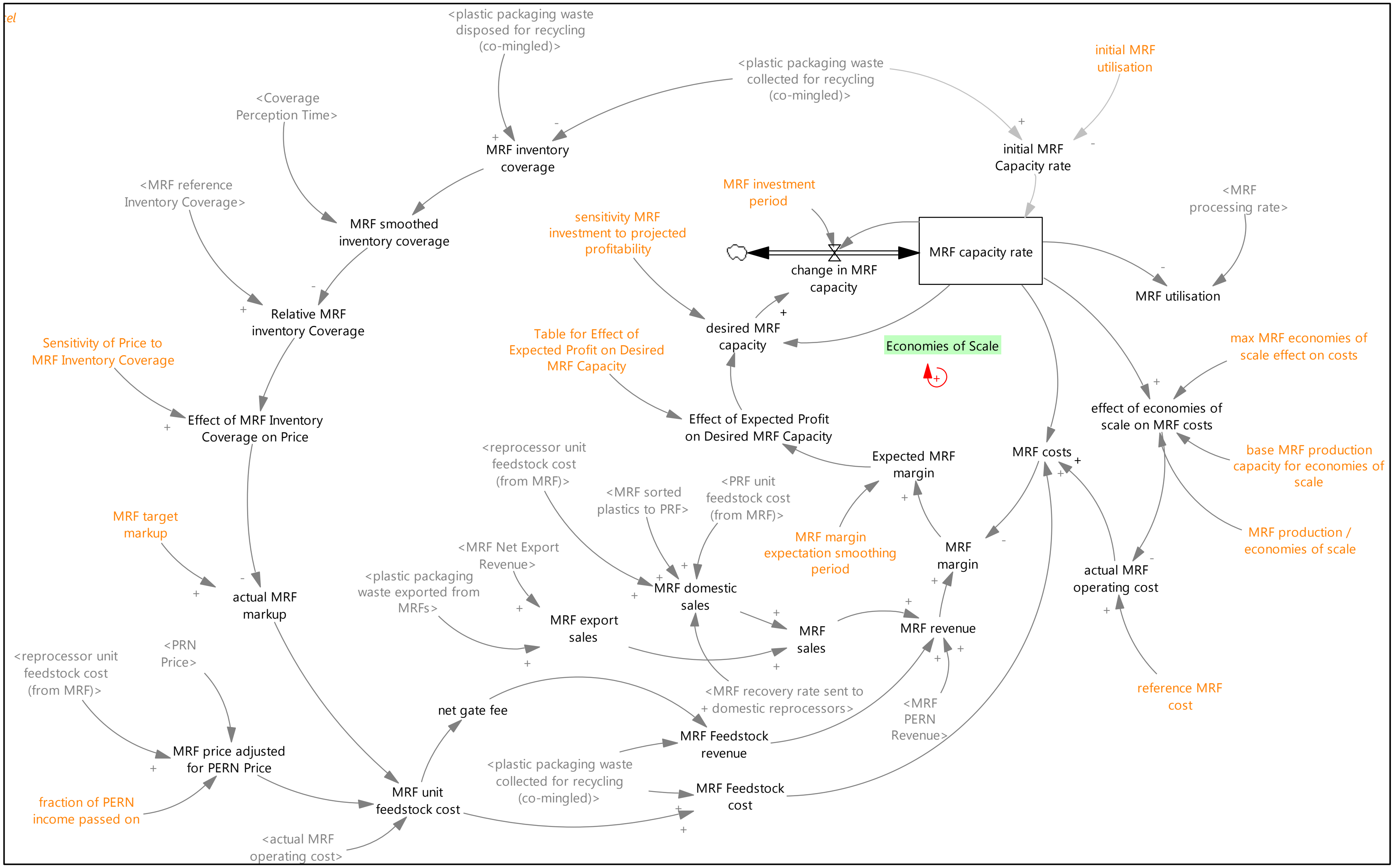


A further element of the pricing mechanism is related to inventory held by MRFs. An inventory higher than some desired level (*MRF reference Inventory Coverage*) would lead to an increase in the fees charged by MRFs, while a shortage of materials would lead to a reduction in fees or even to the widespread introduction of payments from MRFs to LAs. The strength of this relationship is determined by the *Sensitivity of Price to MRF Inventory Coverage.* Figure 5-13 and Table 5-9 show the model structure and assumptions used for MRF capacity.

Table 5-9: Assumptions for MRF Capacity

Name	Description
initial MRF utilisation	Initial MRF processing capacity, as a function of the supply of material to MRF (at the start of the simulation)
max MRF economies of scale effect on costs	Maximum effect of economies of scale (reduction in unit costs). Determined through calibration.
base MRF production capacity for economies of scale	Production capacity to achieve base cost reductions from economies of scale. Determined through calibration.
MRF production / economies of scale	Non-linear table relating MRF production capacity to the effect of economies of scale (achievement of cost reductions)
reference MRF cost	Estimate of MRF operating cost before economies of scale effects. Determined through calibration.
MRF margin expectation smoothing period	MRF margin expectation smoothing period. Determined through calibration.
Table for Effect of Expected Profit on Desired MRF Capacity	The adjustment of desired capacity above or below the current level depends on this function of the expected profitability of new investment
sensitivity MRF investment to projected profitability	Determines the rate of change in investment multiplier as the expected profit margin changes from the reference value. Determined by calibration.
MRF investment period	Period over which industry is able to react to pressures on capacity change. Determined through calibration.
fraction of PERN income passed on	Fraction of unit PERN income 'passed on' to LAs by MRF (in a reduction of charges/ increase in price paid)
MRF reference Inventory Coverage	The normal inventory coverage required to ensure desired levels of service (the desired ability to fill orders). Determined through calibration.
Sensitivity of Price to MRF Inventory Coverage	Controls the response of price to inventory coverage. Must be negative for high inventory to lead to lower prices. Higher absolute values lead to greater price changes for any given inventory coverage level. Determined through calibration.
MRF target mark-up	Expected MRF margins. Determined through calibration.

Figure 5-13: MRF Capacity View

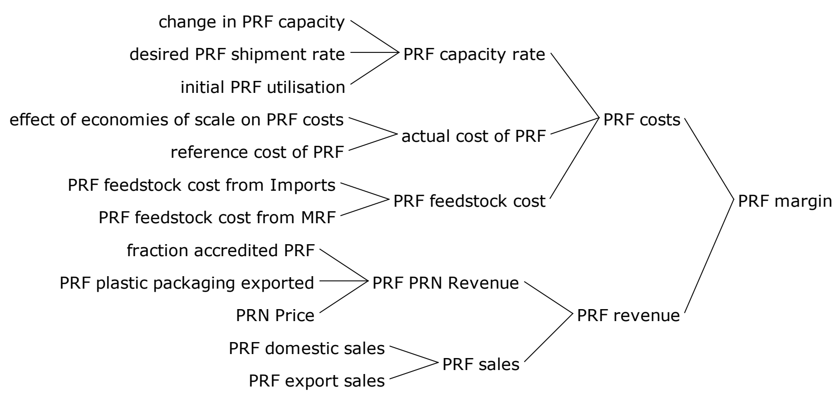


5.2.4.2 PRF Capacity

This view represents the expansion or contraction of the Plastics Recovery Facility (PRF) industry. It also uses a modified version of Sterman's commodity cycle model (Sterman 2000). In essence, the structure assumes the industry will expand if future profitability is beyond some threshold and will expand more quickly as profitability increases. The degree to which the industry will invest and expand is governed by the *sensitivity PRF investment to projected profitability,* which translates *Expected PRF margin* into a *desired PRF capacity*. Any capacity change will be acted upon over an industry *PRF investment period* which represents the speed at which the industry is able to finance and produce new capacity. If profitability falls, of course, the industry may contract.

Margins are determined from revenues (*PRF revenue*) and costs (*PRF costs*). The former is derived from sales to domestic and overseas reprocessors, and the latter from feedstock costs and the export of sorted material via the PERN scheme.

Figure 5-14 - PRF Margin Causal Tree

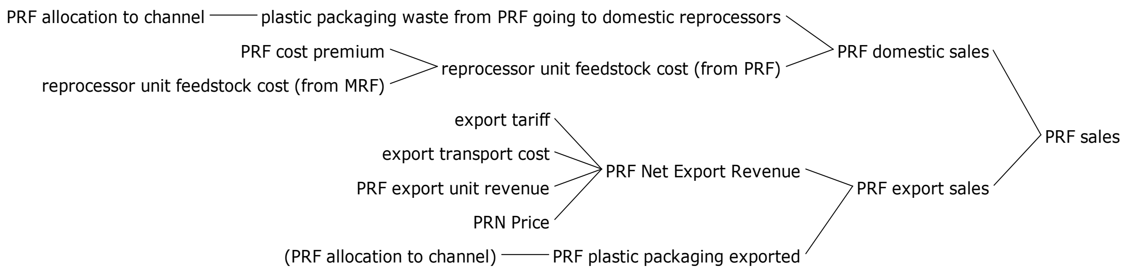


PRF costs are composed of any feedstock costs and *actual cost of PRF* which accounts for a base *reference cost of PRF* modified by any economies of scale. Economies of scale are determined from the lookup table *PRF production / economies of scale*, which takes the *PRF capacity rate* as its input (normalised using the *base PRF production capacity for economies of scale*) with the multiplier *effect of economies of scale on PRF costs* as the resulting output. As PRF industry size increases, so does this multiplier of the *max PRF economies of scale effect on costs*.

The price PRFs are willing to pay for material is determined by the price they receive for sorted material (*PRF price adjusted for PRN Price*), their operating costs (*actual cost of PRF*) and their desired profits (*actual PRF markup*). This is further complicated by the presence of PRN revenue; it is assumed that some portion of that revenue (*fraction of PRF PRN income passed on*) is used to offset the price charged to MRFs (*PRF unit feedstock cost (from MRF)*).

PRF sales revenue is determined by the volume of the material sold and the price attained per tonne. Sales can be made to reprocessors in the UK or overseas; each will have their own volume and price elements.

Figure 5-15 - PRF Sales Causal Tree



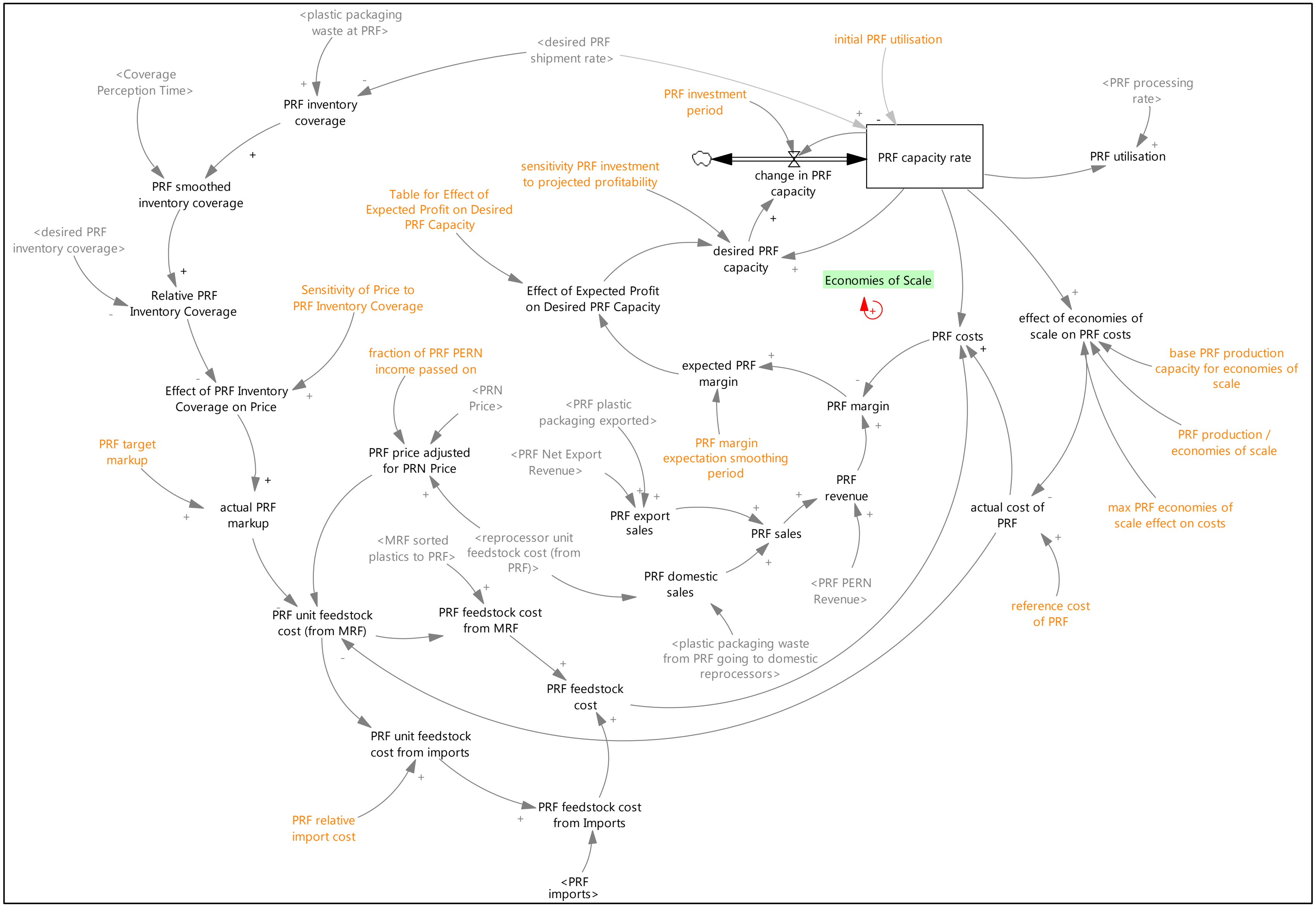
A further element of the pricing mechanism relates to the inventory held by the PRF. An inventory higher than some desired level (*PRF reference Inventory Coverage*) would lead to an increase in the fees charged by PRFs, while a shortage of materials would lead a reduction in fees. The strength of this relationship is determined by the *Sensitivity of Price to PRF Inventory Coverage.*

Figure 5-16 and Table 5-10 show the model structure and assumptions used for PRF capacity.

Table 5-10: Assumptions for PRF Capacity

Name	Description
initial PRF utilisation	PRF capacity utilisation at the start of the simulation
max PRF economies of scale effect on costs	Maximum effect of economies of scale (reduction in unit costs). Determined through calibration.
base PRF production capacity for economies of scale	Production capacity to achieve base cost reductions from economies of scale. Determined through calibration.
PRF production / economies of scale	Non-linear table relating PRF production capacity to the effect of economies of scale (achievement of cost reductions)
reference PRF cost	Estimate of PRF operating cost before economies of scale effects. Determined through calibration.
PRF margin expectation smoothing period	PRF margin expectation smoothing period. Determined through calibration.
Table for Effect of Expected Profit on Desired PRF Capacity	The adjustment of desired capacity above or below the current level depends on this function of the expected profitability of new investment
sensitivity PRF investment to projected profitability	Determines the rate of change in investment multiplier as the expected profit margin changes from the reference value. Determined through calibration.
PRF investment period	Period over which industry is able to react to pressures on capacity change. Determined through calibration.
fraction of PRF PRN income passed on	Fraction of unit PERN income ‘passed on’ to MRFs by PRFs. Determined through calibration.
PRF reference Inventory Coverage	The normal inventory coverage required to ensure desired levels of service (the desired ability to fill orders). Determined through calibration.
Sensitivity of Price to PRF Inventory Coverage	Controls the response of price to inventory coverage. Must be negative for high inventory to lead to lower prices. Higher absolute values lead to greater price changes for any given inventory coverage level. Determined through calibration.
PRF target mark-up	Expected PRF margins. Determined through calibration.

Figure 5-16: PRF Capacity View

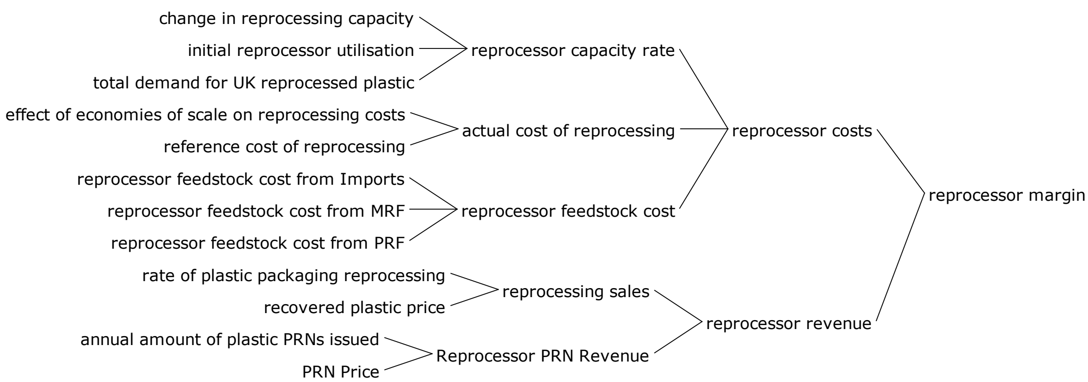


5.2.4.3 Reprocessing Capacity

This view represents the expansion or contraction of the reprocessing industry and uses a modified version of Sterman's commodity cycle model (Sterman 2000). In essence, the structure assumes the industry will expand if future profitability is beyond some threshold and will expand more quickly as profitability increases. The degree to which the industry will invest and expand is governed by the *sensitivity reprocessor investment to projected profitability,* which translates *expected reprocessor margin* into a *desired reprocessor capacity*. Any capacity change will be acted upon over an industry *reprocessing investment period,* representing the speed at which the industry is able to finance and produce new capacity. If profitability falls, of course, the industry may contract.

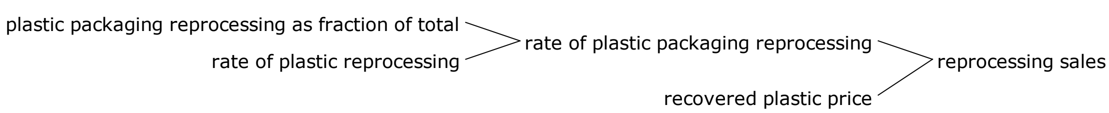
Margins are determined from revenues (*reprocessor revenue*) and costs (*reprocessor costs*), the former derived from sales of reprocessed plastics to domestic and foreign customers, and the latter from any feedstock costs and *actual cost of reprocessing*.

Figure 5-17: Reprocessor Margin Causal Tree



<u>Reprocessor sales</u> revenue is determined by the volume of the material sold and the price attained per tonne. In addition, reprocessors can sell PRNs at the prevailing rate (*Reprocessor PRN Revenue*).

Figure 5-18 - Reprocessor Sales Causal Tree



<u>Reprocessor costs</u> are derived from any feedstock costs and *actual cost of reprocessing,* which accounts for a base *reference cost of reprocessing* modified by any economies of scale. The price reprocessors are willing to pay for materials is determined by the price they receive for reprocessed plastic (*average reprocessed plastic price*), their operating costs (*actual cost of reprocessing*) and their desired profits (*actual reprocessor markup*). This is further complicated by the presence of PRN revenue, and it is assumed that some portion of that revenue (*fraction of PRN income passed on*) is used to offset the price charged to MRFs and PRFs (*reprocessor unit feedstock cost (from MRF)* and *reprocessor unit feedstock cost (from PRF)*).

Economies of scale are determined from the lookup table *reprocessor production / economies of scale* taking the *reprocessor capacity rate* as its input (normalised using the *base reprocessor production capacity for economies of scale*) with the multiplier *effect of economies of scale on reprocessing costs* as the resulting output. As the size of the reprocessor industry increases, so does the multiplier of the *max reprocessor economies of scale effect on costs*.

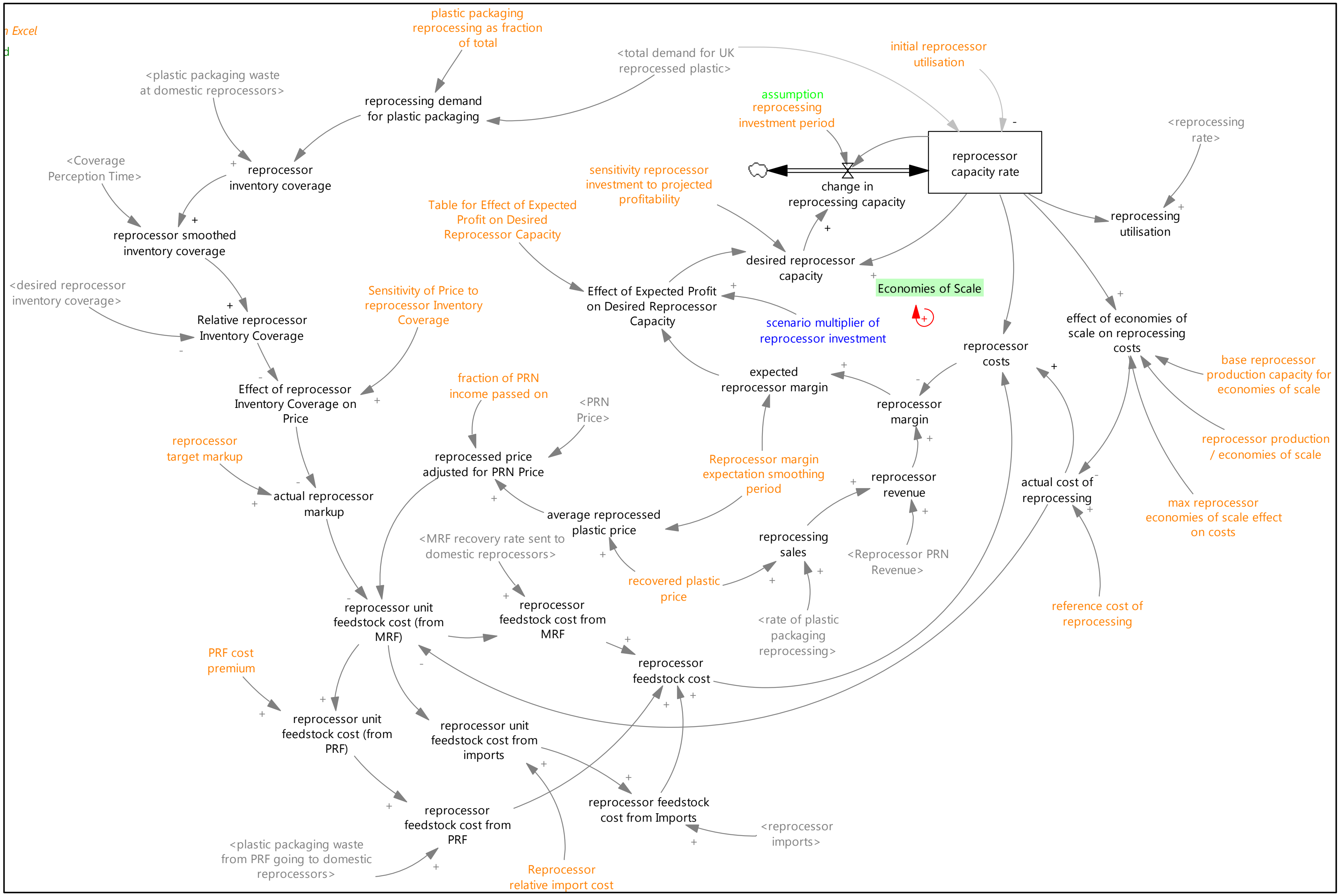
A further element of the pricing mechanism is that from the inventory held by Reprocessors. An inventory higher than some desired level (*Reprocessor Reference Inventory Coverage*) would lead to a reduction in the price reprocessors charge for reprocessed plastics as they attempt to adjust stock levels, while a shortage of material will lead an increase in price. The strength of this relationship is determined by the *Sensitivity of Price to reprocessor Inventory Coverage.*

Figure 5-19 and Table 5-11 show the model structure and assumptions used for reprocessor capacity.

Table 5-11: Assumption for Reprocessing Capacity

Name	Description
initial reprocessor utilisation	Reprocessing capacity utilisation at the start of the simulation
max reprocessor economies of scale effect on costs	Maximum effect of economies of scale (reduction in unit costs). Determined through calibration.
base reprocessor production capacity for economies of scale	Production capacity to achieve base cost reductions from economies of scale. Determined through calibration.
Reprocessor production / economies of scale	Non-linear table relating reprocessor production capacity to the effect of economies of scale (achievement of cost reductions)
reference cost of reprocessing	Estimate of reprocessing operating cost before economies of scale effects. Determined through calibration.
Reprocessor margin expectation smoothing period	Reprocessor margin expectation smoothing period. Determined through calibration.
Table for Effect of Expected Profit on Desired Reprocessor Capacity	The adjustment of desired capacity above or below the current level depends on this function of the expected profitability of new investment
sensitivity reprocessor investment to projected profitability	Determines the rate of change in investment multiplier as the expected profit margin changes from the reference value. Determined through calibration.
reprocessing investment period	Period over which industry is able to react to pressures on capacity change. Determined through calibration.
fraction of PRN income passed on	Fraction of unit PRN income 'passed on' to PRFs/MRFs by reprocessors . Determined through calibration.
Reprocessor reference Inventory Coverage	The normal inventory coverage required to ensure desired levels of service (the desired ability to fill orders). Determined through calibration.
Sensitivity of Price to reprocessor Inventory Coverage	Controls the response of price to inventory coverage. Must be negative for high inventory to lead to lower prices. Higher absolute values lead to greater price changes for any given inventory coverage level. Determined through calibration.
reprocessor target markup	Expected PRF margins. Determined through calibration.
plastic packaging reprocessing as fraction of total	Volume of plastic packaging in reprocessing as a fraction of the total. We are only interested in the plastic packaging element but reprocessors use other source of plastic too.

Figure 5-19: Reprocessor Capacity View



5.2.5 Demand

5.2.5.1 Global Plastics Demand

The UK plastic packaging recycling system operates within a complex global market and so the model was designed to account for interactions with that market. This part of the model would benefit from additional investigation and improvements, but due to time limitations a number of simple assumptions have been made for now.

Reprocessed Plastic Demand: Demand for reprocessed plastic from UK reprocessors is assumed to be a share (*UK share of Global reprocessed plastic demand*) of the total global market (*Global demand for reprocessed plastic*). An estimate of the *initial Global demand for reprocessed plastic* and a value for *annual growth in global demand for plastic* are used to estimate global demand. This demand is for all plastic and not just packaging, so an adjustment was made to ensure an appropriate volume is applied in each circumstance (*plastic packaging reprocessing as fraction of total*). In addition to this adjustment, the overall plastic demand is calibrated to historical data which only includes volumes reported under the PRN system; the true demand will be somewhat higher and so a *multiplier of UK reprocessed plastic demand* is used to account for this.

Recovered Plastic Export Demand: This is the demand for sorted plastics coming out of MRFs. The *Desired MRF Push Rate* reflects the requirement for MRFs to find markets for their throughput. Overseas demand is the net of this desired push rate less the domestic demand (*Export demand for UK recovered plastic*). It is worth noting, however, that allocation of MRF output to each of these demand streams depends on the relative priorities MRFs attribute to each stream, including the price they are able to achieve.

Sorted Plastic Export Demand: This is the demand for polymer-sorted plastics coming out of PRFs. The *desired PRF push rate* reflects the requirement for PRFs to find markets for their throughput. Overseas demand is the net of this desired push rate less the domestic demand (*Export demand for UK sorted plastic*). It is worth noting, however, that allocation of PRF output to each of these demand streams depends on the relative priorities PRFs attribute to each stream, including the price they are able to achieve.

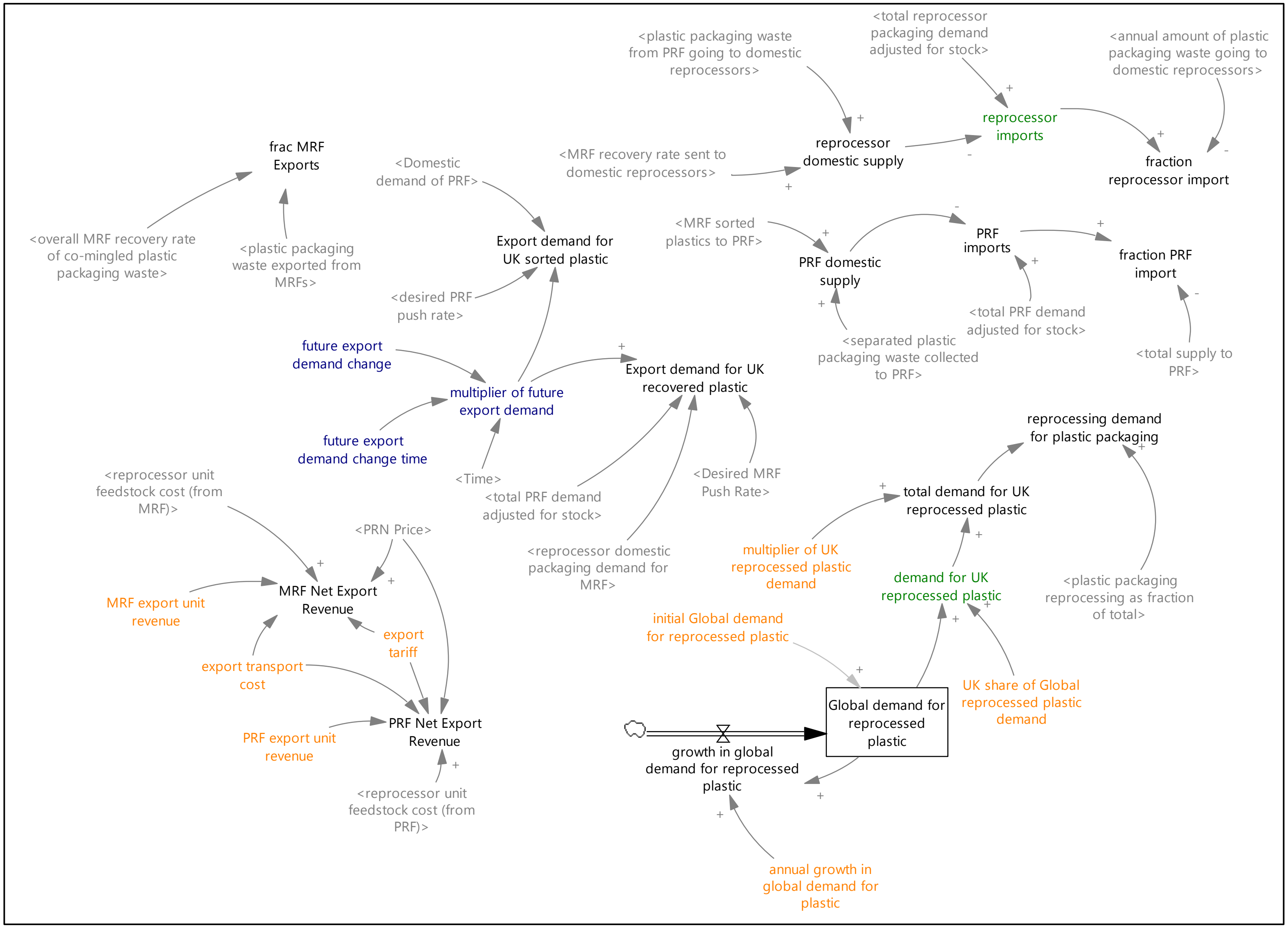
Reprocessor Imports: An assumption was made that reprocessors would require sufficient feedstock to satisfy their output demand. A proportion of this would be satisfied from domestic MRFs/PRFs (*reprocessor domestic supply*) and it is assumed that the remainder would be imported (*reprocessor imports*).

Figure 5-20 and Table 5-12 show the model structure and assumptions used for global plastics demand.

Table 5-12: Assumptions for Global Plastics Demand

Name	Description
annual growth in global demand for plastic	Growth in global demand for all reprocessed plastic. Determined through calibration.
initial Global demand for reprocessed plastic	Global demand for all reprocessed plastic at the start of the simulation. Determined through calibration.
UK share of Global reprocessed plastic demand	UK share of global demand for all reprocessed plastic. Determined through calibration.
multiplier of UK reprocessed plastic demand	The data (to which demand is calibrated) only accounts for PRN system and so the total true demand for reprocessed plastic is higher. Determined through calibration.
MRF export unit revenue	Estimate of MRF export revenue per tonne
export transport cost	Estimate of cost of transporting material overseas
PRF export unit revenue	Estimate of PRF export revenue per tonne
export tariff	Estimate of export tariffs charged per tonne

Figure 5-20: Global Plastics Demand View



5.2.6 Regulatory Framework

5.2.6.1 PRN/PERN Price

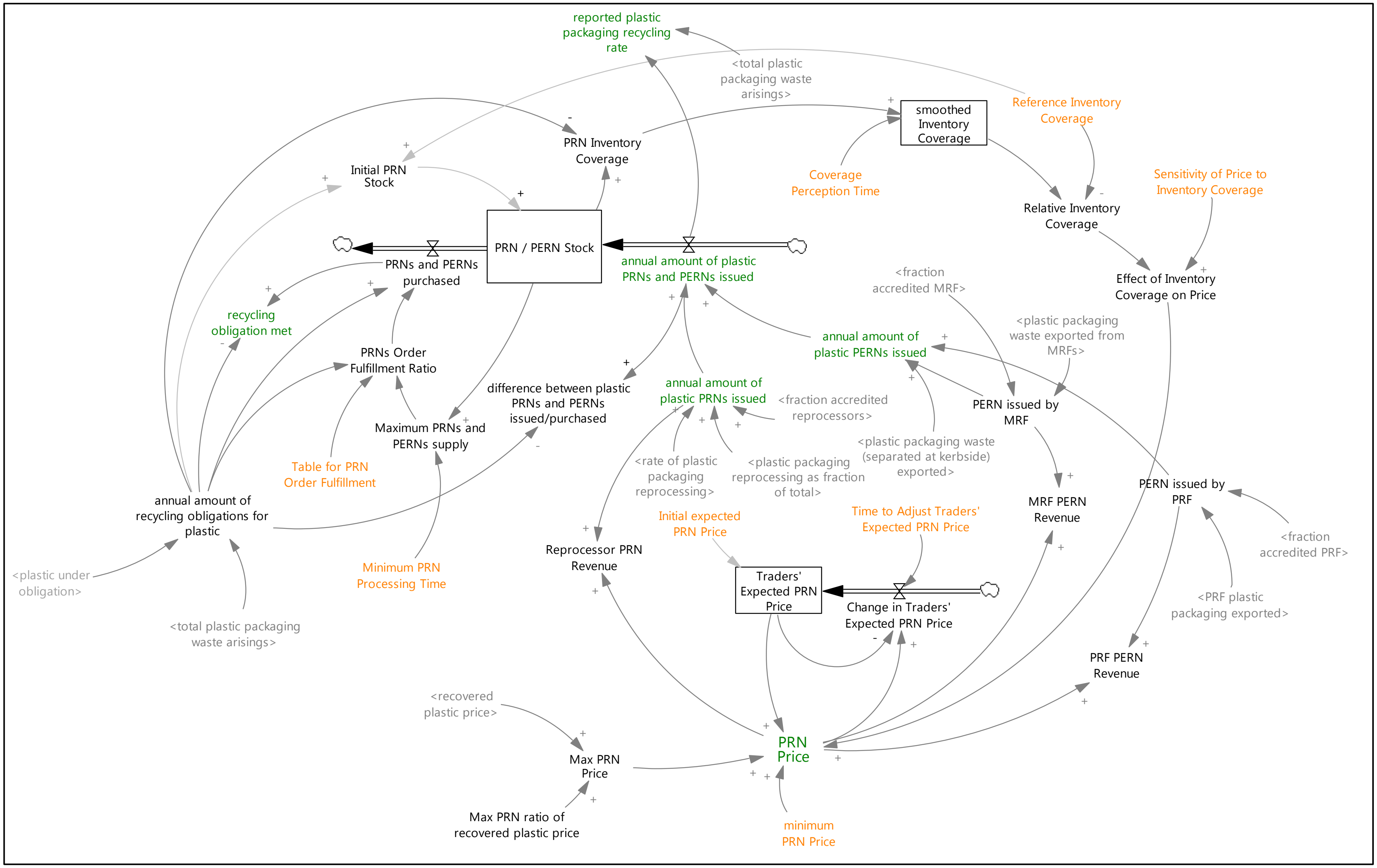
Packaging Recovery Notes (PRN) and Packaging Export Recovery Notes (PERN) can be issued by accredited MRFs, PRFs and reprocessors whenever output is exported (MRFs and PRFs) or processed (reprocessors); certain packaging producers and users are obligated to purchase PRN/PERNs. This PRN/PERN system provides a transparent and simple method of incentivising the recycling and recovery industry and achieving the statutory recycling targets. To model influences on PRN/PERN prices, the team chose to use a modified version of the Sterman commodity cycle model (Sterman 2000). From observation of historical PRN prices, a hypothesis was formed that the price fluctuations were caused wholly or in part by the imbalance between demand for and supply of PRNs; however it should be noted that there are a very large number of factors influencing the PRN price.

On the demand side, plastic packaging producers need to ensure that a certain percentage of the packaging waste they produce is recycled (plastic under obligation). This requirement is met through the purchase of PRNs or PERNs and so the annual amount of recycling obligations for plastic have to be satisfied from the PRN / PERN Stock. This PRN Inventory Coverage is compared with a Reference Inventory Coverage and, should the coverage be greater than or less than the reference, there will be a change in the PRN price (Effect of Inventory Coverage on Price) over a market reaction time denoted by Time to Adjust Traders' Expected PRN Price. Traders' beliefs about the underlying equilibrium price adjust in response to the gap between the indicated price and the current belief. Expected underlying price adjusts, via first-order adaptive expectations, to the actual price, which is constrained to be greater than a minimum level. On the supply side, the volume of material exported by MRFs and PRFs (annual amount of plastic packaging waste exported) and rate of plastic packaging reprocessing is combined with the fraction accredited MRF and fraction accredited reprocessors to calculate the volume of PERNs/PRNs issued. Table 5-13 shows the model structure and assumptions used for PRN/PERN price.

Table 5-13: Assumptions for PRN/PERN Price

Name	Description
Coverage Perception Time	The average time required to perceive and react to inventory coverage. Determined through calibration.
Reference Inventory Coverage	The normal inventory coverage required to ensure desired levels of service (the desired ability to fill orders). Determined through calibration.
Sensitivity of Price to Inventory Coverage	Controls the response of price to inventory coverage. Must be negative for high inventory to lead to lower prices. Higher absolute values lead to greater price changes for any given inventory coverage level. Determined through calibration.
Initial expected PRN Price	The initial price of the commodity. Used to initialize unit costs and price expectations so the system begins in equilibrium. Determined through calibration.
Time to Adjust Traders' Expected PRN Price	Traders' beliefs about the underlying equilibrium price adjust to actual prices over this period. Determined through calibration.
Minimum PRN Price	Assumption about the absolute minimum price expected for PRN/PERN
Max PRN ratio of recovered plastic price	When setting a reasonable maximum PRN price, this value sets the maximum PRN price as a fraction of the prevailing price of recovered plastics. This ensures PRN prices do not become ridiculously high during periods of 'high stress' when the supply/demand imbalance is high. This would most likely occur during extreme-condition testing.
Minimum PRN processing time	Period of time in processing PRN/PERN sales (matching availability of supply with demand). Determined through calibration.
Table for PRN Order Fulfilment	The ability to ship is constrained by inventory availability. As the inventory level drops, the fraction of customer orders that can be filled decreases. When inventory is zero, shipments cease. Unfilled customer orders are lost.

Figure 5-21: PRN/PERN Price View



5.2.6.2 Plastics Obligation

The Producer Responsibility regulations require packaging producers to purchase PRNs or PERNs from the waste industry for a certain fraction of the plastics packaging they use in their business (obligated amounts). The model reflects the historical data on PRN/PERN obligations, set over the period of simulated time from the start to the present day (*data plastic under obligation*), and also allows the user to input a future growth rate (*future annual increase in obligation*) in order to experiment with future increases in the obligation. The model structure makes use of the *data plastic under obligation* value until a user-defined *obligation experiment time,* from which time on the *future annual increase in obligation* takes over in determining the overall *plastic under obligation.*

Figure 5-22 - Plastics Under Obligation Causal Tree

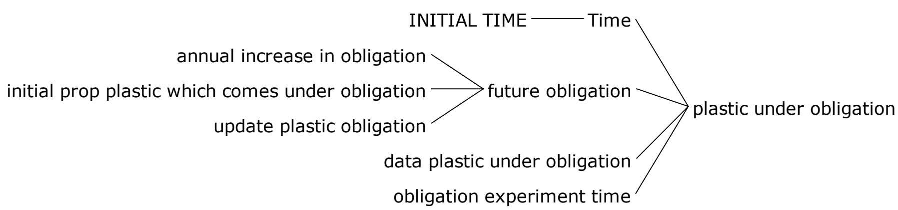
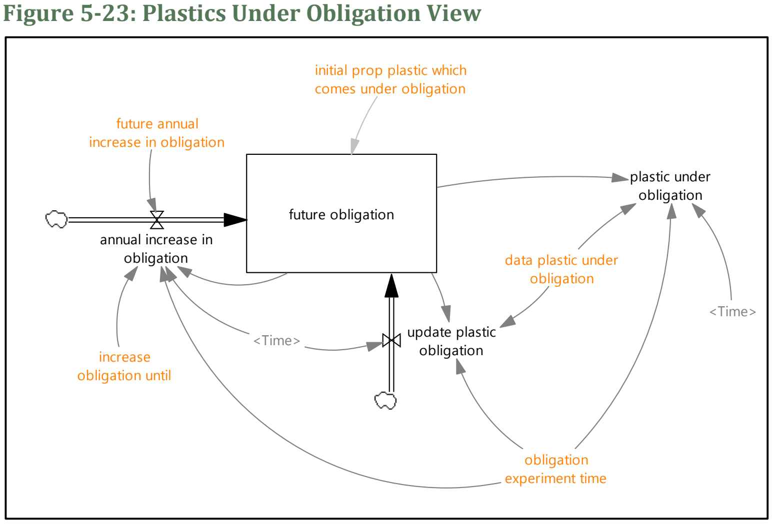


Figure 5-23 and Table 5-14 show the model structure and assumptions for plastics under obligation.

Table 5-14: Assumptions for Plastics Under Obligation

Name	Description
initial prop plastic which comes under obligation	Initial plastic packaging coming under recycling obligation
data plastic under obligation	Data on historical plastic under obligation. This will be active only until the 'experiment time' when it will be replaced by the internally generated 'future obligation'
obligation experiment time	Time at which data is discarded and future growth/decline assumptions become active. For example, after this date, landfill tax is no longer data-driven but determined by user-assumptions on annual growth
future annual increase in obligation	This becomes active after 'experiment time' and until 'increase obligation until' time. The annual increase is performed starting from the data existing at the 'experiment time'.
increase obligation until	Plastic packaging under recycling obligation will continue to increase at the 'future annual increase in obligation' rate until this time

Figure 5-23: Plastics Under Obligation View



5.2.6.3 PRN/PERN Accreditation

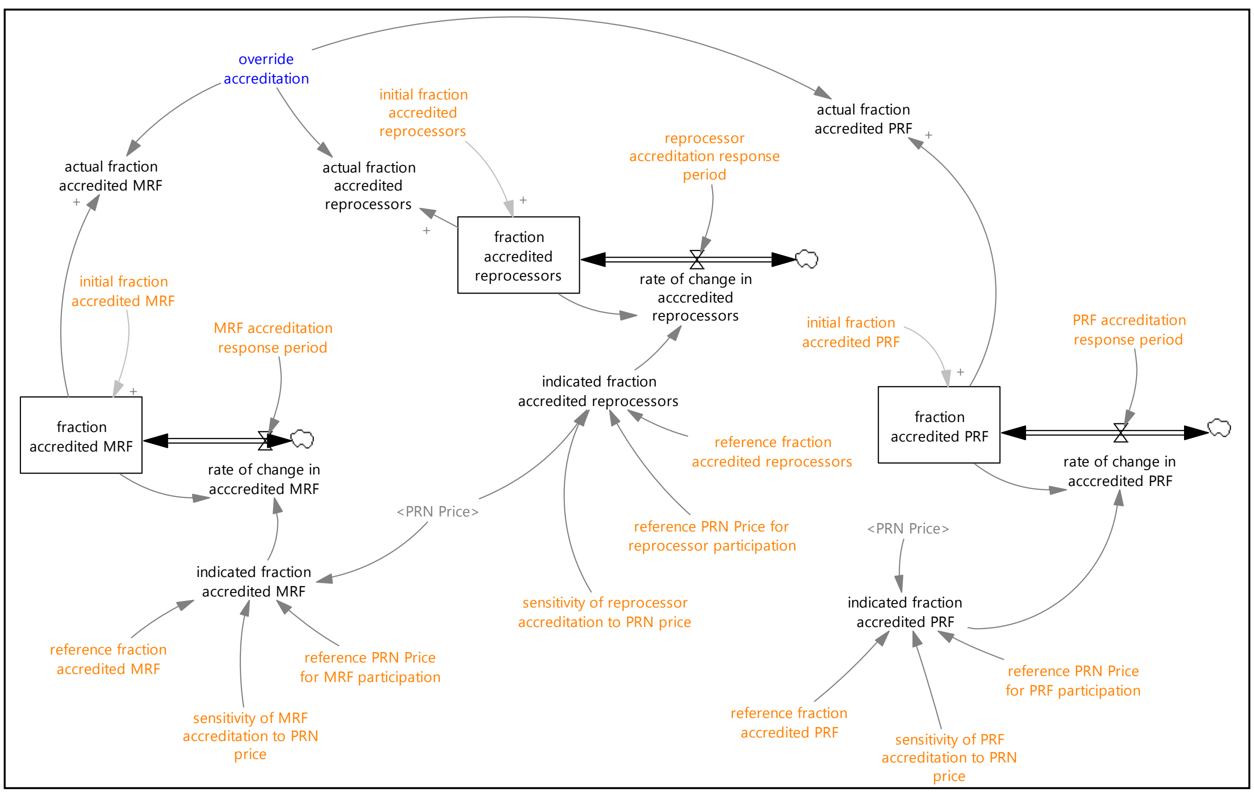
As part of the commodity cycle influence and our hypothesis that supply/demand relationships are responsible for the long-wave PRN/PERN price movements, the PRN/PERN accreditation structure attempts to link the current *PRN Price* with the issuing of PRNs and PERNs by MRFs/PRFs and reprocessors. In both cases, a *reference PRN Price for reprocessor participation* is compared to the actual *PRN Price* and, should the actual price be at this reference value, a *reference fraction accredited reprocessors* results. The rate of increase in this fraction as the *PRN Price* increases is determined by the *sensitivity of reprocessor accreditation to PRN price.* The resulting *indicated fraction accredited reprocessors* becomes the actual *fraction accredited reprocessors* as the industry reacts to the price signals over a *reprocessor accreditation response period.*

Figure 5-24 and Table 5-15 show the model structure and assumptions used for PRN/PERN accreditation

Table 5-15: Assumptions for PRN/PERN Accreditation

Name	Description
initial fraction accredited reprocessors	Fraction of all reprocessors issuing PRN at the start of the simulation. Determined through calibration.
reprocessor accreditation response period	Reprocessing industry response time to changes in PRN price as they affect accreditation for issuing of PRN. Determined through calibration.
reference fraction accredited reprocessors	Fraction of reprocessing volume accredited for PRN if PRN price is at the reference price. Determined through calibration.
reference PRN Price for reprocessor participation	PRN price at which the reference participation in PRN issuing would results. If PRN price is above this, then accreditation would be more widespread. Determined through calibration.
sensitivity of reprocessor accreditation to PRN price	Strength of relationship between changes in PRN price and the fraction of reprocessor volume accredited for issuing of PRNs. Determined through calibration.

Figure 5-24: PRN/PERN Accreditation View



5.2.6.4 Landfill Tax

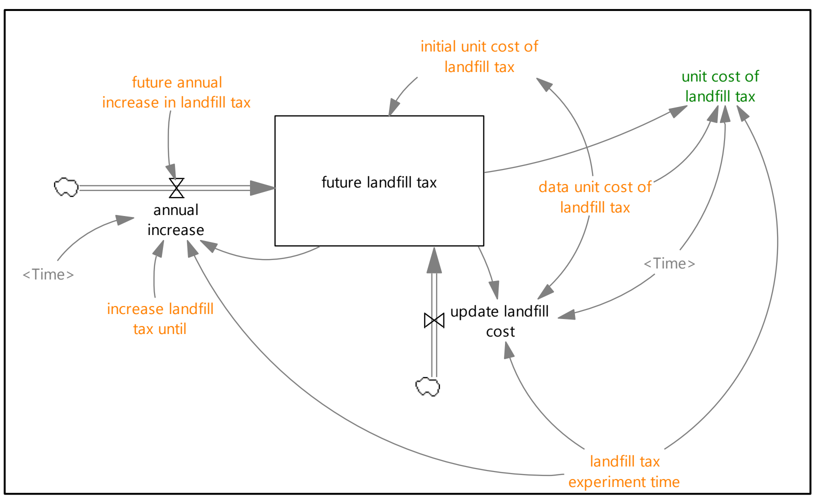
LAs pay a landfill tax for each tonne of waste diverted to landfill (*unit cost of landfill tax*). In the model, landfill tax levels were input according to historical and forecast data for the period of simulated time, from the start to the present day (*data unit cost of landfill tax*). In addition, a variable was introduced to allow the user to input a future growth rate (*future annual increase in landfill tax*) in order to explore possible scenarios. The model structure makes use of the value *data unit cost of landfill tax* until a user-defined *landfill tax experiment time,* from when on the *future annual increase in landfill tax* takes over in determining the overall *unit cost of landfill tax.* The time series of landfill tax is set by the user in the input data spreadsheet, and it is possible to manually input incremental increases for any period into the future. These will be used by the model for the time period leading up to *landfill tax experiment time*.

Figure 5-25 and Table 5-16 show the model structure and assumptions used for landfill tax.

Table 5-16: Assumptions for Landfill Tax

Name	Description
initial unit cost of landfill tax	Initial landfill tax at the start of the simulation
data unit cost of landfill tax	Data on historical landfill tax. This will be active only until the 'experiment time' when it will be replaced by the internally generated 'future landfill tax'.
landfill tax experiment time	Time at which data is discarded and future growth/decline assumptions become active. For example, after this date, landfill tax is no longer data-driven but determined by user-assumptions on annual growth
future annual increase in landfill tax	This becomes active after 'experiment time' and until 'increase landfill tax until' time. The annual increase is performed starting from the data existing at the 'experiment time'.
increase landfill tax until	Landfill taxes will continue to increase at the 'future annual increase in landfill tax' rate until this time

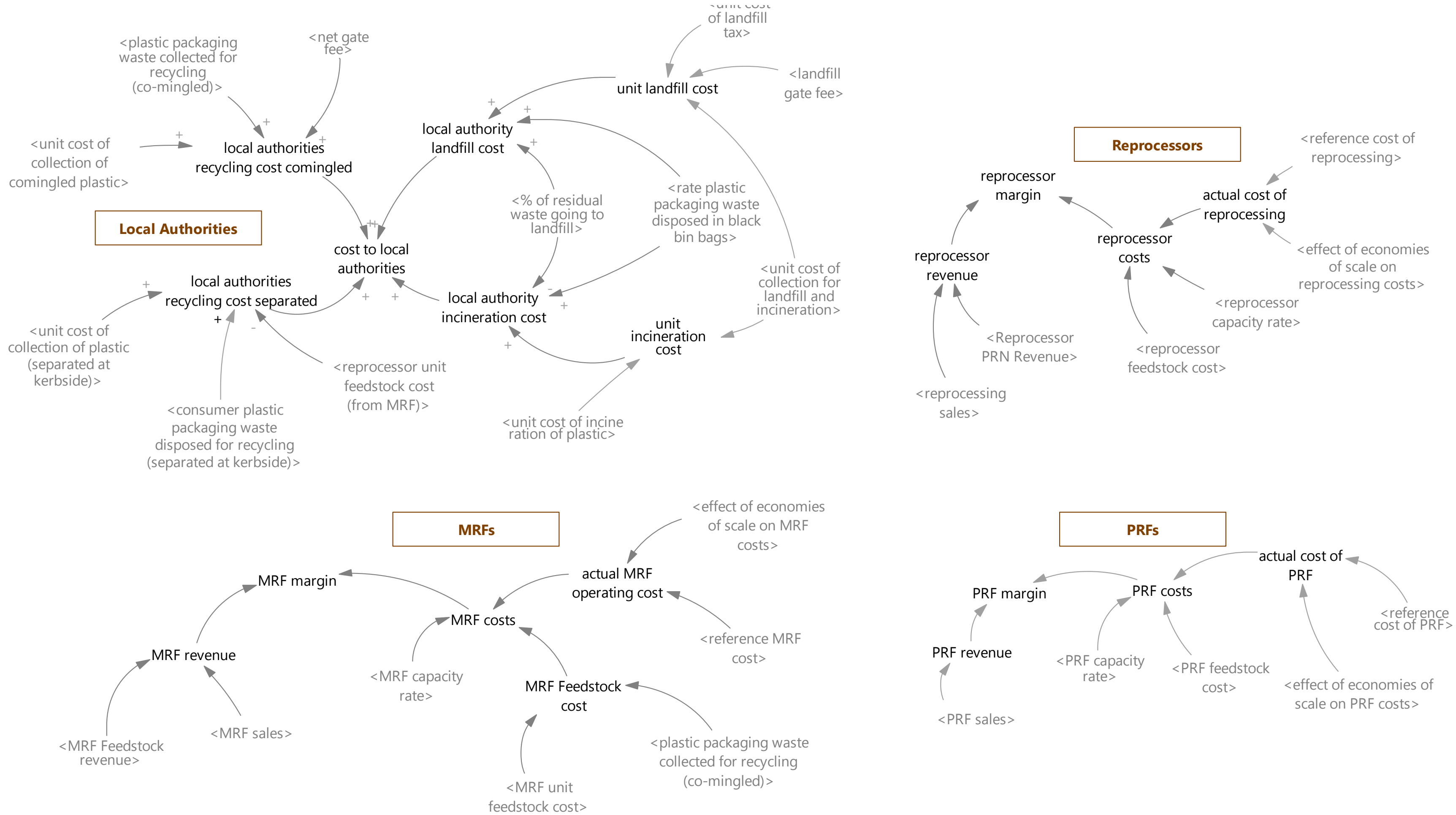
Figure 5-25: Landfill Tax View



5.2.7 Financial - Costs as Perceived by Different Stakeholders

This view is an account of the various costs incurred by the key stakeholders: LAs, MRFs, PRFs, and reprocessors. The *cost to local authorities* is the total of the cost of all streams of waste flow from households in the LA areas. In the waste industry (MRFs, PRFs, and reprocessors) margins drive investment decisions and so this forms the focus for industry financials in the model. Each industry element has its own overall financial output, and the structures are identical (Figure 5-26).

Figure 5-26: Costs as Perceived by Different Stakeholders View



5.3 Model Calibration and Verification

Calibration involves finding the values of model constants that make the model generate behaviour curves that best fit the real world data. Manual calibration is a slow, painstaking process involving manipulation of the input assumptions, the running of the model, and the visual assessment of "goodness of fit" for a range of outputs. Over the years, SD software tools have evolved in order to assist in this process, the most notable being the use of optimisation algorithms. In calibration optimisation the pay-off is calculated as the square of the accumulated differences between each historical and model-generated data point, (sum of squared error), the minimisation of which will result in a tendency to select model constant values minimising the difference between the historical data and the results generated by the model over the same historical period. Once a good fit has been achieved, the software provides a list of the constant values selected during calibration and these can be automatically used as input assumptions for future simulation runs.

Regarding verification, during the development of the model the authors met several times with key policy makers and analysts at Defra, and continually assessed the structure, input data and model outputs in order to enhance confidence in the model. Verification efforts included automated and manual checks for unit (of measurement) consistency, mass balance checks, and checks for syntax errors. The model was fully documented as it was built using the in-built comments tool within the Vensim equation editor. The full model documentation has also been generated in Excel format making use of these internal documentations and is presented as an accompanying document to this report.

5.3.1 Calibration and Balance Check Views

Calibration screens have been set up for a number of calibration areas in order to help the model user assess the calibration goodness-of-fit.

LA Calibration Screen: This screen shows graphical output for arisings and both consumer and non-consumer waste collection.

MRF Capacity Calibration: This screen shows some graphical output to assist in visualising the calibration of MRF capacity.

Mass Balance Checks: One important step in model validation consists in ensuring conservation of material within the model. In a model such as this, with multiple flows into and out of stocks and complex allocation routines, a mass balance check (MBC) is an essential tool to support model validation. If, for example, the modeller had added a flow draining a particular stock and this flow was supposed to then flow into another stock but the connection was not added, the mass balance check will show this as a loss of material from the system. Mass balance checks need to return a constant output over time (not necessarily zero). Due to rounding errors the mass balance checks may result in small, negligible, variations; these are acceptable.

5.3.2 Vensim Calibration Files

The calibration procedure currently runs over approximately 300,000 simulations and takes around 40 minutes to complete. Two files are required to be set up for calibration: a payoff definition file (VPD) and an optimisation control file (VOC).

Calibrated Variables (VPD File): First of all, the model requires time-series data for as many of the model variables as possible. To date, time series data for at least part of the period from 2001 to 2012 has been collected for seventeen variables. Each variable has a weight associated with it which reflects the order of magnitude of the time series; larger values are given lower weights so as to normalise them as equal in importance, as far as the calibration routine is concerned (shown in

Table 5-17). During future model development these weights should also reflect the *quality* of the time series used, with lower-quality time-series affording lower weights.

Table 5-17: Calibrated Values and their Weightings

Name	Weight
Reprocessor capacity rate	0.0000008
MRF capacity rate	5.555555 E-07
annual amount of plastic PRNs and PERNs issued	0.0000004
annual amount of plastic PERNs issued	0.0000005
annual amount of plastic PRNs issued	0.000001
plastic packaging waste going to domestic landfill	2.857142 E-07
plastic packaging waste going to incineration	0.000001
net gate fee	0.01
reprocessor imports	2.666666 E-06
"reprocessor unit feedstock cost (from MRF)"	0.001
reprocessing utilisation	0.22222222
MRF utilisation	0.26666666
PRF utilisation	0.30769230
PRF capacity rate	5.33333333 E-07
reported plastic packaging recycling rate	1
recycling obligation met	0.2
PRN Price	0.0066666

Each of these variables has a time-series equivalent in the data model that will read in required data from the data source file (in Excel) and produce the historical data set for comparison with the model-generated output. The data model processes data read from Excel files into a Vensim VDF (Vensim Data File) format. Since all VDF format files can be opened and viewed in Vensim, the historical time series can be viewed alongside the model-generated output in the same graph.

Calibration Parameters (VOC File): The calibration process uses Vensim's optimisation capabilities to minimise the difference between the historical time-series and model-generated results. The "payoff", therefore, consists of minimising the sum of the square of the differences across all of the variables listed above. Vensim will then vary a list of user-defined input assumptions (parameters) between sensible upper and lower limits, in order to find a combination that enables the best fit across those multiple variables. A full list of the parameters in the latest Vensim Optimisation Control (VOC) file is provided in APPENDIX C: Parameters, Range and Calibration Values for Variables in the PPR Model.

5.3.3 Calibration Results

This section provides results of the model calibration for thirteen of the key variables in the model. Note: All the figures in this section show historical datasets in red and the calibration results produced by the model in blue.

5.3.3.1 Household and Non-Household Plastic Packaging Waste Collected

Although the data provided for household and non-household waste collected only included packaging waste reported in the PRN system (for which a multiplier was needed to account for non-reported waste and losses in the supply chain), nevertheless it was useful to calibrate to this data prior to the adjustment made using this multiplier.

Figure 5-27: Calibration of Household Packaging Waste Collected (red=historical, blue=model calibration)

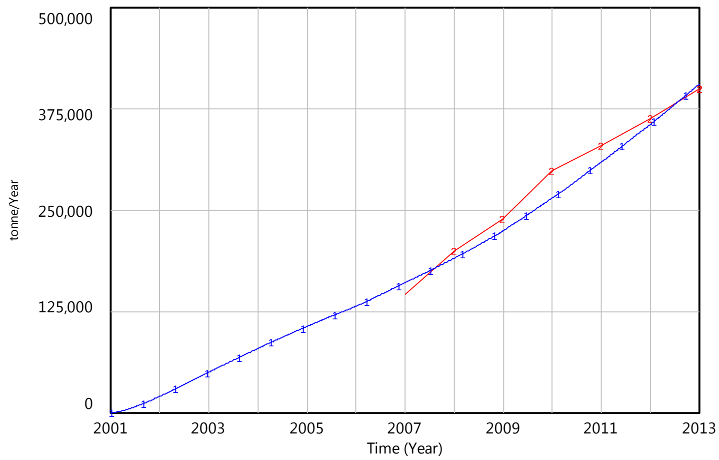
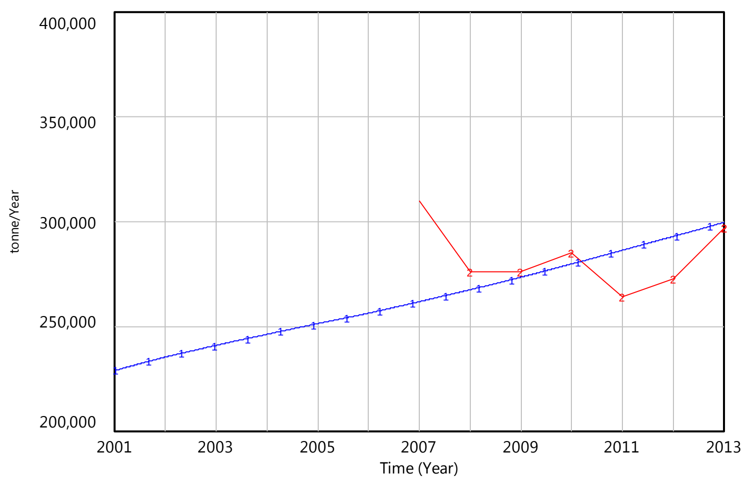


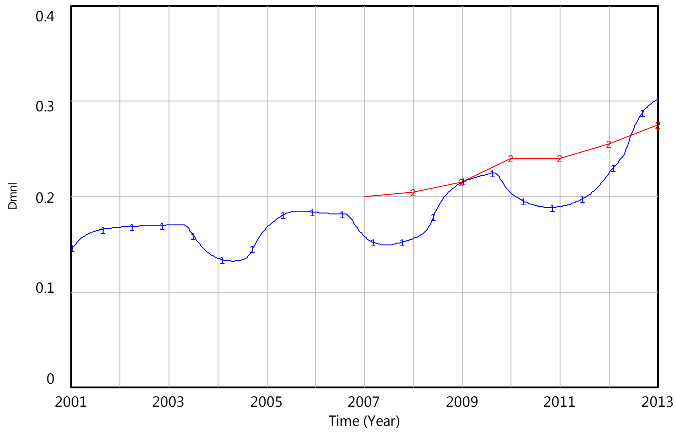
Figure 5-28: Calibration of Non-Household Packaging Waste Collected (red=historical, blue=model calibration)



5.3.3.2 Reported Recycling Rate

The reported recycling rate is measured as the ratio of reported PRNs and PERNs issued to reported plastic packaging waste arisings. PRNs are issued by reprocessors when they receive recyclates suitable for reprocessing. PERNs are issued by exporters of sorted material to be recycled overseas. Calculating the recycling rate should therefore be a simple process of recording the volume of material passing through the reprocessing system. However, not all reprocessors are accredited for the issuing of PRNs/PERNs, and of those facilities which are accredited, they may decide not to issue recycling notes all the time – typically they will not if the prevailing PRN/PERN price is low. This ratio, therefore, underestimates the actual recycling rate. Calibration to this historical time series was difficult, mostly due to the lack of sufficient (and well-defined) data on the volume of material collected for recycling. Data provided reflected the volume of PRNs/PERNs issued, and so an adjustment had to be made to account for the volume of material passing through without PRNs/PERNs being issued, plus an allowance for rejections due to quality issues such as contamination. The cyclic nature of the model results are caused (in the model) by the reactions of those issuing PRNs/PERNs, and these reactions are, in turn, due to changes in the prices for PRNs and PERNs. The historical data, however, suggests that the behaviour displayed by the model may be in error since the reported recycling rate does not display this cyclic behaviour; this will require further investigation.

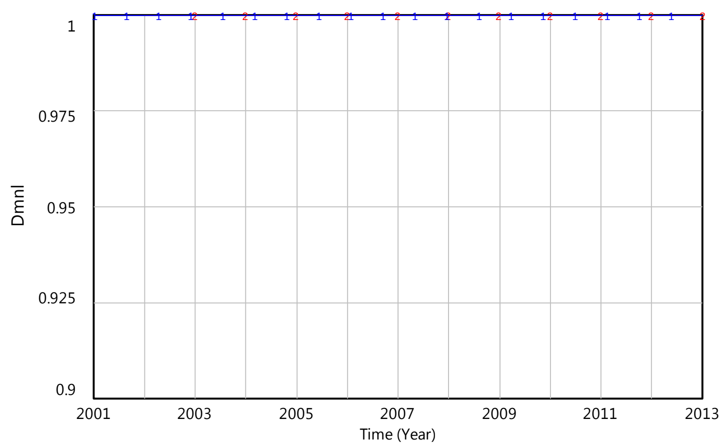
Figure 5-29: Calibration of Reported Recycling Rate (red=historical, blue=model calibration)



5.3.3.3 Recycling Obligation Met

This metric accounts for the volume of PRN/PERN purchases relative to the obligations set out by government. Evidence suggests that this has been 100% up until the present day, and the calibration reflects this well.

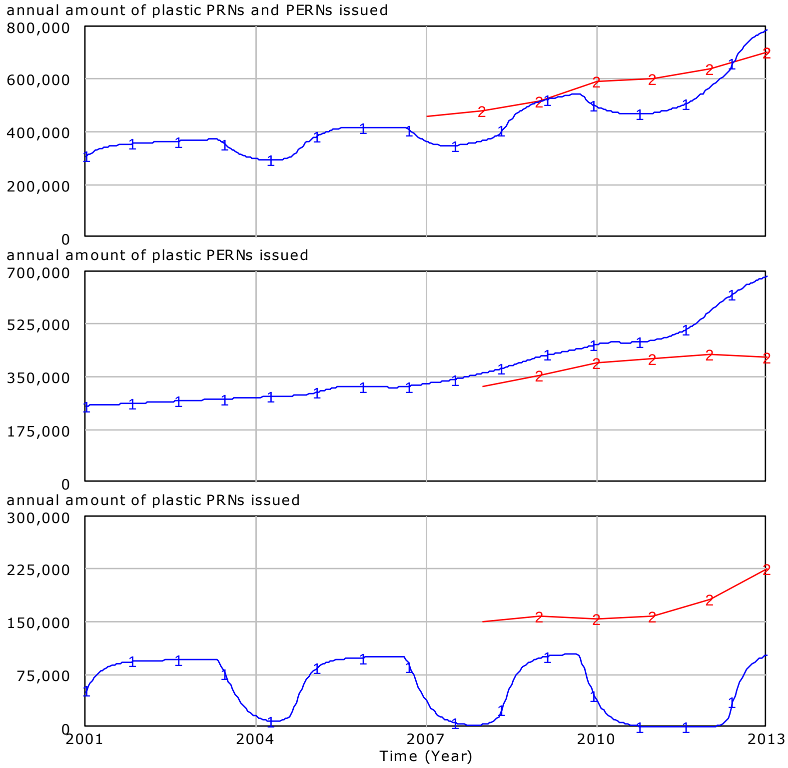
Figure 5-30: Calibration of Recycling Obligation Met (red=historical, blue=model calibration)



5.3.3.4 Issuing of PRNs and PERNs

Good data exists for the annual volume of PERNs and PRNs issued, although the calibration shows a poor match for volumes of PRNs and PERNs when viewed separately. This could be due to the lack of sufficient data on historical drivers for MRF, PRF and Reprocessor participation in the PRN process (as a result of fluctuating PRN price). If the PRN/PERN issue data is accurate, this could cast doubt on the hypothesis driving cyclic behaviour in PRN price (5.3.3.5); this requires further study. Figure 5-31 shows three graphs of, respectively, annual amount of plastic PRNs and PERNs issued, annual amount of plastic PERNs issued, and annual amount of plastic PRNs issues.

Figure 5-31: Calibration of PERN/PRN Issues (red=historical, blue=model calibration)



5.3.3.5 PRN Price

Analysis of historical PERN and PRN price data revealed a cyclical rising and falling of prices. A dynamic hypothesis was formed to explain this pattern: If demand for PERNs/PRNs increases then, given no change in supply, availability becomes short and prices rise. Issuers, given the cost of accreditation and administration, increase the proportion of the volume exported / reprocessed as PERNs/PRNs respectively, increasing availability in the market. This increased availability takes time to be realised and eventually leads to a dampening and then reversal of the price rise. As PRN prices fall below a certain level, fewer producers issue fewer PERNs/PRNs, thus shortening supply. Eventually, supply becomes short once more and prices rise as a direct result. The overall effect is of market price instability which is common in similar commodity systems where investments in capacity can rise above the level justified by the prevailing unit revenues, resulting in cyclical over capacity and collapse in prices. In this case it is not the producers' capacity that is responsible for this behaviour, but their investment in issuing (or otherwise) recycling notes. This supply/demand interaction (negative feedback loop), coupled with delays in the system, seems to determine the cyclical nature of the PRN/PERN price.

Figure 5-32 shows the main feedback loop and delays responsible for this behaviour (as a high-level overview), while Figure 5-33 illustrates the goodness-of-fit for PRN price, with a periodicity of approximately 3.5 years.

Figure 5-32: Overview of PRN Stock Price Oscillation

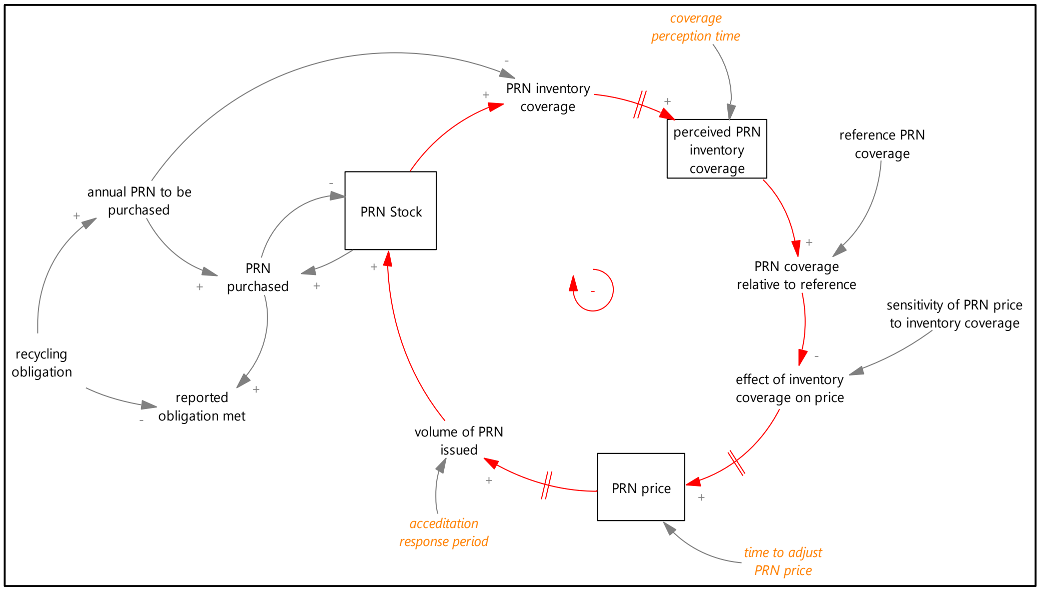
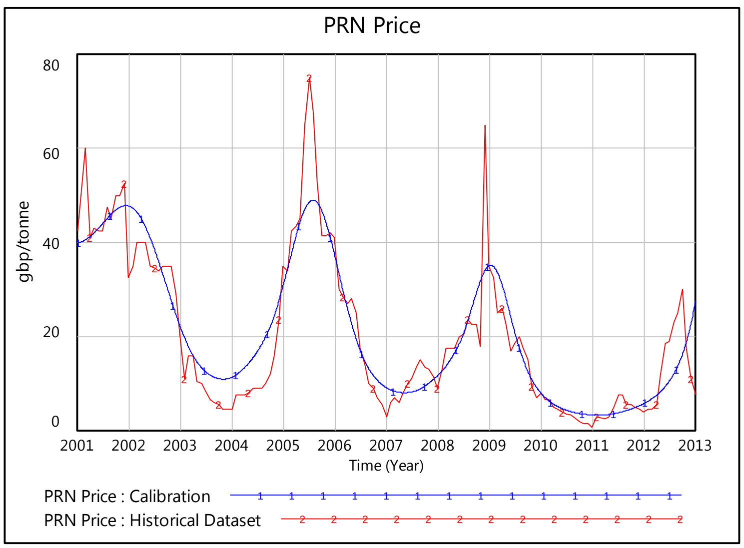


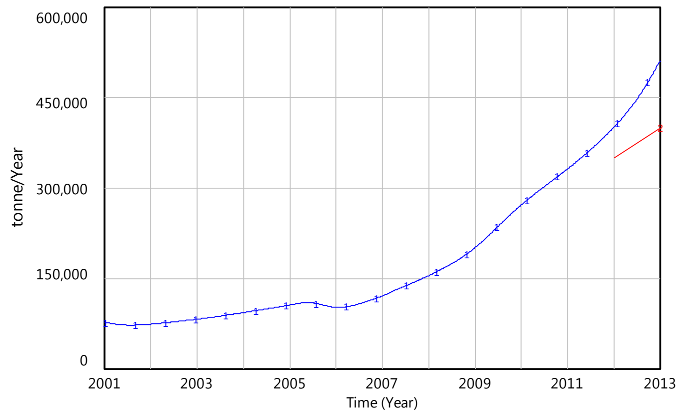
Figure 5-33: Calibration of PRN Price (red=historical, blue=model calibration)



5.3.3.6 PRF Capacity

Data for PRF capacity was found only for the years 2011 and 2012 (model time is 2012, representing the end of 2011 or beginning of 2012) at 350,000 and 400,000 tonnes/year. Partly due to the limited data points available for calibration, the PRF capacity has been slightly overestimated by the model.

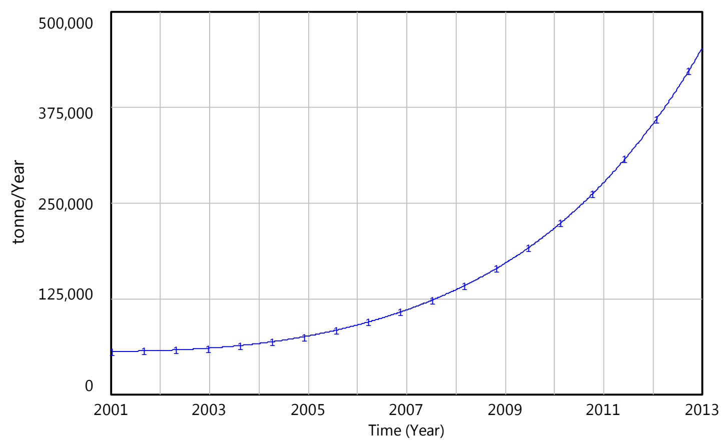
Figure 5-34: Calibration of PRF Capacity (red=historical, blue=model calibration)



5.3.3.7 MRF Capacity

Data for MRF capacity was found only for the year 2011 (model time is 2012, representing the end of 2011 or beginning of 2012) at 360,000 tonnes/year.. The calibrated time series passes close to this point in 2012, although a greater number of data points would be beneficial.

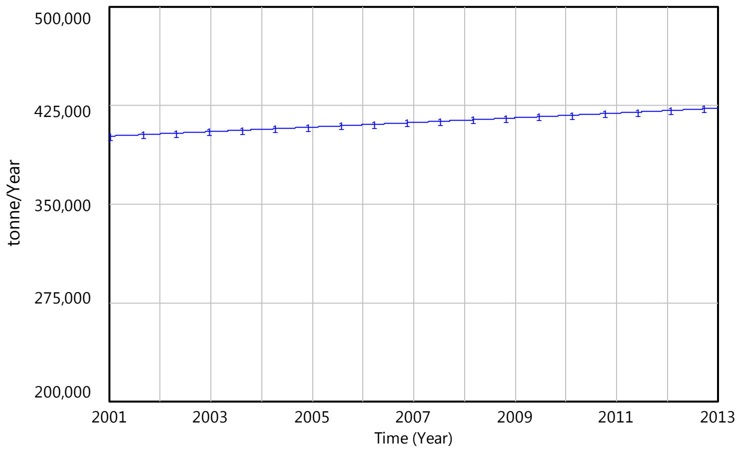
Figure 5-35: Calibration of MRF Capacity (red=historical, blue=model calibration)



5.3.3.8 Reprocessor Capacity

Data for Reprocessor capacity was found only for the year 2011 (model time is 2012, representing the end of 2011 or beginning of 2012). Historical data for Reprocessor capacity was 378,460 tonnes/year in 2012. The calibrated time series slightly over-estimates the capacity. As with all other calibration variables with insufficient time-series data, data gathering will need to be enhanced in order to further enable the calibration process.

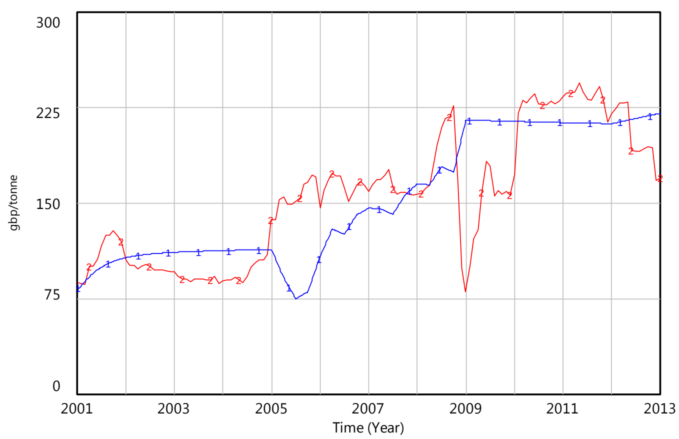
Figure 5-36: Calibration of Reprocessor Capacity (red=historical, blue=model calibration)



5.3.3.9 Reprocessor unit feedstock cost (from MRF)

Since the model does not currently distinguish between different types of plastic packaging waste, an average price across all types was used for the historical time series. This metric represents the price paid to MRFs/PRFs by UK reprocessors for their output. Prices are in the right order of magnitude but do not track the variations in the historical data very well. This could be improved by including the influence of GDP per capita, and the relationship with desired profits to be made at each stage in the supply chain.

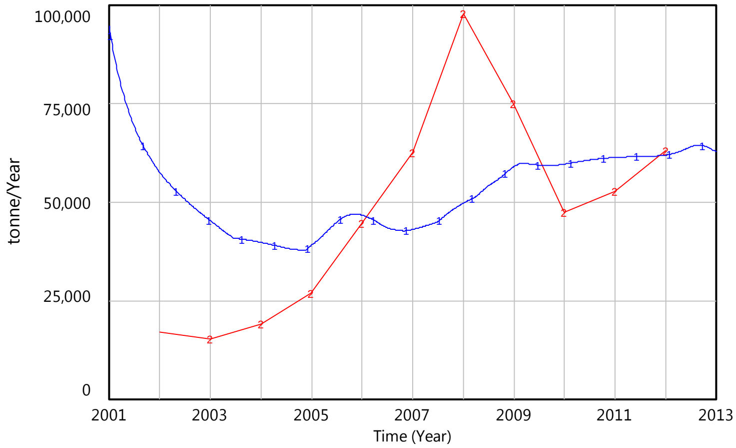
Figure 5-37: Calibration of Price of Sorted Plastics (red=historical, blue=model calibration)



5.3.3.10 Reprocessor Imports

Data on reprocessor imports was obtained for 2001 through to 2011. Calibration of this parameter was for the purpose of ensuring a correct relative balance between reprocessor feedstock acquired domestically or imported. The dynamics of this balance have yet to be investigated in full and may be improved with the expansion of the model to include import/export dynamics in more detail. At the very least, the spike in historical data for the year 2008 (or more rather, the collapse in imports after 2008) needs to be investigated.

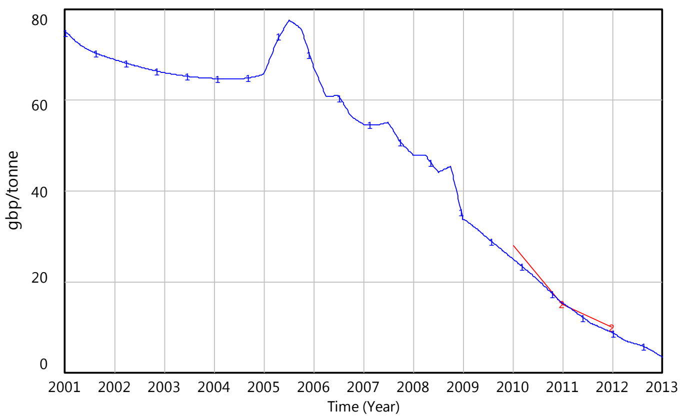
Figure 5-38: Calibration of Reprocessor Imports (red=historical, blue=model calibration)



5.3.3.11 Net Gate Fee

This is the fee charged by MRFs (on average) per tonne of material they accept for sorting. Historical data was provided for 2009, 2010 and 2011 and the model fit can be seen in the graph below. The downwards trajectory indicates an increase in the value of material to be recycled and suggests a future in which LAs may receive an income from MRFs, as demand from MRFs (and others) increases and supplies become scarce.

Figure 5-39: Calibration of Net Gate Fee (red=historical, blue=model calibration)



A final note on calibration: The model is currently a work in progress and, since systems such as the plastic packaging recycling system are interconnected and holistic in nature, it follows that further work will be required to improve the calibration results provided in this section. Indeed, much would be gained from the identification and use of additional time-series data for the system during the next stage of model development.

5.4 Policy Scenarios

The calibrated model was used to evaluate how the behaviour of the system (as represented by the model) is likely to change in response to changes in input assumptions and policies. There is a vast array of possible assumptions and policies that could be tested with such a model; a small number were chosen to be run as scenarios and are discussed in this section.

5.4.1 Scenario Development

For the purpose of evaluating the usefulness of the model it was decided to enable the "what if" analysis to take place over the entire date range of the simulation – from 2001 to 2018. In general, it may be preferable to run a model in the period for which there is historical data (in this case, 2001 to 2012) to faithfully replicate this data, and then allow policies and assumptions to change only in the forecast period of the simulation. This model, however, is in the early stages of development and use, and it was thought more useful to examine the model behaviour as it diverges from the known historical trajectory over the historical period and a little into the future.

In order to run multiple scenarios sequentially, without having to resort to multiple hands-on interactions with the modelling environment using the dashboards and other interaction methods, Vensim provides a scripting language in the form of commands compiled into command script files. A script has been created for the four scenarios discussed below (DEFRA Scenarios Script Ventana 002.cmd). Commands within the script enable assumptions to be changed and simulations performed with no user intervention. There are three "what if" scenarios and a baseline scenario, which is the calibrated model run to 2017 instead of stopping at 2012 (i.e. beyond the period for which there is historical data), using baseline assumptions and the best calibration values found during the calibration process. These scenarios are not an indication of future policy development and should not be considered separately from this project.

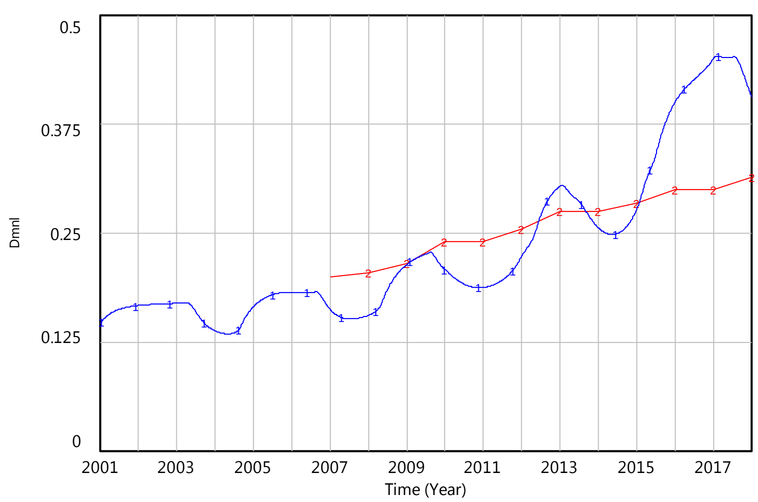
5.4.2 Baseline Scenario

The baseline scenario assumes no changes to the current assumptions including the latest packaging targets to 2017. Presented below are the key outputs from the model for the period 2001 to 2017. A summary table of the values used for variables in the baseline simulation is shown in Appendix D.

5.4.2.1 Baseline Reported Recycling Rate

The reported packaging recycling rate exceeds the estimates assumed in the historical and forecast data projected over the 2015 to 2018 period.

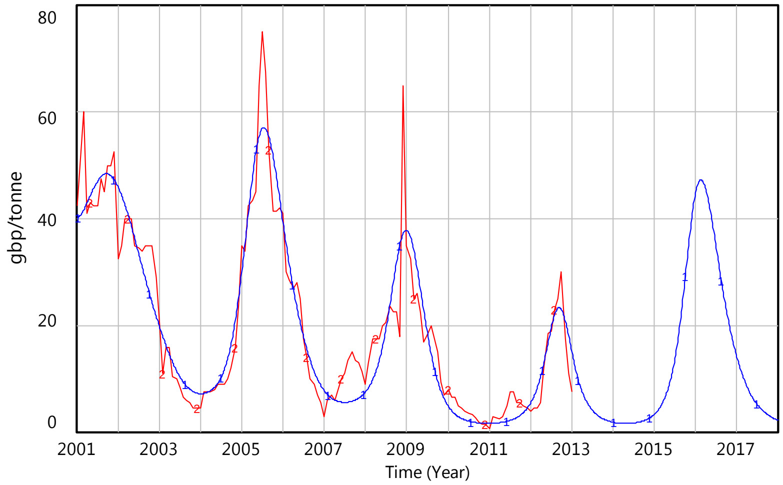
Figure 5-40: Baseline Reported Recycling Rate (baseline in blue, historical in red)



5.4.2.2 Baseline PRN Price

The PRN price continues to fluctuate and produces a further price spike at the end of 2015/ beginning of 2016, maintaining the approximately 3.5 year frequency of cyclic behaviour. The amplitude of this additional price spike is higher than previously, as a result of a much steeper increase in the volume of material coming under obligation after 2013 due to the increase in the targets. The steeper increase causes a larger imbalance in the system and triggers a stronger response.

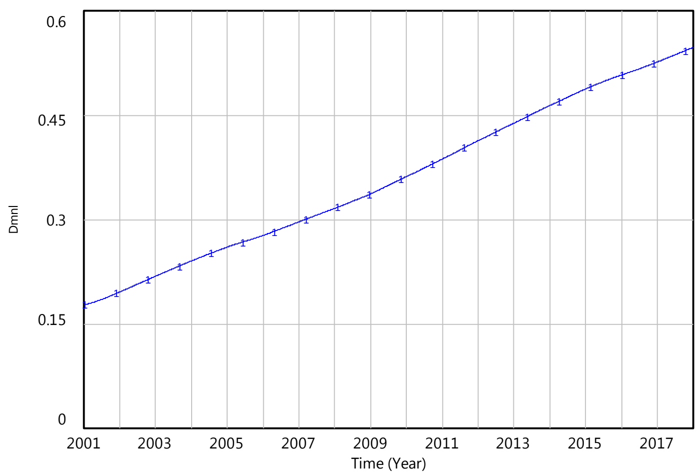
Figure 5-41: Baseline PRN Price (baseline in blue, historical in red)



5.4.2.3 *Baseline Actual Recycling Rate*

The actual recycling rate achieved (fraction of plastic packaging waste collected for recycling) continues to grow and reaches 55% by the end of 2017.

Figure 5-42: Baseline Actual Recycling Rate



5.4.2.4 *Baseline Cost to Local Authorities*

The total LA cost of disposal of plastic packaging waste continues to rise until sometime in 2014, when total costs decline to pre-2001 levels. The causal graphs shown in Figure 5-44 illustrate the reasons why. Landfill costs account for the "jagged" nature of total costs as each increase in landfill tax is implemented, but the combination of increasing diversion of waste into the recycling system and continuing reduction in net gate fees charged by MRFs, plus revenues from the sale of separated material to PRFs (negative costs), are responsible for the eventual downward trend in LA costs.

Figure 5-43: Baseline Cost to Local Authorities,

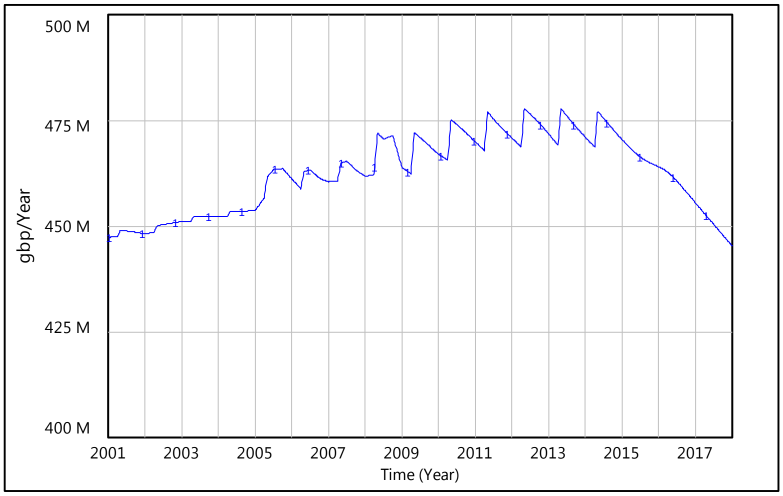
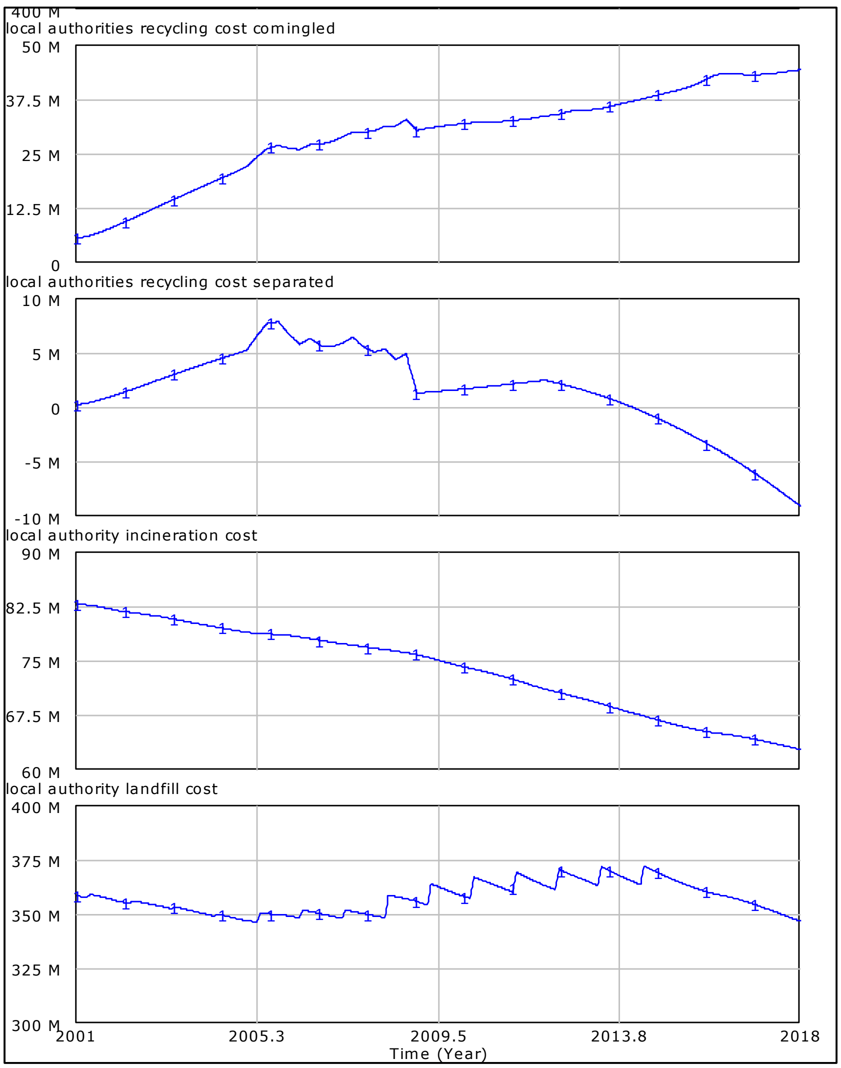


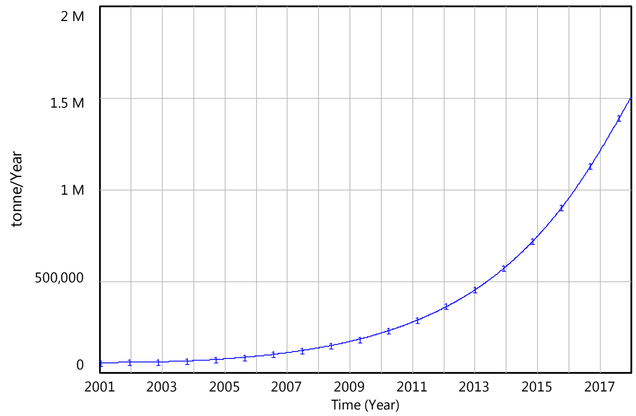
Figure 5-44: Baseline LA Recycling Cost Comingled, LA Recycling Cost Separated, LA Incineration Cost, LA Landfill Cost



5.4.2.5 Baseline MRF Capacity

MRF capacity continues to increase, from 450,000 tonnes/year at the end of 2012, to 1.5 M tonnes/year by the end of 2017, a rise of 230%. Revenues rise from M£56 to over M£100.

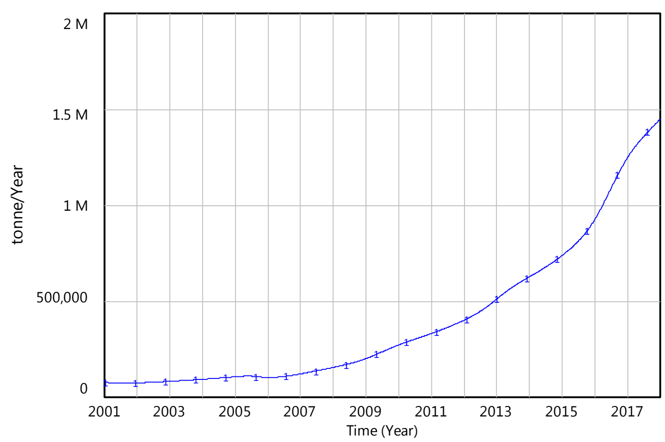
Figure 5-45: Baseline MRF Capacity



5.4.2.6 Baseline PRF Capacity

PRF capacity also continues to rise from a little over 500,000 tonnes/year in 2012 to 1.45 M tonnes/year in 2017, a rise of 190% with revenues also increasing from M£79 to M£255 over the same period. The increased generation of material (from collection of commercial and household plastic packaging waste) increases the throughput of material in the system, driving up potential profitability.

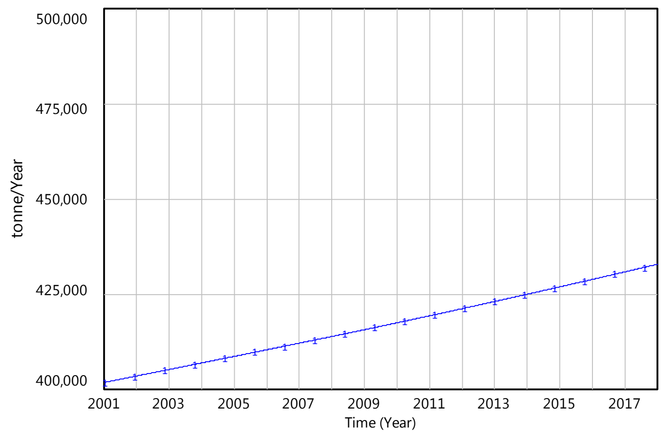
Figure 5-46: Baseline PRF Capacity



5.4.2.7 Baseline Reprocessor Capacity

Capacity increase in the reprocessing industry is more linear and reflects the simplistic nature of recycled plastic demand in the model, whereby a simple initial value and annual growth parameter are used to fit to historical data. Capacity rises from 423,000 tonnes/year to 433,000 tonnes/year over the period 2013 to 2017.

Figure 5-47: Baseline Reprocessor Capacity



5.4.3 Scenario A: Reduction in Overseas Demand for UK Plastic Recyclates

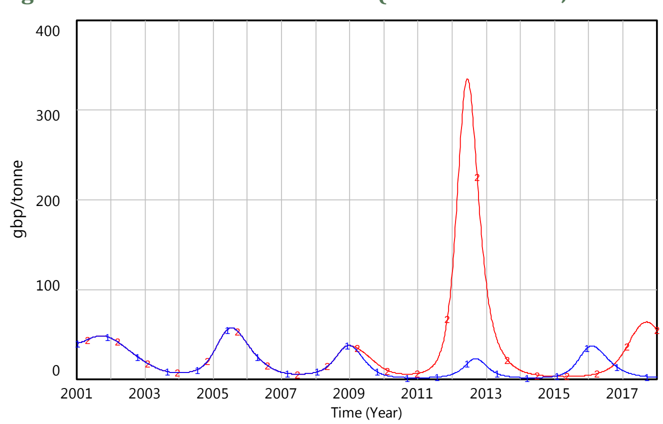
Purpose: This is an attempt to represent the impact of reduction in demand for output from UK MRFs as global requirements for increased plastic quality rise.

Assumption: At the start of 2009, overseas demand for material sorted by MRFs and PRFs is reduced by 50% and remains so for the duration of the simulated period.

5.4.3.1 Scenario A PRN Price

As a result of the decrease in demand from overseas, less volume of PERNs are issued, leading to a large spike in the PRN price during 2012 as supply becomes short. This leads to an increase in the revenue MRFs can generate from the remaining exports market and tends to mitigate the losses from the 50% reduction in demand. Unit revenues from the remaining 50% are increased and are more favourable than supply to domestic PRFs and reprocessors.

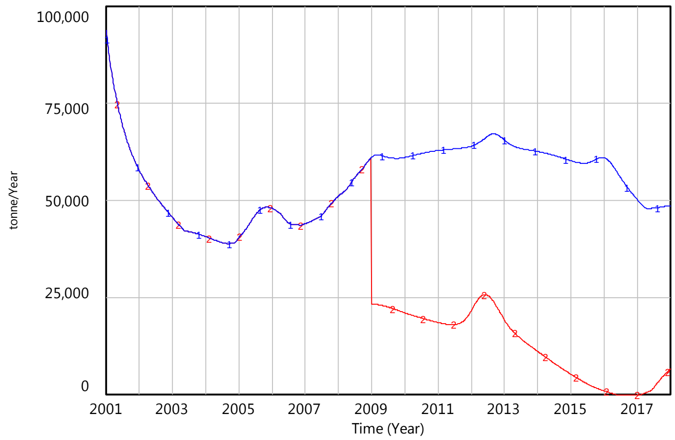
Figure 5-48: Scenario A PRN Price (baseline in blue, scenario A in red)



5.4.3.2 Scenario A Reprocessor Imports

As export demand of MRFs is reduced, more volume is shifted towards domestic PRFs and, as a result, imports made by PRFs are also reduced. The same is observed for reprocessor imports; reduction in overseas demand for MRF and PRF output make more of that output available to domestic reprocessors and so imports drop accordingly.

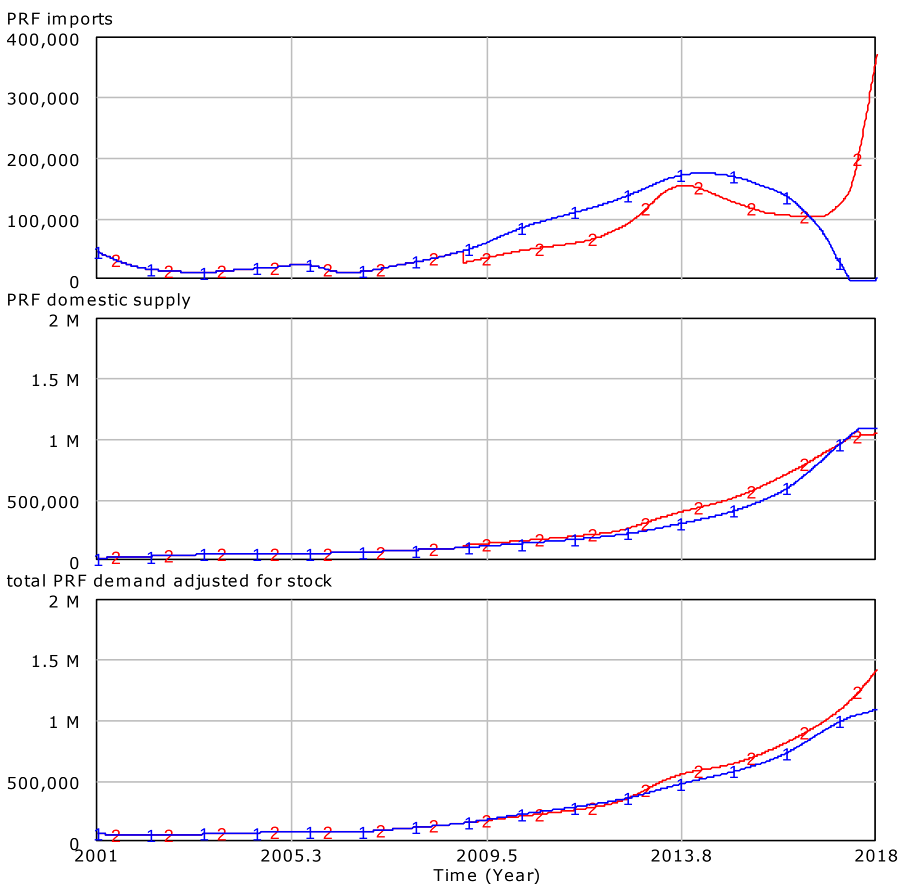
Figure 5-49: Scenario A Reprocessor Imports (baseline in blue, scenario A in red)



5.4.3.3 Scenario A PRF Imports

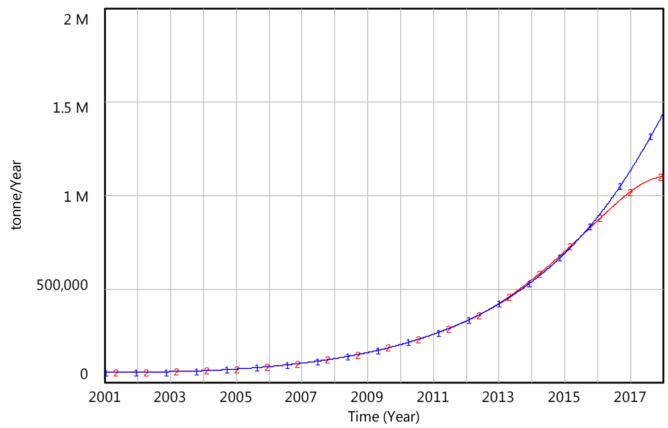
Changes in the import of materials to PRFs are a little more complicated than for reprocessors. Initially the imports are reduced as MRFs supply greater volumes to PRFs, but a combination of greater PRF demand (from MRFs, due to a drop in export demand of PRFs) and a lowering of MRF capacity leads to a resumption in the increase of PRF imports over the baseline scenario. Figure 5-50 shows PRF imports, PRF domestic supply, and PRF demand adjusted for slack.

Figure 5-50: Scenario A PRF Imports Causal Graphs (baseline in blue, scenario A in red)



5.4.3.4 Scenario A MRF Capacity

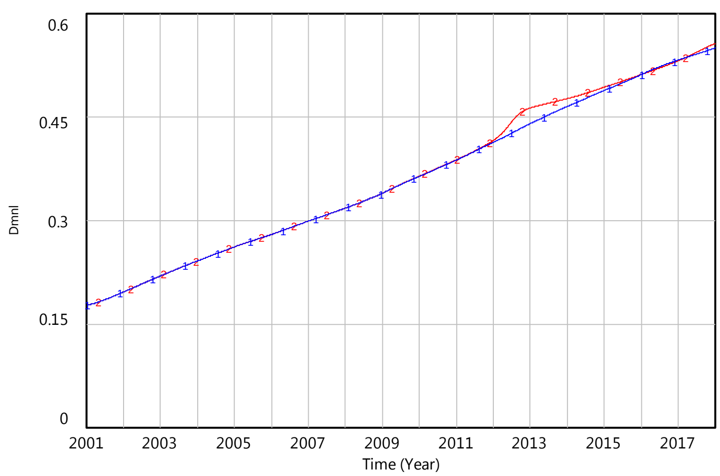
Figure 5-51: Scenario A MRF Capacity (baseline in blue, scenario A in red)



5.4.3.5 Scenario A Actual Recycling Rate

The actual recycling rate increases marginally due to a temporary decrease in the charges made by MRFs to LAs.

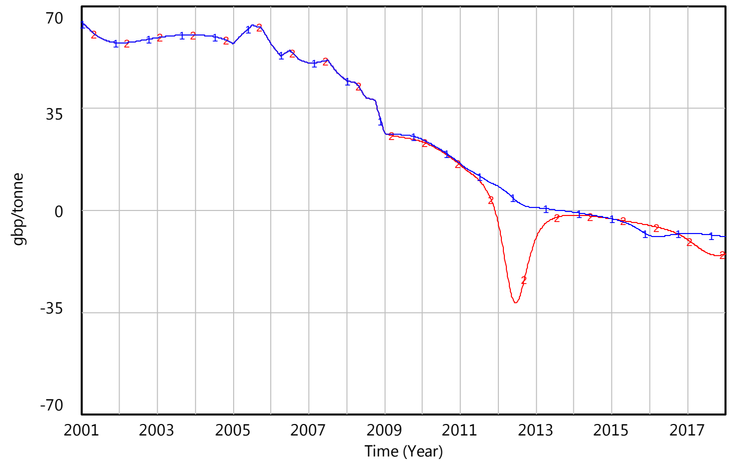
Figure 5-52: Scenario A Actual Recycling Rate (baseline in blue, scenario A in red)



5.4.3.6 Scenario A Net Gate Fee

The model makes the assumption that MRFs are able to discount the price they charge PRFs and reprocessors for their output by some fraction of the prevailing PERN price (*fraction of PERN income passed on*). During the noted spike in PERN/PRN price, this allowed for deep discounts and resulted in the relative cost of collection for recycling dropping below that observed in the baseline.

Figure 5-53: Scenario A Net Gate Fees (baseline in blue, scenario A in red)



5.4.4 Scenario B: Improved Household Plastic Recycling Participation

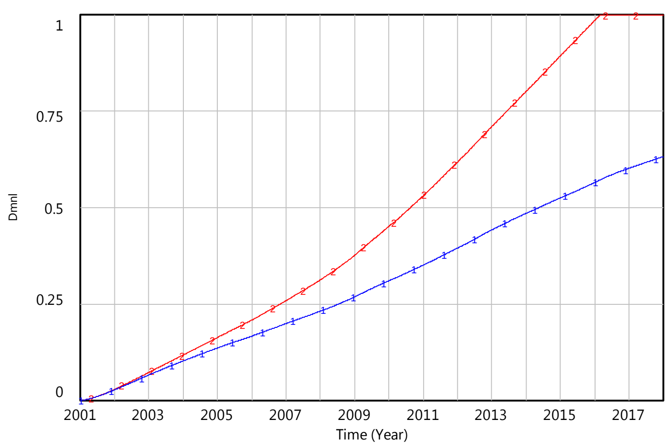
Purpose: To evaluate the impact on the system of increasing the fraction of plastic packaging material collected by local authorities for recycling.

Assumption: A multiplier of the prevailing collections fraction (endogenous and influenced by relative recycling cost) grows at a rate of 5% per annum.

5.4.4.1 Scenario B Actual Recycling Rates

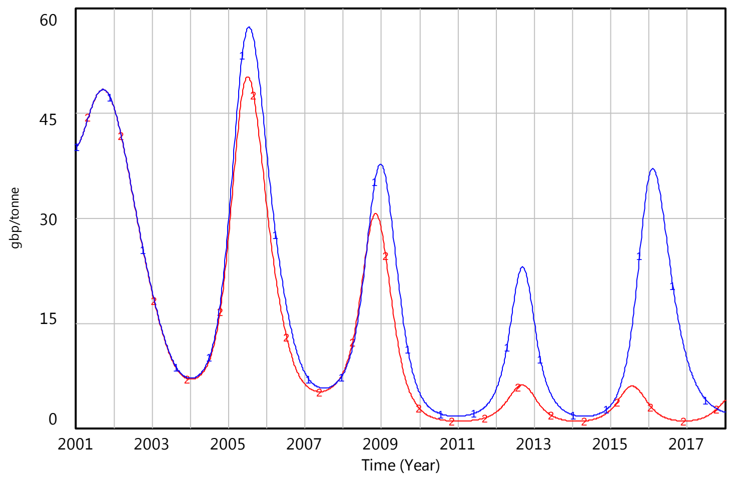
The actual household recycling rate in this extreme-condition scenario reaches 100% by the end of 2016 while the overall (household and commercial) actual recycling rate reaches 76%. The reported recycling rate, however, fluctuates around the same value as in the baseline as participation in the PRN system fluctuates. Exports of materials are increased as the flow-through from consumers is increased, but participation in the PRN system is suppressed (below the baseline) as a result of lower PRN prices. The reasons for the fluctuation in participation need to be examined more closely as it may be possible that the hypothesis relating participation with PRN price fluctuations is has not been captured accurately.

Figure 5-54: Scenario B Actual Recycling Rate (baseline in blue, scenario B in red)



5.4.4.2 Scenario B PRN Price

Figure 5-55: Scenario B PRN Price (baseline in blue, scenario B in red)



5.4.4.3 Scenario B MRF and PRF Capacity

Both MRF and PRF capacity increase above the baseline case, reflecting the increased throughout and profitability of operations. Reprocessor capacity remains unchanged as the simple demand assumptions for reprocessed plastics are unchanged.

Figure 5-57: Scenario B MRF Capacity (baseline in blue, scenario B in red)

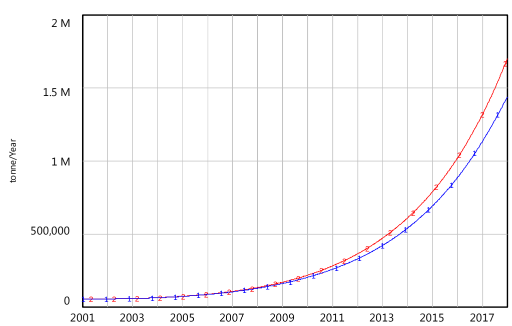
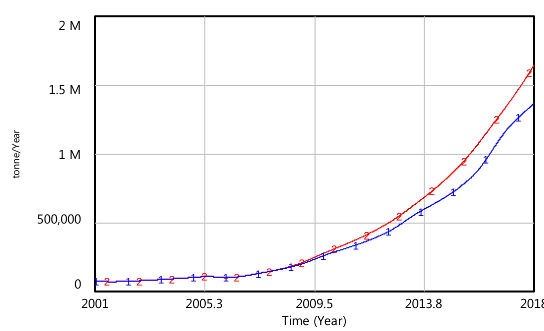


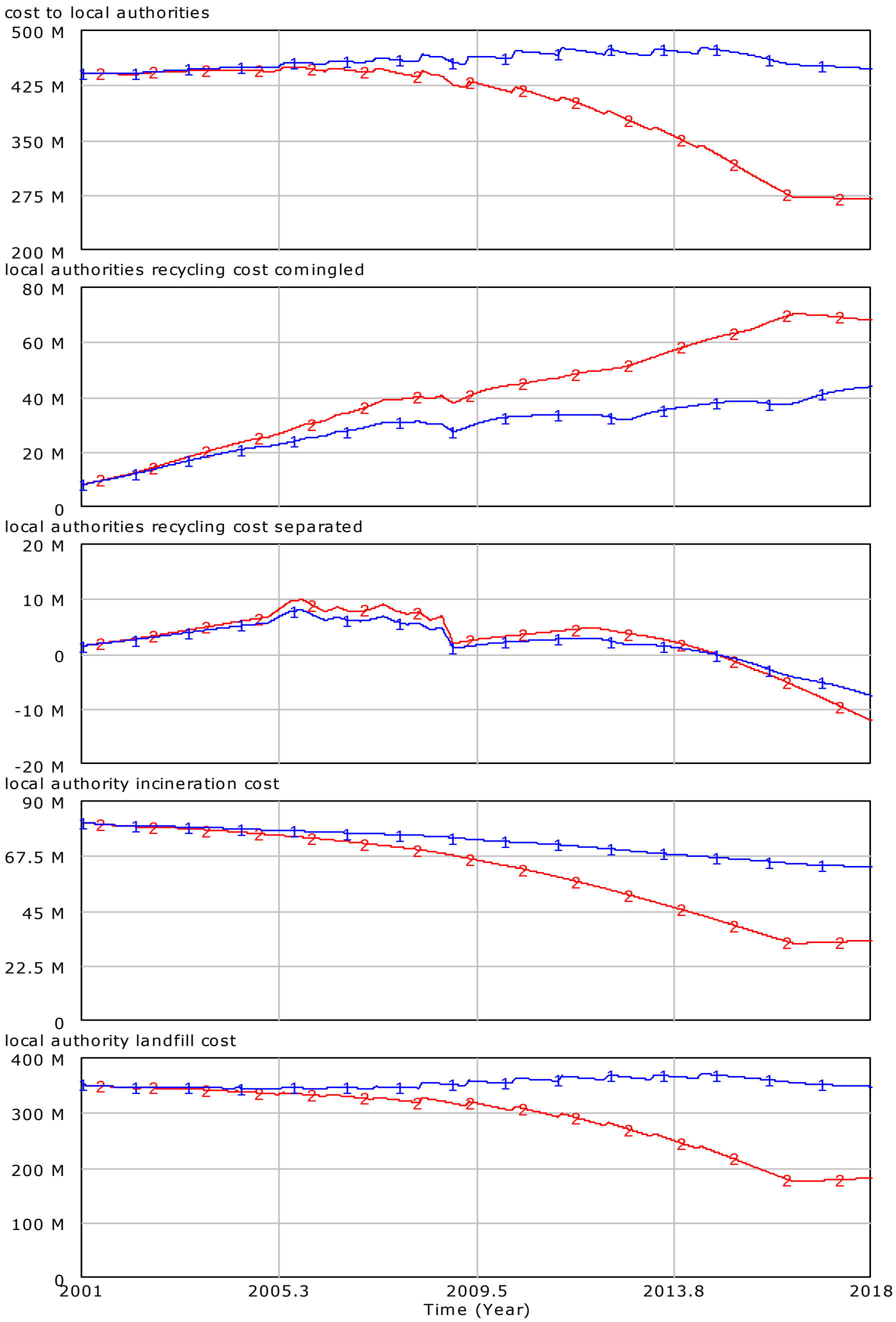
Figure 5-56: Scenario B PRF Capacity (baseline in blue, scenario B in red)



5.4.4.4 Scenario B Stakeholder Costs

Costs to LAs are highly influenced by the assumption changes in this extreme-case scenario. Increased participation in plastic packaging recycling results in significant reductions in costs, as the balance between cost of landfill, etc. and recycling change. In the latter case, costs turn to revenue as volumes increase and the revenue paid per tonne rises above the collection costs. The causal graphs below show the contributing costs, and it can be clearly seen that, although the cost of collection of co-mingled waste rises, the cost of landfill and incineration drop while the "cost" of collection of kerbside separated plastic packaging turns into a revenue as prices paid by reprocessors increase.

Figure 5-58: Scenario B Cost to LAs (baseline in blue, scenario B in red)

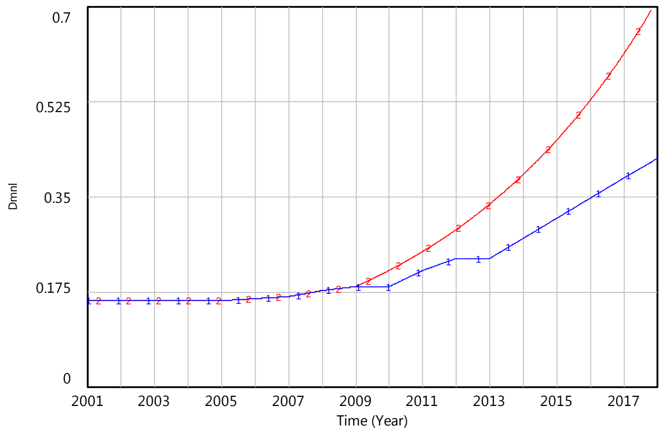


5.4.5 Scenario C: Higher Obligation Targets

Purpose: Investigate the system response to increased obligations of plastic packaging users (not consumers).

Assumption: From 2009, obligations to purchase PRNs and PERNs rise by 15% per annum (shown in Figure 5-59).

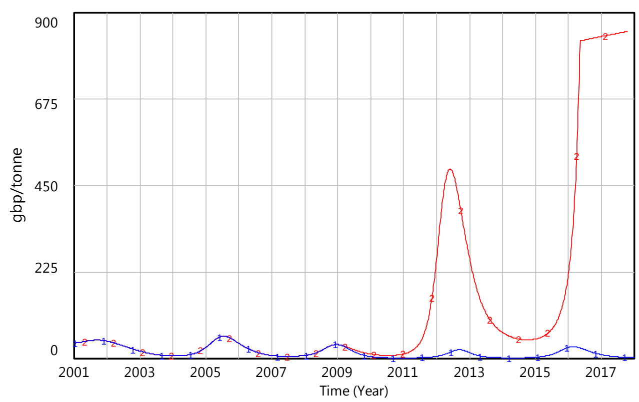
Figure 5-59: Scenario C Plastic under Obligation (baseline in blue, scenario C in red)



5.4.5.1 Scenario C PRN Price

The volume of PRNs/PERNs purchased relative to the volume of plastic packaging arisings (reported recycling rate) increases over the baseline scenario, as expected. The obligations are met for the entire period as both the volume of PRNs and PERNs issued increases in response to the PRN price signal; a greater fraction of material processed in the industry comes under the PRN scheme.

Figure 5-60: Scenario C PRN Price (baseline in blue, scenario C in red)



5.4.5.2 Scenario C Actual and Reported Plastic Recycling Rates

In the case of the actual recycling rate (ratio of material collected for recycling to total arisings), this is increased only slightly, in direct response to the savings passed down to LAs through PRN payments. In the baseline scenario, the real recycling rate was much higher than the reported, while here it is somewhat lower. This indicates that measuring recycling rates through the PRN system can often provide an inaccurate picture of what is happening in reality..

Figure 5-62: Scenario C Reported Recycling Rate (baseline in blue, scenario C in red)

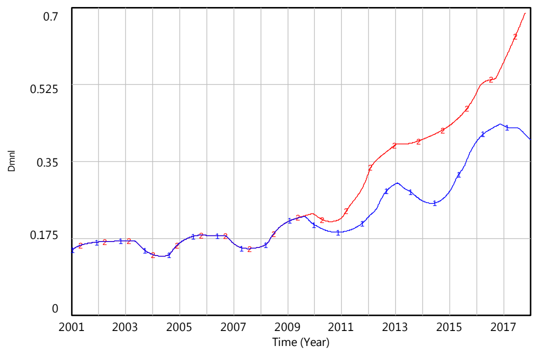
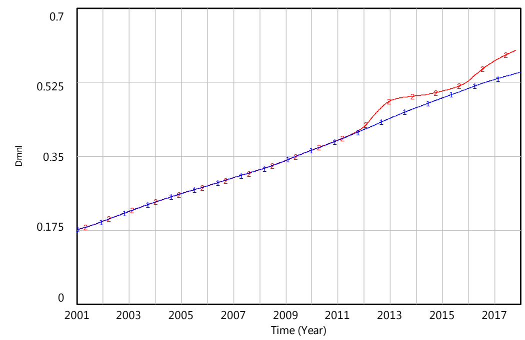


Figure 5-61: Scenario C Actual recycling rate (baseline in blue, scenario C in red)



5.4.5.3 Scenario C MRF and PRF Capacity

The increase in obligations results in more pressure on the PRN market and the resulting increase in PRN price brings rewards to exporters of material. Both MRF and PRF capacity increases with these increases in profit, the former as a result of increased throughput in addition to increased profits from PERN sales, while the latter benefits also from increased demand and profits from PERN sales.

Figure 5-64: Scenario C MRF Capacity (baseline in blue, scenario C in red)

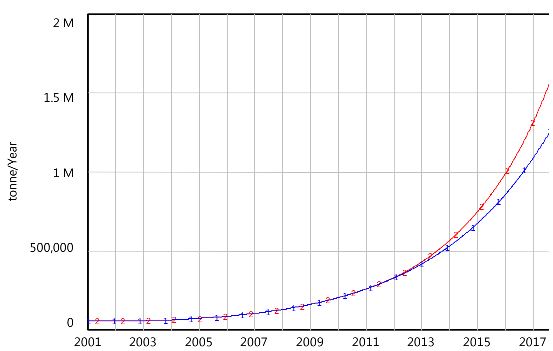
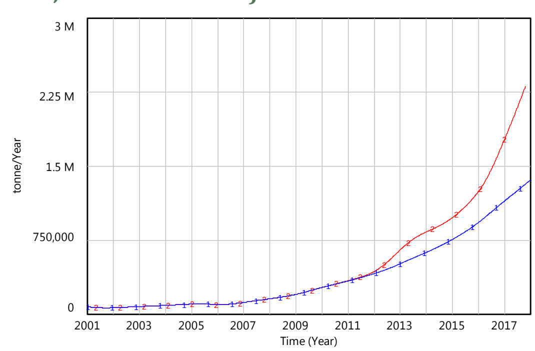


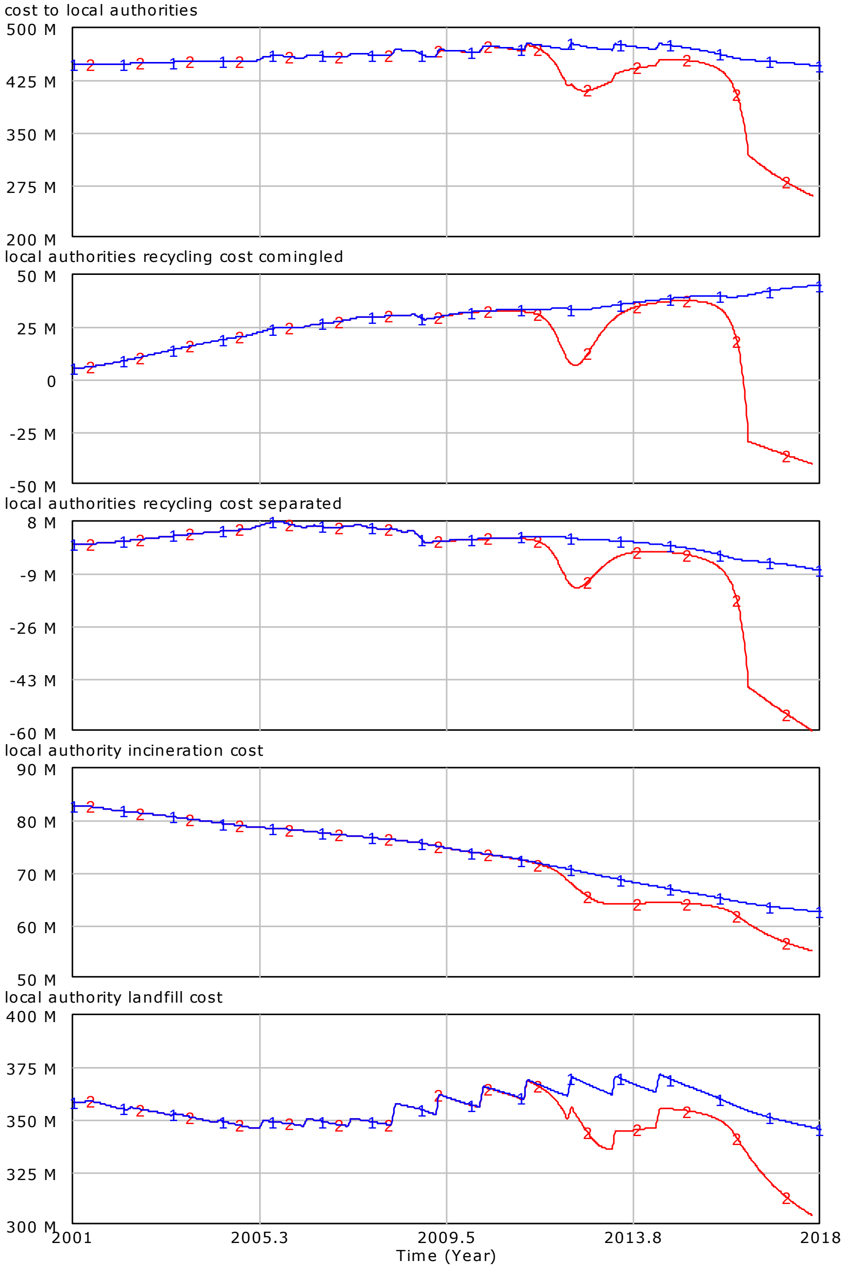
Figure 5-63: Scenario C PRF Capacity (baseline in blue, scenario C in red)



5.4.5.4 Scenario C Local Authority Costs

Costs to LAs are much reduced as large PERN/PRN profits filter down, to their benefit. LAs benefit from lower charges/higher prices paid for material due to high PRN/PERN prices and the fraction of PRN/PERNs being passed down.

Figure 5-65: Scenario C Local Authority Costs Causal Graphs (baseline in blue, scenario C in red)



5.4.6 Scenario D: Increased Price of Recycled Plastic

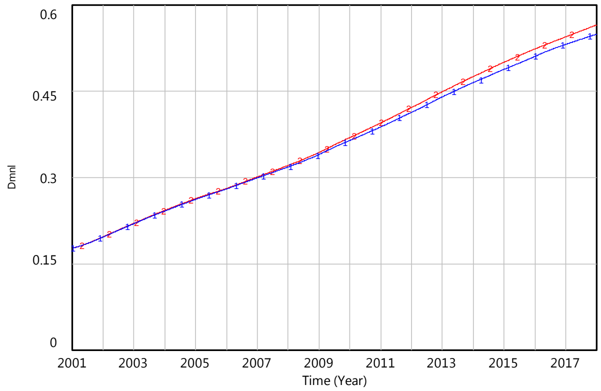
Purpose: To test the impact of a greater price for reprocessed plastics (in response to greater virgin plastic prices)

Assumption: Recycled plastic prices are 10% higher than in the baseline.

5.4.6.1 Scenario D Actual Plastic Packaging Recycling Rate

This simple test of the model leads to a modest increase in the actual recycling rate as the higher prices lead to increased profits for reprocessors which then filter down to lower charges from (and, eventually, higher prices paid by) MRFs to local authorities and private companies collecting from commercial clients.

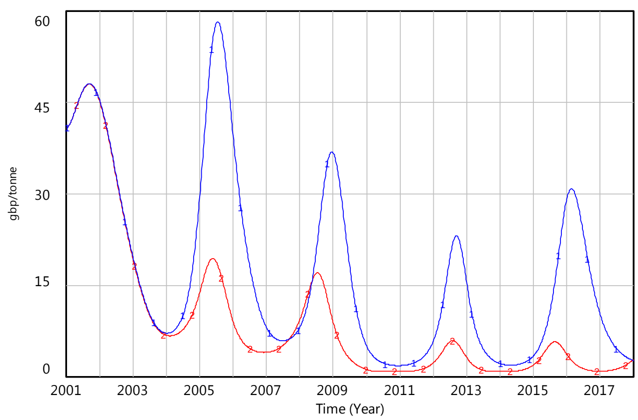
Figure 5-66: Scenario D Actual Plastic Packaging Recycling Rate (baseline in blue, scenario D in red)



5.4.6.2 Scenario D PRN Price

PRN prices are suppressed under this scenario as inventory coverage varies to a lesser degree than in the baseline scenario, due to the higher prices filtering down as revenues from reprocessors to MRFs and PRFs. PRFs are able to increase capacity more quickly than in the baseline and, consequently, export more and issue more PERNs. This small difference in the early years of the simulated period depresses PRN prices to such a degree that small changes in supply/demand balance (that had previously been responsible for large oscillations in PRN price) result in smaller PRN price oscillations. Again, this warrants a closer look at the relationship between PRN price and the issuing of PRNs/PERNs as well as the assumptions made on overseas demand.

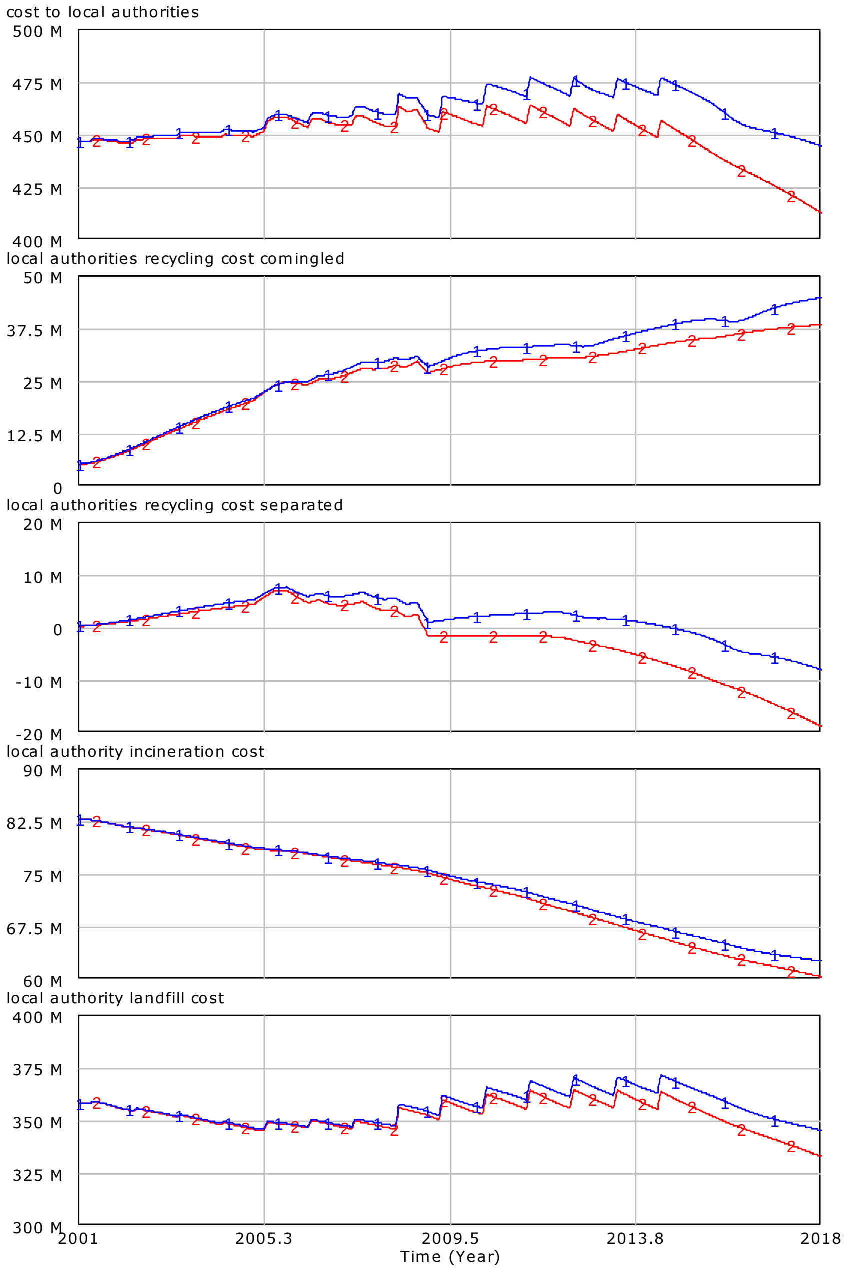
Figure 5-67: Scenario D PRN Price (baseline in blue, scenario D in red)



5.4.6.3 Scenario D Cost to Local Authorities

Higher prices paid for recycled plastic filter down though the supply chain (upstream) and reduce all aspects of LA costs. Higher prices paid mean lower gate fees for co-mingled material and higher prices paid for kerbside separated plastic packaging. In addition, the relative cost of recycling declines (due to the above-mentioned results), the proportion of LAs collecting packaging waste increases, and the overall volume diverted to landfill decreases.

Figure 5-68: Scenario D Cost to LAs Causal Graphs (baseline in blue, scenario D in red)



5.5 Sensitivity Analysis

It is useful to analyse the sensitivity of the results from the model to changes in the data input assumptions. By varying the values of input assumptions and monitoring the change in the metrics of interest a picture of the sensitivity of the model to data assumptions emerges. This is achieved here by using the Vensim optimiser, which comprises the following tasks:

- Runs an automatic "parameter percent" sensitivity analysis which takes each input and modifies it by plus then minus a certain percentage (20% is chosen in this example).
- Runs a simulation and records the change in the selected payoff function; in this model the reported recycling rate has been used.
- Ranks each input in order of the size of the impact its change makes on the payoff function.

- Takes the top 10 ranked inputs and performs Vensim sensitivity analysis, recording the range of outputs for a number of metrics.

In order to perform the sensitivity analysis, 71 input constants were chosen (essentially all input assumptions except those for which sensitivity analysis is meaningless, such as parameters performing units of measurement conversion) and values changed by +20% and for -20% from baseline values. The top ten inputs influencing the reported recycling rate, ranked in order of magnitude of influence, are shown in Table 5-18. The +/-20% columns show the percentage change in the payoff monitored by the software, namely the cumulative difference between the sensitivity experiment and the baseline simulation for reported recycling rate. The column labelled "Largest" shows the absolute maximum percentage impact on reported recycling rate as a result of a 20% increase or decrease in the value of the parameter.

Table 5-18: Top Ten Inputs Influencing Reported Recycling Rate

Parameter	Description	-20%	20%	Largest
PRF cost premium=1.2	Multiplier of cost of MRF supply to Reprocessors, from PRF (for the higher quality)	-0.80%	0.11%	0.80%
reprocessor target markup=4.5	Expectations of markup for processors	0.22%	-0.69%	0.69%
base reprocessor production capacity for economies of scale=502624	Production capacity to achieve base cost reductions from economies of scale	0.15%	-0.45%	0.45%
UK share of Global reprocessed plastic demand=3.25	UK share of the global demand for reprocessed plastics	-0.40%	-0.30%	0.40%
Time to Adjust Traders' Expected PRN Price=0.664333	Trader's belief about the underlying equilibrium price adjust to actual prices over this period	-0.34%	0.10%	0.34%
max reprocessor economies of scale effect on costs=0.74497	Maximum effect of economies of scale (reduction in unit costs)	-0.33%	0.24%	0.33%
separate waste to reprocessor %[Commercial]=19	Assumption on the percentage of collected (separated) plastics sent to UK reprocessors	-0.31%	-0.04%	0.31%
Sensitivity of Price to Inventory Coverage=-2.58115	Controls the response of PRN price to PRN inventory coverage. Must be negative for high inventory to lead to lower prices. Higher absolute values lead to greater price changes for any given inventory coverage level.	-0.18%	0.23%	0.23%
Sensitivity of Price to reprocessor Inventory Coverage=-0.570222	Controls the response of reprocessor markup (price) to reprocessor inventory coverage. Must be negative for high inventory to lead to lower prices. Higher absolute values lead to greater price changes for any given inventory coverage level.	-0.04%	-0.18%	0.18%
reprocessor stock adjustment period=0.5	Period over which the reprocessing industry would like to adjust stock levels to desired level	-0.12%	-0.05%	0.12%

5.5.1 Multivariate Sensitivity Analysis

The next stage was to take the top ten variables identified and create an experiment using the Vensim sensitivity analysis feature, enabling multivariate sensitivity analysis for these variables over a sensible range of input values. Table 5-19: shows the parameters, their baseline values (those in red were computed during calibration), and the ranges taken during multivariate sensitivity analysis (simply +/-10% of the baseline value in this example, but ranges should be agreed with policy makers in any future model use).

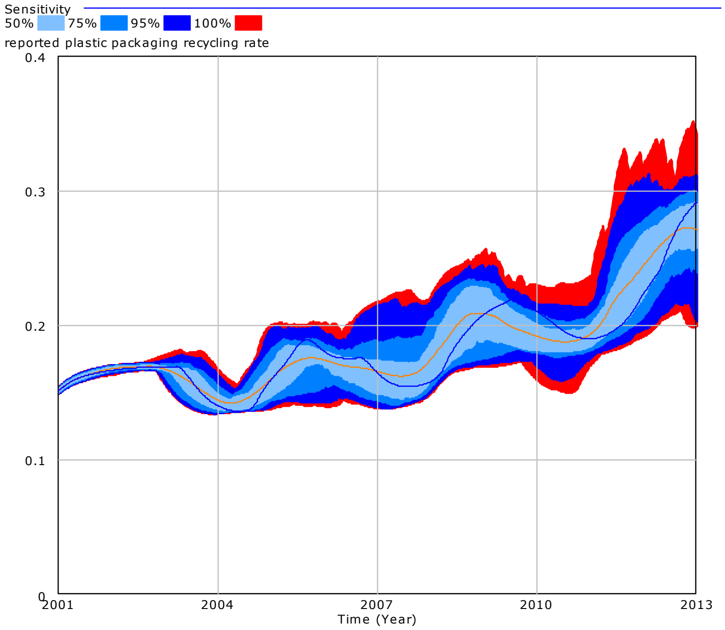
Table 5-19: Results of Multivariate Sensitivity Analysis

Parameter	Baseline	Range	Notes
PRF cost premium	1.2x	1.08 to 1.32	Multiplier of cost of MRF supply to Reprocessors, from PRF (for the higher quality)
reprocessor target markup	4.5x	4.05 to 4.95	Expectations of markup for processors
base reprocessor production capacity for economies of scale	502,624 tonne/year	452,361 to 552,886	Production capacity to achieve base cost reductions from economies of scale
UK share of Global reprocessed plastic demand	3.25% (Estimate)	2.925 to 3.575	UK share of the global demand for reprocessed plastics
Time to Adjust Traders' Expected PRN Price	0.66 year	0.59 to 0.73	Trader's belief about the underlying equilibrium price adjust to actual prices over this period
max reprocessor economies of scale effect on costs	0.75	0.67 to 0.82	Maximum effect of economies of scale (reduction in unit costs)
separate waste to reprocessor %[Commercial]	19% (Plasflow)	17.1 to 20.9	Assumption on the percentage of collected (separated) plastics sent to UK reprocessors
Sensitivity of Price to Inventory Coverage	-2.58	-2.32 to -2.84	Controls the response of PRN price to PRN inventory coverage. Must be negative for high inventory to lead to lower prices. Higher absolute values lead to greater price changes for any given inventory coverage level.
Sensitivity of Price to reprocessor Inventory Coverage	-0.57	-0.51 to -0.63	Controls the response of reprocessor markup (price) to reprocessor inventory coverage. Must be negative for high inventory to lead to lower prices. Higher absolute values lead to greater price changes for any given inventory coverage level.
reprocessor stock adjustment period	0.386 year	0.348 to 0.425	Period over which the reprocessing industry would like to adjust stock levels to desired level

Example results for some of the outputs after 200 sensitivity simulations are shown below. In these graphs, confidence bounds using the percentiles 50%, 75%, 95% and 100% are shown as coloured bands. These are computed at each point in time by ordering and sampling all the simulation runs. Thus, for example, for a confidence bound at 50%, 25% of the runs will have a value larger than the top of the confidence bound and 25% will have a value lower than the bottom of the confidence bound. To interpret this, 50% of all the sensitivity runs fall within the central 50% band, 75% within the 75% band (and including those in the 50% band), and so on.

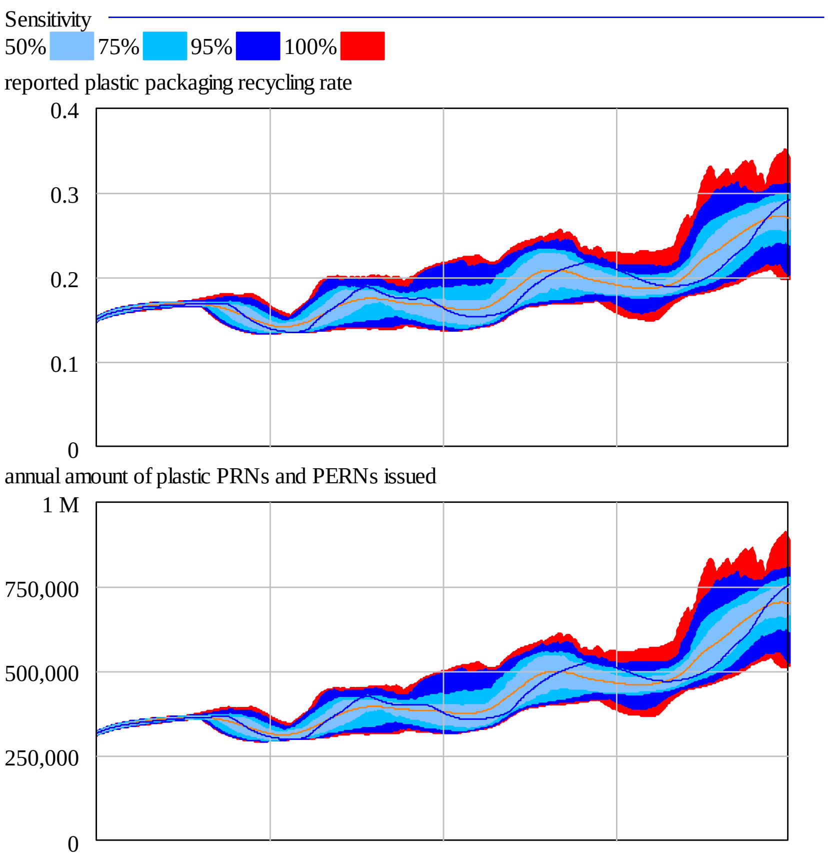
Reported Recycling Rate: Figure 5-69: shows the range of possible reported recycling rates during the simulated period given the variability of the input assumptions. By the end of the simulation, the recycling rate ranges from 32% to nearly 56%, with an average at 43%. The baseline run (shown as a blue run) is slightly over 39%.

Figure 5-69: Range of Possible Reported Recycling Rates



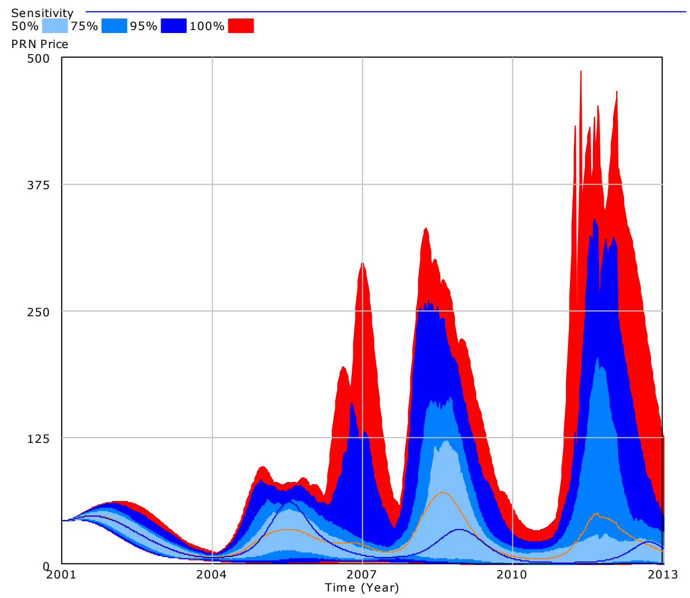
Causal tracing is still possible even with a sensitivity output. Figure 5-70 shows the sensitivity output for the main influences on the reported recycling rate, with the main influence being the fluctuation in the issuing of PRNs and PERNs (since *reported* recycling rates are calculated as the ratio of PRNs issued to waste arisings, with the latter unchanging).

Figure 5-70: Sensitivity Output for Main Influence on Reported Recycling Rate



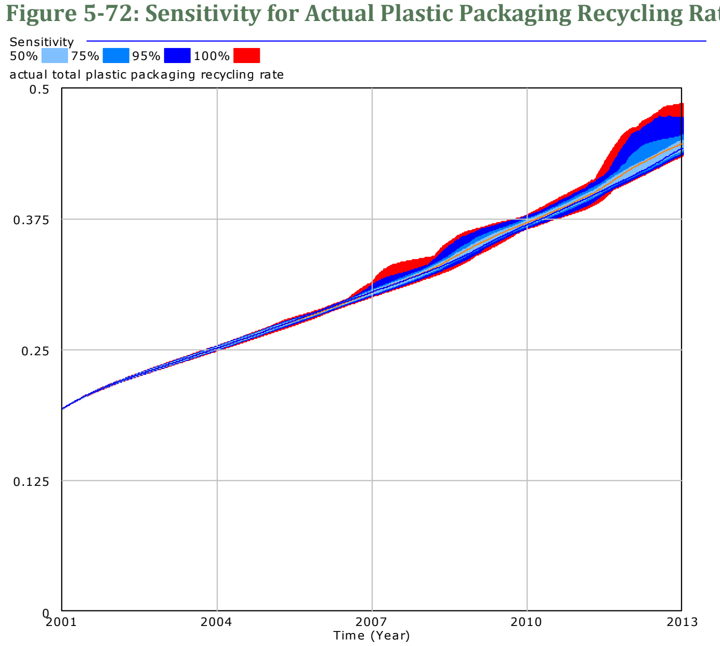
The cause of these variations can be traced to wild variability in the peaks and troughs of PRN/PERN price between the 200 simulations (Figure 5-71), indicating the model is expressing great sensitivity to modest changes in input for the PRN price. One possible reason for this is that the import/export sector in the model is immature and a number of simplifying assumptions are making the behaviour unreasonable outside of the tight bounds governed by the calibrated data set. For example, additional throughput from PRFs can always find a buyer in the model (exports), regardless of price. An expansion of the import/export area of the model is therefore required to address this . This will be able to make best use of any enhancements to the representation of quality, since quality and cost will determine the markets for UK imports and exports.

Figure 5-71: Sensitivity for PRN Price



The actual recycling rate (ratio of plastic packaging collected for recycling to total arisings) also varies between simulations, although the variability is much reduced (Figure 5-72). The chief driver of changes in the collection of material for recycling at the moment is the cost of doing so when compared to alternatives such as landfill or incineration. Variation (between runs and in simulated time) in the costs paid by LAs when disposing of material for recycling is a result of the wild variations in PRN/PERN prices and the trickle-down effect of this additional revenue.

Figure 5-72: Sensitivity for Actual Plastic Packaging Recycling Rate



5.5.2 Dashboards

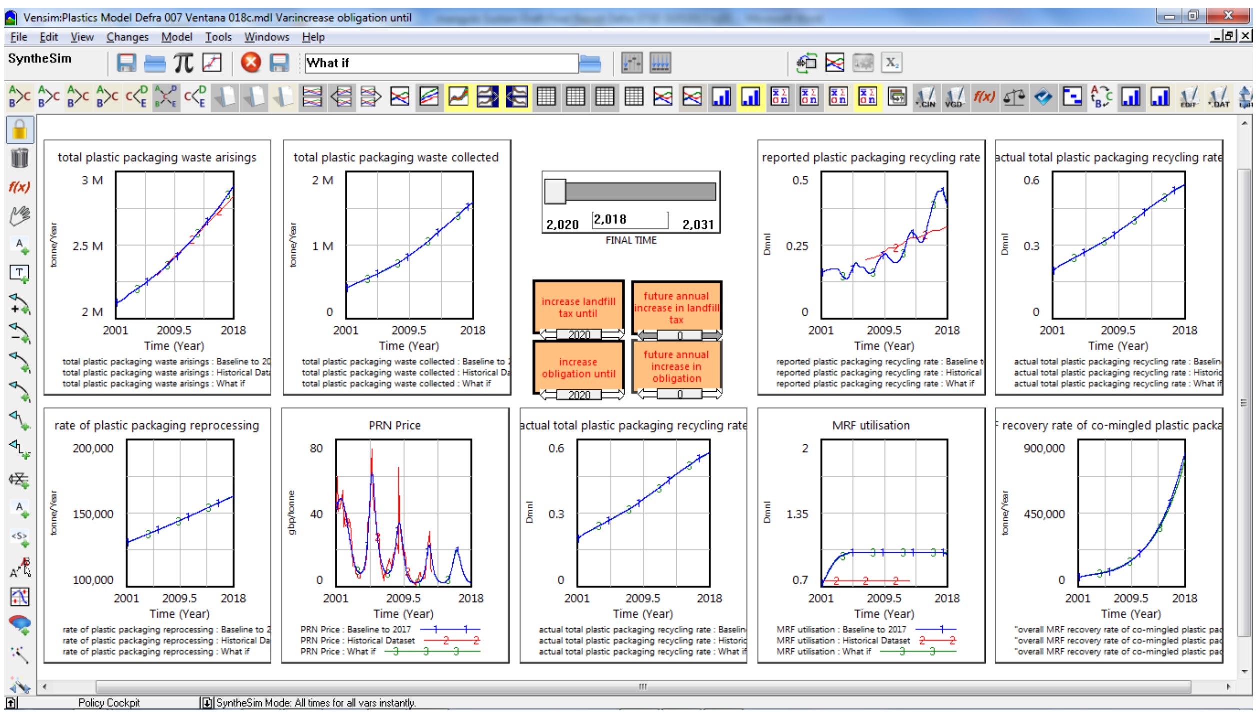
Dashboards are a useful means of visualising the key variables of interest when certain scenarios are being explored or policies analysed. They can be produced and easily updated as their usefulness changes. Adding constants to the view will enable slider-bars to appear during Synthesim mode, allowing the user to modify the input assumption and visualise the resulting change in the metrics of interest. Three dashboards have been added to the model.

Policy Dashboard: A series of graphs showing policy outcomes are shown, together with a small number of input assumptions regarding increases in landfill tax and plastics under obligation.

Financial Dashboard: A series of financial metrics are shown, together with a small number of input assumptions regarding increases in landfill tax and plastics under obligation.

Targets Cockpit: A simple output for the recycling obligation met, this particular dashboard was used as a quick access to check the satisfaction of recycling obligations.

Figure 5-73: Example Screen Shot of Dashboard



6.0 Summary of Project Results

This section presents a summary of how ST and SD were applied during the project to explore WP and PPR, and what insights were gained through this process.

6.1 Lessons Learned and Open Questions

Key points taken from several discussions held during the project are presented here.

6.1.1 Benefits

- During the modelling process data was brought together from a variety of sources on the subjects being modelled.
- The modelling process brought together people from different policy areas.
- Several analysts reported that it's difficult to "keep many issues in my head at the same time"; the model acts as a tool so the whole system can be viewed, holding that knowledge about different parts of the system in one place.
- The models (once parameterised) are dynamic and can be simulated over time.
- For the subject of WP, one of the first problems was to identify what is important in the system and how system elements are related. The use of system methods meant that this task was performed in a structured and systemic way, bringing some order to a rather large and complex problem.
- Analysts found much value in the fact that the WP model provides a "big picture", enabling them to drill down on the things they are really interested in.
- The WP model was found to be rich in unpicking some of the key questions about WP.
- The model building started to get people to think of the problem as a system.
- The whole process was a wider exploration of the technique. People are more aware of the technique now, and this has been quite positive.

6.1.2 Drawbacks and Difficulties

- In general, it is best to build models that are problem focused rather than system focused. Because no boundary was defined for the WP stream before modelling started, we ended up modelling the flow of materials throughout most of the economy (in other words, we modelled most of the system rather than a particular problem). This meant we created a large model with too many parameters to populate within the project timeframe.
- The way a model represents the real world may need some getting used to for some experts, and trust in models will need to be built up over time. They may find such types of models lacking in accuracy compared to the normal level of evidence they expect. Additionally, models may mix data from different disciplines – which is necessary if models are to include everything that is important in driving system behaviour. For example, including soft variables such as social norms brings the need for professional judgment and use of social science data, which some may find strange to mix with more empirical economic data.
- The model can show key relationships between actors and actions, but modelling deeper questions such as what drives people to desire new goods is much more difficult; whether or not these need to be modelled is an open question for modellers.

- The sub-models could be seen as contentious by some, if people perceive that the models are saying "this is how the world is" rather than the intent, which is "this is a useful representation of how the world is based on our mental models".
- Policy makers were concerned about the time and effort needed to get the model developed as far as they were. They found the WP model to be an interesting piece of work, but developing it required the time of policy makers because they are the ones with the knowledge. The usefulness of this effort was doubted because of the model not being populated with data.

6.1.3 Evidence Makers' Viewpoint

- The sub-models will be valuable in articulating government's role and influence on the subjects of the sub-models. Although 90% of work is done by businesses and consumers, government need to understand how and where they influence this activity. For example, thinking about some of the EU and domestic targets for recycling, and how businesses run, how does that influence what's in the sub-models? Maybe the system is not reinforcing what government wants to happen. Could the desired outcomes be achieved without having negative effects on the system?
- The model feels like a comprehensive view of what options are available.
- The model helps us to identify what it is that only government can do.
- The model could be adapted for different business models and products by changing weightings and data. For example, for the idea of a Product Service System, if the product is more like a PSS it will lie more on left side of the Material Flows Map. Innovation from different business models might change some of the flows.
- When you see the system in a structural way it helps you to think about missing inputs.
- The model is impressive, even without data, in its richness, in unpicking some difficult questions. You don't have to hold all the concepts in your head to have a discussion because it's there in the mode, and we can pick one bit of it and test how interactions can be mapped out.
- One of the key values is being able to see that there is one area where government have a role that can be articulated more clearly, and it is useful when thinking about that area to be aware of how that interacts with the rest of the system.
- The model creates questions such as whether government is in the way of WP, and whether we are creating policy for now rather than for people in transition. All parts of the system are interacting when transitions happen.
- If we can understand the dynamic processes, it means that when we are concentrating on a small area that is legitimate for us to act in, we can see what's likely to happen. The model requires stress testing to see how we do that in practice.
- There can be positive and negative impacts of change (e.g. increasing refurbishment potential could decrease WP), which is why you would create a model like this. Once you've got the data in it, you could test how different policy options would affect different flows. Because it includes decision making, uncertainty about how consumers respond, and innovation, you should be able to run the model to give you an idea of the unintended consequences of policies.

6.1.4 Policy Makers' Viewpoint

- We're interested in materials because of the impacts on the environment of waste. In terms of why Defra's interested in this, somewhere within the Material Flows Map is the question of how government is influencing the flows.
- We can use the map to ask what existing policies are affecting material use, and where public sector activity is acting to prevent WP.
- We want to encourage new business models, but policies may not be flexible enough to allow the transition. For example, consumer licensing. We haven't got a licence for businesses that want to transition. Could this model demonstrate this? We could use it to imagine the transition to a new steady state.
- The model has been useful for consolidating evidence.
- The model is a tool for articulating a structure, but how it can be used to determine policy when there are so many other things that go into what policies you take forward? It's a piece of a puzzle rather than an answer in itself. Sometimes, it's a matter of political decision making.
- There is a danger that this model will be perceived as making value judgments.
- We need to justify why Defra is doing work like this. There are questions about what government should do – it has to be things that private sector can't do. Given that things work differently for every product and we're not trying to reengineer products, what part can government play?
- We might be able to use the model to predict outcomes for particular cases but maybe we could have got that through regular discussions.

6.1.5 Industry Expert's Viewpoint

- I could imagine presenting the model to a workshop of business leaders, with a series of questions related to the sub-models. We could ask them what they think might happen in the future to different variables. There are questions for businesses about what parts of the system they have control over. We could investigate the sub-models by getting people to play around with the model and see how things change.
- Sometimes in workshops you can provide a lot of information but get nothing back from participants. This model could help engage people within workshops. I would like to present this model in a workshop with industry, for example sitting down and showing it to someone who's hostile to the idea of WP. I could present different parts of the model, and we could discuss where their role is, where government's role is, what the material flows are, etc. It would be a non-confrontational way of communicating.
- I'm going to be taking this away and using it in our design for sustainability workshop. We could look at what would be beneficial for businesses to promote WP, from a policy point of view.

6.1.6 Approach to Model Building

- There was concern about how long the WP workshops took, especially for policy makers. By contrast, the recycling model was created via a series of shorter sessions, with the modeller doing all of the model building.
- Modelling works better for discrete questions.
- Another way to model is to gather information via short sessions. For example, an open discussion with a group of experts on innovation and then another session with science

experts. The model is then created with three or four people around a table or directly in Vensim. Policy people won't generally give more than two hours for model building in one session so their time must be well used.

- It might be more efficient in future to do smaller sub-models internally, and then combine them.
- A lot of skill is needed to capture the essence of the problem in a simple model as possible.
- For the WP model, it might have been preferable to have developed the Material Flows Map before doing the workshops. We might have built a more integrated model that is easier to understand, focused on the physical flows. On the other hand, by presenting something, rather than a blank sheet, people might have left things out that are in fact important. And it is not certain that the map would have been as useful without input from the workshops.
- It would be good to highlight places in the model where we know that a relationship is being described in a way that is too simple, and more detail needs to be added to represent more complex relationships.

6.2 Waste Prevention Stream Results

6.2.1 General Observations

We have found that the "system that produces waste" is highly complex, multilayered, and its behaviour is best understood when evidence is viewed over a long time frame. The system of interest has been analysed only at the macro level. Time did not allow for any modelling to be done at the micro level. The Material Flows Map was well received by everyone to whom it was presented. They found it to be the most simple and most complete part of the model and most people broadly agree with its representation of the real world. The sub-models are a little more contentious and they will require a good deal more development and exposure to different stakeholders before they are accepted as being a useful representation of the real world; some seem to work only for some sectors or products. However, it should be pointed out that the flow map is not actually an SD model and can't be run on its own.

The WP practices we have considered for the model can been seen as having two principal effects: reducing the waste by-products from the supply chain, and increasing the lifetime of use of products once in consumer hands. Both of these will slow down the total rate of waste generation related to economic activity. In reality WP practices only happen when they are possible to do (i.e. the structure that supports them is in place) and when they are attractive to individual decision-makers in households and organisations. Influences on attractiveness include the relative cost and convenience of reacquisition to new for consumers, and the cost and feasibility of implementing WP within organisations. For example, for retailers to re-use materials in end of line products rather than sending them to landfill would require investment of labour costs for the separation of waste and investment in the logistics of material reuse – which is not always profitable to do when materials and waste disposal are relatively so much cheaper.

Some WP practices are dependent on each other and some are not. Producers and suppliers may reduce waste purely for profit reasons, independent of how their products are used or "end-of-lifed"; consumers may extend product lifetimes independent of the intentions of producers. However, there is a key dependency between producer product design and some consumer WP practices: consumers cannot repair products not designed for repair and cannot keep products until they wear out if they become technically obsolete well before; they cannot choose a remanufactured product if none is offered. Thus, the model links these factors, and the dynamics between supply chain and consumer actions could be explored in a quantitative way if the model were parameterised.

The question of what metric to use in the model for material flows was discussed at the workshops. The consensus was that weight would be the most suitable for the model because is it standard across different data sources, but it is lacking in its ability to represent all of the impacts of interest. Weight does not reflect the full implications of the goal of WP, which is to reduce the environmental impact of waste and improve resource efficiency. The relationship between the generation of waste and its environmental impact is complex, and using weight as a metric can be misleading – for example, '*moving towards more lightweight packaging does not necessarily reduce the environmental impact of packaging, either during its end-of-life phase or over its entire life-cycle'.* (European Commission 2004) Ongoing work within the EU's Resource Efficiency Roadmap[26] is developing a set of more comprehensive indicators which includes: a lead indicator (GDP divided by Domestic Material Consumption); a dashboard of macro consumption and production indicators on materials, water, land and carbon; and thematic indicators that monitor the transformation of the economy, natural capital, and key sectors. These indicators would be more suitable to use in a version of the WP model that separates different types of products or material flows.

The goal of WP has been described in economic terms as decoupling between economic activity and waste generation, and there is evidence that decoupling has been happening in the UK. However, it's not clear whether this is intentional decoupling or a result of general economic trends. A study into policies for waste decoupling in Sweden found that decoupling requires decreases in the waste intensity of the principal drivers of waste generation, which are '*technical change, economic growth and household consumption'*. (Sjöström & Östblom 2010) These are macroeconomic factors and it appears unlikely that they would be addressed solely for WP. If it is difficult to identify an effect from WP within larger macroeconomic trends, another way to measure WP would be to develop a new indicator that represents the "circularity" of resource use in the economy. A set of indicators could be calculated as the ratio of one or more flows against a contrasting flow in the material flows map, such as the ratio between the annual tonnes of products supplied to consumers and businesses to the annual tonnes of products disposed of (and used to their full value, such as when food is eaten).

6.2.2 Methodological Issues

We note here some observations about the methodology used for the WP stream.

Mental models: WP is an activity that potentially touches all of us and discussing it can generate strong personal feelings. Participants in the workshops were likely sharing subjective feelings and personal wishes at times. We tried to model the system "as is" and keep policy wishes out of the modelling process, but other wishes may have crept in. The idea of "circularity" cropped up several times during discussions, but this was not included in the model explicitly.

Genericness: The WP model is not truly generic in its current form. For example, when modelling the flows of food the model should be able to show some products entering the system and then being consumed (e.g. eaten), with their weight going to zero rather than eventually flowing out of the system as material waste. Currently the model is more oriented towards durable products; however, it is expected that making it suitable for non-durables would not require very large structural changes.

Subjectivity: SD modelling tends to sit within a functionalist paradigm – we create models and then regard them as representing the "real world" and therefore as, at least partially, objective; however, their creation has involved a fair degree of subjectivity. Sterman's (Sterman 2000) approach of "double loop learning" acknowledges this subjectivity and attempts to mitigate it through a process that iteratively updates models as feedback is gained from observing what the "real world" does.

[26] http://ec.europa.eu/environment/resource_efficiency/targets_indicators/roadmap/index_en.htm

However, the behaviour of our system of interest only becomes apparent when observed over long time scales – years to decades – so it is debateable as to how applicable double loop learning will be for the WP model.

Problem Structuring and Problem Solving: One concept from ST articulated by (Ring, 1998) is that the "the purpose of the system is what it does" – not what we would like it to do, or what we designed it to do. Additionally, (Yearworth et al. 2013) state that wicked problems can never be solved as such, but structured – systems modelling is a way of engaging with problems through a process of enquiry. Thus, one of the benefits of this project has been that it allowed a problem structuring and an interpretivist stance to be taken when viewing the problem of WP – different from the more common functionalist policy engineering view – with the model a subjective intellectual device useful for making sense of complexity. Despite this suggestion of interpretivism, the WP model has as its backbone material flows that are real and measurable, with much of the interpretation embedded in the seven sub-models that drive the flows of materials. Thus the approach we have taken moves towards an interpretivist position but still sits within functionalism consistent with Lane's analysis of system dynamics practice (Lane 2001).

Soft Variables: One of the strengths and differentiating features of the SD method is its ability to model a system's behavioural characteristics over time. To achieve this, it is important to identify the most crucial variables and include them all, even if it means including a variable for which there is little numerical data. (Coyle 2000) discusses potential problems when soft variables are included in a model, given a numerical value and included in functions, especially non-linear functions. He states that when several qualitative variables are used together, the number of uncertainties rises dramatically, and these uncertainties can combine and compound so that it becomes impossible to believe the model's output. This issue will be of concern if the WP model is parameterised.

Communication Tool: Defra policy makers may wish to use this model to communicate the WP policy issue to other parts of government and to ministers, partly to enable others to understand the breadth and complexity of the WP issue. Government have previously used systems diagrams, such as for the Foresight Committee's Obesity study[27], and have found the approach useful in at least identifying all facets of a problem and how they are interrelated, even if the model is not able to test interventions. We believe the WP model can serve this purpose in its current state.

Dynamic Complexity: The use of SD for this project is argued on the basis that most systems are sufficiently dynamically complex that simulation is required in order to understand behaviour, yet although WP fits the definition of a wicked problem (Rittel & Webber 1973) no obvious surprises have arisen from the model and the supporting data so far. At the macro level the WP model appears to agree with basic economic theory about supply and demand. Part of the reason for this could be because the model is based largely on mental models and these don't always reflect reality accurately. As voiced by experts during the workshops, part of the difficulty in promoting WP is the high level of heterogeneity in the range of activities that lead to waste. We suspect that interesting and surprising dynamics may exist between the micro and macro levels of the system, and that these will be significantly different for different types of products (e.g. food versus electronics).

Micro and Macro: (Goldspink & Kay 2007) discuss problems in understanding the dynamics between micro and macro behaviours. The authors evaluate two slogans: "think global, act local‟ conveys a message about individuals effecting global change; "think local, act global‟ reflects the idea that local solutions can be produced by harnessing contributions from wide-spread sources. Although both slogans highlight issues of scope (local versus global) there is also an implied issue of level, with the suggestion that individual agency can have large-scale social impacts. The paper

[27] http://www.bis.gov.uk/assets/foresight/docs/obesity/17.pdf

states that it's not possible to say much about '*how and when individuals acting locally may have wider effects, nor how disparate individual contributions may be effectively harnessed so as to generate coherent solutions to local problems*' (ibid), finding that the unresolved nature of the problem reflects its intellectual formidability. The decision making of many stakeholders depends, at least in part, on the decision making of stakeholders at higher levels – decisions made by those at the macro level will often be felt as structural factors (in other words, a "given") by those at lower levels. For example, companies may feel pressured into following a short-term business model by the financial sector's demand for high quarterly profits (although some companies remain immune to this pressure, such as the Patagonia clothing company[28]). To an individual, organisations and suppliers may feel like the structure. There are also some overarching structures at play which many are not aware of, such as regulations governing business and international trade. All of these issues have not been fully explored yet but could turn out to be important to WP.

6.2.3 Applying "Places to Intervene" to Waste Prevention

Table 6-1 presents the barriers to WP identified in section 3.1.1.2 amalgamated into eight key barriers, along with insights from the model about the reasons for the barriers, and possible interventions that could overcome the barriers which are suggested by applying Meadows' Places to Intervene (Meadows 1997).

Table 6-1: Possible Places to Intervene for Waste Prevention

Barrier	Insight from Model	Potential Interventions
Social norms: Accepted social standards on consumerism and waste, influencing individual decision-making	A reinforcing loop between consumerist social norms and economic growth (including disposable income) has led most people to become used to having more and buying more. This trend was only slowed down by the reduction in availability of capital since 2008. Waste trends for households are highly correlated with consumption trends.	There is probably more structural effect than agency in people's decision making on consumption, with the reinforcing loop largely driven by the macro level goal of the system (economic growth), which eventually leads to the availability of products that are relatively cheap compared to income. Only once the effects of waste and resource inefficiency are seen to be impacting human well-being will there be an imperative to change the overarching system goal; however, there is a long information delay between creating waste and becoming aware of its long-term environmental effects.
The role of politics: WP behaviours grounded in long-standing, deeply personal beliefs and values, difficult territory for politics	WP practices are highly heterogeneous for different types of products and for different sectors within society, but there are general principles for WP across the whole economy when accounting for physical flows of materials and goods as illustrated in the material flows map.	When targeting a particular product type, waste stream, or sector for WP, incentives, standards and taxes can increase or decrease flow rates. Because this is a sensitive area, it may be easier to intervene upstream within the supply chain than downstream with consumers. For example, setting standards for manufacturers to take lifetime responsibility for their products would increase design for repairability and remanufacture and make products more robust, leading to more people being able to repair or reuse products.

[28] For Patagonia's stance on consumerism, see www.thecleanestline.com/2011/11/dont-buy-this-jacket-black-friday-and-the-new-york-times.html

Barrier	Insight from Model	Potential Interventions
Environmental externalities: decision makers do not have to directly pay appropriate and full costs of the effects of waste	This is reflected in the magnitude of material flows coming into the UK from overseas, and by the lack of information feedback and weak balancing loops linking the creators of waste to the effects of the waste they create (environmental damage and climate change), especially at source.	Changing the rules on International trade, to establish minimum environmental standards for manufacturing and the supply of resources would create a feedback loop between different sectors of global society, preventing the "race to the bottom" syndrome for sourcing materials and products. Existing exceptions to this race to the bottom (e.g. Patagonia) provide examples for other companies to voluntarily account for externalities rather than waiting for top-level rule changes.
Split incentives: The beneficiaries of WP actions may not be the same as those who incur the cost of those actions	The Business Models sub-model shows the possibility of increasing lifetime product stewardship through environmentally sustainable business models, but the financial rewards for companies to do this are not clear in the short term and so there is no reinforcing loop driving this. There is a lack of feedback between producers and users.	The way businesses make money can change to encourage smart, resource-efficient sales rather than simply more sales. Self-organisation, the ability of a system to change itself, is one aspect to consider. The diversity of human cultures enables social evolution, and so the intervention is to encourage variability, experimentation and diversity in business models to achieve both business success and environmental health.
Informational: Consumers and businesses may not be aware of the full costs of waste or preventative actions they could take to reduce it	There is a general lack of information feedback to those making decisions that lead to waste, especially at the point of decision making for consumption. There is no information feedback in the consumption pull sub-model for the effects of waste.	Many people are not well informed about what impact their purchasing decisions and their decisions on how to end-of-life a product will have. Information provided at the right point could enable more WP. For example, producers/retailers could be required to label products with their embedded GHG, hazardous waste, and material waste impacts, allowing consumers to make an informed choice.
Financial: WP actions may require initial investments before benefits can be realised, which can be affected by reduced access to credit.	This is largely for producers who may need to change their production processes and internal policies to implement WP. In the model, material efficiency is driven mostly by the cost of materials and the cost of waste. Only when this is high enough will there be investment in WP. Whether there is in fact capital available to invest depends on the health of the company.	Government can provide financial assistance through interventions such as the Green Bank for WP actions that require investment, and they can provide information on the potential economic value of WP. However, WP often requires innovation, and if the cost of waste and materials remain relatively low then the imperative to act will be less. In fact (Brouillat & Oltra 2011) find that *'the capacity of economic instruments to favour radical technological change is empirically limited'*. Thus, removing the financial barrier may be only part of the solution.
Corporate culture: Business cultures can be unsupportive of WP, with a lack of leadership commitment; decision makers in organisations often underestimate the value of long-term benefits versus short-term costs	This lack of long-term thinking is represented in the Business Models sub-model (% of companies following a short-term business model). The reverse can be seen in the remanufacturing sub-model where investment in remanufacturing facilities can lead to a longer-term relationship between companies and their customers (although this only makes sense for more expensive products).	This is similar to the split incentives barrier, but the focus is on the reinforcing loop of shorter business cycles leading to short-term planning. Reducing the gain in a reinforcing loop can be achieved through reducing the strength of the factors driving it. In this case, the strength of the financial sector's influence on the real economy could be reduced, but this would require a change in macroeconomic rules which is unlikely. However, there are some examples of successful leadership from some business leaders in long-term thinking which indicate the possibility of a societal paradigm change on waste.

Barrier	Insight from Model	Potential Interventions
Competing Goals: The widespread practices of recycling and landfill diversion can act as barriers to preventing waste at source	Landfill tax is represented in the model as driving WP, but there is anecdotal evidence that recycling incentives encourage recycling over WP. Thus there may be mixed effects from landfill tax on WP. WP is affected by other policies on health and safety, free trade, and consumer rights. These policies may have to be revised to reflect the trade off between their goals and the goal of WP.	The intervention point can be moved up the waste hierarchy to encourage action before materials become designated as waste (either to be recycled or landfilled), through actions such as material recovery between C&I organisations, and take back schemes for consumers. It may be needed to provide both a "stick" that sees waste disposal (including recycling) made more expensive and a "carrot" that makes WP cheaper and easier to do through provision of additional structure, information, and incentives. The difficulty may be in defining exactly what WP is in each sector.

6.3 Recycling Stream Results

Recycling policy makers reported that they found the project really useful, even though it did not progress exactly as expected, based on its design. They found participating in the project to have been a valuable experience and that it significantly increased their understanding of ST and SD. The project provided some valuable outcomes and information which they can apply in future.

From a policy perspective, the PPR model has served two main purposes. First, it has helped to structure much more precisely current knowledge of the system, bringing together different individuals' understanding of parts of the system and wider consensus of how each of the parts interact. The visual capability of the SD model played a crucial role facilitating the communication between policy experts and other stakeholders with the modelling team. Second, given that enough information and data about the system and component variables was available, we were able to parameterise the model to run a series of test policy scenarios and learn how to use the model as a tool for policy appraisal.

The focus in the PPR stream has been more on the "harder" aspects of the systems approach, including mathematical modelling, data gathering, calibration, scenario development and sensitivity analysis. The modelling process has also been used as a framework to gather and document data from a wide range of sources in a structured and unambiguous manner, which occurred as the data sheet for the model, used for input and calibration purposes, was being built. The process helped to identify gaps and inconsistencies with the data. The evidence and analysis team considers this to be an important, although originally unexpected, benefit of the model and they are considering applying a similar approach in other areas.

In terms of interpreting the outputs of the model at this stage, although the model has been parameterised, it needs to undergo further calibration, testing and interrogation of the results, which is a lengthy process. A lack of time on the part of both Defra staff and the modelling team has meant that the required level of confidence in its outputs has not yet been achieved. Nevertheless, this report provides a detailed account of the model, its capability and the test scenarios, and this will provide Defra analysts with the knowledge and toolset to take the model to the next stage and inform real policy making using the test scenarios as a starting point.

In terms of new understandings gained from the model, it appears that the main demand shifter in the system is potential shocks to the price of virgin materials. Since recovered plastics are used as a substitute for virgin plastics, an increase in the price of virgin plastics will cause demand for recovered plastics to increase. In the long run, that demand will drive the price of recovered plastics, and then a more normal ratio will be established between virgin and recovered plastics prices, consistent with the recovered plastics industry producing to full capacity.

International recovered plastic prices follow closely the price of virgin plastics, rather than the cost of producing plastics, and the quantity produced shifts around to reflect shifts in the capacity of the recovered plastics industry in each country, which is driven by factors like the countries' regulatory regimes. If production exists outside the UK, for example in the case of reprocessing, then there can be positive growth implications for increasing domestic capacity. However, in the long term, impact is likely to be determined by the competitiveness of that additional capacity. If there are lower costs overseas, business may receive a higher price for exporting recovered material than selling to domestic reprocessors, MRFs and PRFs. However, when taking costs of transportation into account, domestic businesses may value a locally sourced supply of recycled material and may be willing to pay a higher price for the security of supply.

There is currently insufficient information to determine the barriers to expansion of the reprocessing industry and the long term competitiveness of domestic operators. However, innovation to reduce costs of sorting and treatment could increase the quality and value of recovered material, helping to reduce international cost differentials and helping growth in the domestic industry. It is currently unclear whether scale is a significant factor affecting growth of the reprocessing sector.

6.4 Future Developments

Both of the models created during the project would benefit from being further developed. This section outlines potential further work on the models.

6.4.1 General Modelling Approaches

- **Relationship with economic modelling:** It is clear that SD is capable of modelling systems that are traditionally described by economic models, and that SD models that include economic systems need to be able to describe variables that are held in dynamic equilibrium by a supply and demand relationship. Although this is often under-represented in SD, examples do exist (for example, Sterman presents a basic supply and demand model, including price elasticity, in Chapter 13 of (Sterman, 2000)). We would recommend that Defra creates more integration between SD and economics modelling activities. This would help to improve the perception of this type of modelling by economists and improve the rigour of SD models in dealing with supply⇔price⇔demand relationships.
- **Interpretation of Quantitative Results:** SD models represent the dynamics of a system, and any insights into the future behaviour of a system that are produced by the model indicate what would happen only if the dynamics stayed the same in future. Any trends shown in model runs will only be as realistic as the data that was available to populate the model. No model behaves exactly like the real world, and its representation of the behaviour of the real world system will always need to be improved over time though regular comparison with empirical data and review by stakeholders. Within a complex system there may well be layers of structure difficult to see, which are contributing to system behaviour.
- **Practicality of using ST and SD methods at Defra:** At project initiation it was anticipated that much of the modelling work would be done internally at Defra, with the project team available for training, guidance, leading workshops, model reviews and some model building. Although the project team got a good deal of input from Defra staff, most of the Vensim model building was in fact done by the project team, with only one Defra staff member getting directly involved. To acquire skills in ST and SD methods would require much more time than the three days of training provided through this project. We recommend that to embed these methods into Defra's core skills a commitment is made by several staff members to use the methods within live project work.

6.4.2 Future Development of the WP Model

The structure of the WP model as it stands at project completion offers many possible avenues of development and use.

6.4.2.1 Use of the WP Model to Support Policy Making

These ideas were put forward in discussions on future use of the WP model:

- Model the process of transition from one business model type to a more resource efficient one through innovation.
- The model could be used to test structural changes to the system, such as new connections between different actors.
- The model currently provides a very broad picture of waste and how it interacts with the economy. This wider perspective could be taken into account, while going into more detail on particular parts of the system. This could be done by applying another Operational Research technique. The model could then be shown to potential partners in innovation, to support the business case for increased resource efficiency.
- Current regulations have been developed for particular types of businesses, but policies might not be flexible enough to allow transition to new business models. The complexity of that relationship has not been explored but could be through the model. This would allow government to act to remove barriers and facilitate business model transitions.
- The model could be used to better understand the temporal aspects of material efficiency – how do product design lifetime, fashion lifetime, and lifetime of need all drive the rates of the flows?
- The model could be used by policy makers and analysts to talk through conceptual ideas, even if the model is not parameterised.
- The model could be used as a feedback and interaction tool for stakeholders.
- Although it's beneficial to have the current level of detail in the model, which was needed to show basic relationships in the economy, it's not going to be possible to parameterise it as it is. But the model could be simplified by abstracting up to another level and reducing the number of variables. This would make parameterisation possible.
- Alternatively, parts of the model could be taken out, expanded, and more detail added. This would work for policy areas for which there is ample knowledge.
- The Material Flows Map could be utilised without the whole model being parameterised. If it was connected only to the variables that feed directly into it, they would become exogenous variables. Then it would be possible to play with Vensim sliders to see what effects changes in one variable have on others. For example, the proportion of material from households sent for reuse could be included, but not the variables that determine why they do so. However, this could be misleading if the relationships are too simplified.
- A version of the full model could be developed only for a particular product type and/or type of waste about which there is enough evidence, and then parameterised.

6.4.2.2 Use of the Model to Explore Wider Questions

There are many interesting questions that the model could be used to investigate. For example, increases in material flows in the WP pathways would likely lead to decreases in the rate of waste generation; however, it is not clear what impact this would have on overall economic activity and thus on waste intensity. We would expect to see a net benefit from reduced waste on the supply side. Increasing economic activity in the sectors that service the WP pathways – the repair industry, remanufacturers, and traders in second hand goods – would benefit the economy in general unless these are done through unofficial channels. The well-articulated statement of structure provided by the model (as identified in the collection of stocks in the model) invites several avenues of further enquiry at a higher level, over a longer time frame, and focusing on the relationship between structure and agency:

- Is the "system that produces waste" in fact dominated by structure and one in which agency has little effect, or is there potential for bottom-up change?
- What top-down structural and policy changes would improve the take up of WP practices and what secondary effects could these changes provoke? Who is best placed to instigate these changes?
- What evolution of structure could happen through bottom-up social movements regarding waste and consumption?
- At what level within the structure would it be best to apply policy – macro, micro, individual or organisational, or a combination of all of these?
- How long does it take for change to permeate the system, and how large does the imperative to act have to be to initiate change?

6.4.3 Future Development of the PPR Model

The recycling model has undergone rapid transition from an initial design to a reasonably complex simulation model backed by stakeholder knowledge and available data. It is paramount, however, that the model development be continued if it is to realise its true potential in the support of policy options. However, even without this further development, the model still provides benefits in the form of captured knowledge about system performance and the system structures thought to be responsible for certain observed behaviours. As a knowledge management tool, therefore, the model has already proven to be of some benefit. Specific areas of needed improvement include:

Imports and exports: The interactions (imports and exports) between the UK industry and international markets cannot be ignored. Currently, the PPR model is unable to explicitly represent the interactions between quality, cost, demand and the international market for recycled materials. In this current model, simple assumptions are made regarding the relative advantage of exports versus provision of material to domestic PRFs and reprocessors, and for the sourcing of material by PRFs and reprocessors from overseas. The issue of quality of material interacts strongly with this issue.

Data Repository: The current Excel spreadsheet used by the model only contains a subset of the data required by the model. In this early stage of model development and learning about the system, and given the limited resources allocated to the project, it became impractical to add all data elements while the model was being developed (although this is now in the process of being developed). Many variables were renamed or even removed as alternative structures were examined. In a more mature model the spreadsheet include all parameter values required.

Other Materials: Once the model has been made more robust for PPR, it could be extended to include other packaging materials such as glass or aluminium. This was originally intended, but time did not allow for it within the project timeframe (collecting data on a particular material stream e.g. plastics from all the different data sources can take considerable effort/time).

Business Models: It would be helpful to develop detail and more theory on how business models used in the waste management industry differ from other standard business models. We might evaluate whether all of Sterman's business assumptions are relevant and applicable to waste management industries.

Adding Detail: The model would benefit from further exposure to policy makers and other experts in the field with the emphasis on identifying those influences most likely to affect the UK share of demand at each stage in the PPR supply chain. Tasks would include adding detail to the model in several areas:

- **Data collection and validation**
  - Market for all plastics
  - Prices paid for plastics in global markets.
  - Further enhancements of data on recycling collections and capacities within the industry
- **Model improvements**
  - Model of virgin plastic / recycled plastic price interactions
  - Explicit representation of plastics by polymer type, which may lead to a neat way to represent quality dynamics more effectively
  - Better representation of international markets and UK position within the market

Outstanding Questions: At the end of the project, after a review of the draft report several questions were posed by policy makers working in recycling. They are a good example of the iterative development needed to create a robust and useful model, in which models are built, run, reviewed and updated, and further evidence is added. There was not time to respond fully to these questions and so they are documented here as points to address if and when the model is further developed.

- Section 5.2.2.1
  - A request for more detail on the basis for the proportional assumption on the split between kerbside waste sent to domestic reprocessors, PRFs, or for export.
- Section 5.2.2.2
  - A question on the use of principles used by Sterman in (Sterman 2001) and whether they hold true for waste, where there is a limited amount being produced each day, compared to the business case where production capacity is constantly being adjusted to meet changes in demand.
  - A question about the calibration process which set initial conditions to desired values, and whether this causes any problems with calibration.
- Section 5.2.2.3
  - Whether there are any behavioural limitations to the growth rate in recycling participation.
- Section 5.2.6.1
  - A question about the rationale for using a modified version of the Sterman commodity cycle model (Sterman 2000) to model influences on PRN/PERN prices.
- Section 5.3.3.2
  - A comment that the PRN/PERN price would have to be very low in order for recycling notes not to be issued, as paper PRNs are around £1 and still get issued
  - A request for documentation on how the adjustment was made to account for the volume of material passing through without PRNs/PERNs being issued.
  - A challenge on the causes of the cyclic nature of the model – the PRN shows cyclic behaviour because the target is set and everything else has to adjust to meet it.

- Section 5.3.3.11
    - A question about whether the downwards trajectory is just projecting a trend from current figures.
    - A request for a summary of what types of calibration seem to work (or not), and why.
- Section 5.4.2.4
    - A question about baseline costs to LA – whether the cost is the total collection costs for all packaging or collection costs for households, or for municipal waste.
- Section 5.4.2.5
    - Whether revenues that rise to over M£100 are total revenues.
- Section 5.5
    - A request for more detail on the top ten inputs influencing the reported recycling rate, and whether they are as expected.

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8.0 APPENDIX A: System Dynamics Theory and Conventions

This section defines conventions used in this report with regard to SD modelling. It also provides some background on the SD approach. However, this is not by any means a definitive or comprehensive description of the SD approach; it merely provides the background the authors felt was necessary for any newcomer to SD to understand this report. Suggested further reading on SD is provided at the end of this section.

8.1 General Conventions

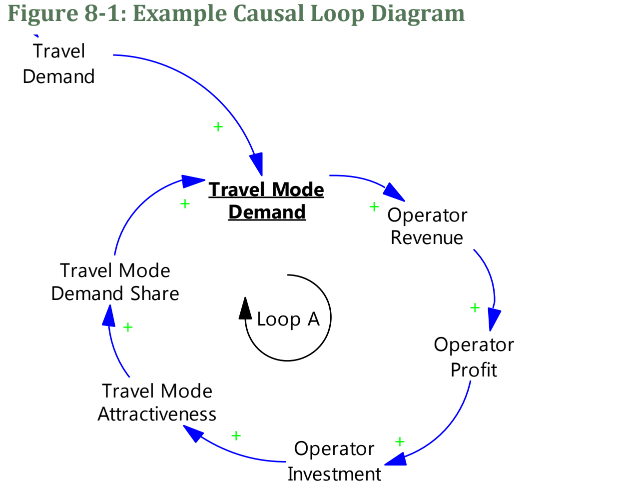
- Variable names in the model are written in *italics*.
- Shadow (or ghost) variables are elements of the model existing in another module (view) but replicated for use within the current module. They take the appearance of the original variable surrounded by "<>", such as *vehicle sales* becoming *<vehicle sales>*.
- Feedback loops are indicated by a circular symbol with an arrow head containing a "+" sign (or "R" for reinforcing), or a "–" sign (or "B" for balancing).

8.2 Causal Loop Diagrams

Causal Loop Diagrams (CLDs) consist of variables connected by arrows, which represent causal links between the variables. Each causal link is assigned a polarity, either positive (indicated by a "+" sign) or negative (indicated by a "-" sign) to indicate how the dependent variable changes due to a change of the independent variable. The addition of two parallel lines to an influence arrow indicates that there is a delay in the causal influence. Important feedback loops are highlighted by a loop identifier, which shows whether the loop is a positive (reinforcing, "R") or negative (balancing, "B") feedback.

A simple example of a CLD is shown in Figure 8-1. Its dynamic hypothesis is explained as follows:

Figure 8-1: Example Causal Loop Diagram



Travel Demand determines the *Travel Mode Demand*. The "+" sign next to the arrow head denotes that, all else being equal, a rise in *Travel Demand* will lead to a rise in *Travel Mode Demand*. A rise in *Travel Mode Demand* will increase *Operator Revenue*, and in turn *Operator Profit*. This allows for greater investment by the operator in their mode of transport – improving equipment stock or infrastructure – which would positively influence the *Travel Mode Attractiveness.* The more attractive the travel mode, the greater share of *Travel Demand* will be met by that mode.

There are two types of feedback loop; positive or reinforcing loops, and negative or balancing (controlling) loops. The example above is a positive feedback loop. An example of a negative feedback loop would be the impact of economic growth on mineral resource markets. Economic growth leads to increased demand for mineral resources, which in turn leads to higher market prices for these resources. However, higher resource prices lead to higher prices for consumer and capital goods, which in turn eventually dampens demand in the broader economy, thus reducing pressure on resource prices. The interaction between these feedback loops ensures that raw material prices do not increase exponentially.

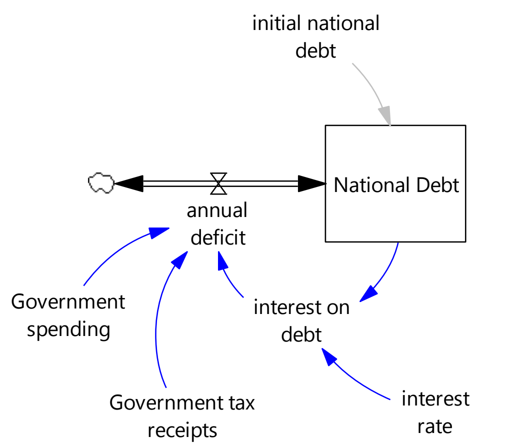
8.3 Stock and Flow Diagrams

'Stocks and flows, along with feedback, are the two central concepts of dynamic systems theory.' (Sterman 2000) Stocks (or levels) are accumulations in a system and represent the current state of that system. Stocks are shown as boxes with arrows flowing into and/or out of them, representing the flows (or rates) having influence on the stocks. For example, in Figure 8-2 the stock of vehicles currently on the road is increased by the flow of new sales each year and decreased by the flow of decommissioning of vehicles at the end of their life.

Figure 8-2: Example Stock and Flow Diagram (SFD)

Figure 8-3 shows how a stock can be influenced by additional variables as well as the flows. The national debt is changed by the flow value *annual deficit*, which is the difference between government earnings and expenditure each year. This can be positive or negative, and so the flow is shown with arrows in both directions (a bi-flow). The influences on *annual deficit* are linked into the rest of the model using arrows that show the direction of their influence. This expansion of the influences into their component parts is critical to the understanding and validation of a model. For example, *interest on debt* is calculated from the current *national debt* and the prevailing *interest rate*.

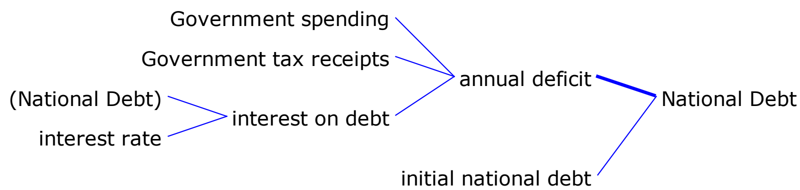
Figure 8-3: Example SFD with Auxiliaries



8.4 Causal Trees

Causal Trees™, a feature of Vensim, are a graphical representation of the structure of a model associated with a specific variable. The tree displays all the variables that cause the variable of interest and the structure by which they are related. For example, Figure 8-4 shows a causal tree for the variable *national debt*. Here, *annual deficit* and *initial national debt* are shown to influence *national debt.* In turn, *annual deficit* is influenced by *government spending, government tax receipts* and *interest on debt.* Finally, *interest on debt* is influenced by the *interest rate* and the *national debt* (shown in parentheses to indicate that it already exists in the causal tree; because it is the variable of interest there must be feedback at work).

Figure 8-4: Example Causal Tree



Complementary views to the causal tree are the "uses" tree and "causes & uses tree", examples of which are shown in Figure 8-5 and Figure 8-6.

Figure 8-5: Example Uses Tree

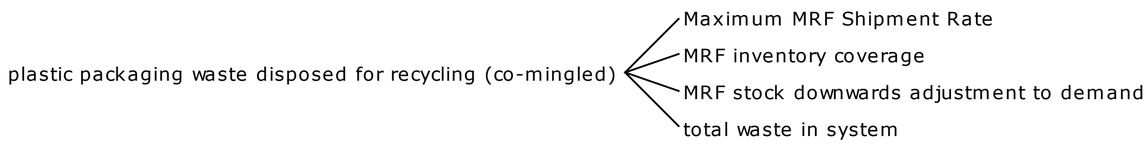
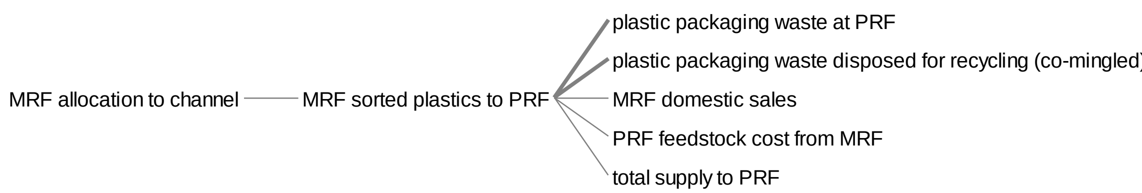


Figure 8-6: Example Causal and Uses Tree



8.5 Non-Linear Relationships and Look-up Tables

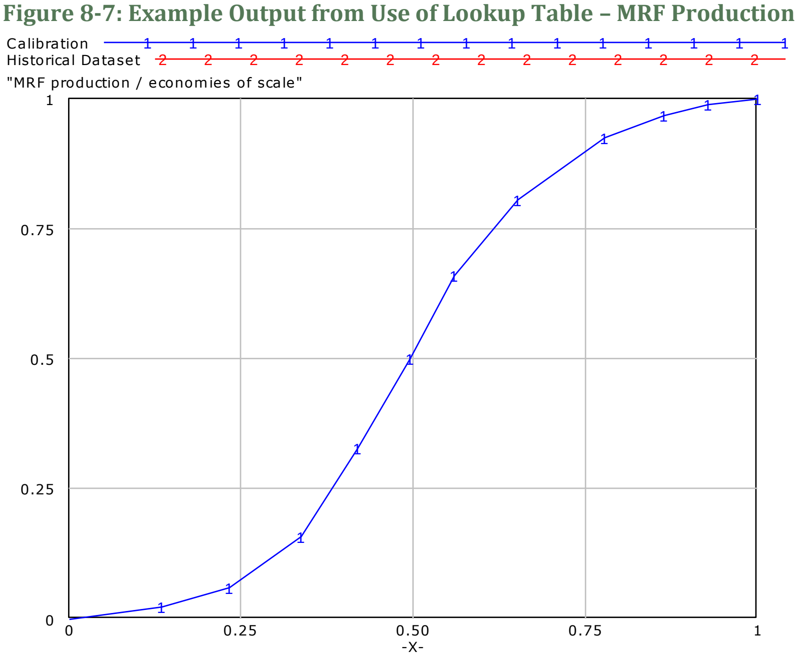
The relationship between variables in the model is most often determined by a simple mathematical equation. In some cases, where relationships are not easily defined by a linear type equation, a lookup table of related data is used to characterise the relationship. Lookup tables are a standard approach to representing non-linear relationships between two variables in system dynamics. In "Business Dynamics" (Sterman 2000) Sterman provides guidelines for the formulation of such lookup tables:

1. Normalise input and output;
2. Identify reference points where the values are determined by definition;
3. Identify reference policies;
4. Consider extreme conditions;
5. Specify the domain of the independent variable so it includes the full range of possible values;
6. Identify the plausible shapes for the function within the feasible region defined by the extreme conditions, reference points and reference policy line;
7. Specify the values for the graph points using data, where available, but also judgemental estimates which can sometimes *'provide sufficient accuracy, particularly early in a project, and help focus subsequent modelling and data collection efforts'* (ibid)
8. Run the model and test behaviour is reasonable
9. Test the sensitivity of the results to plausible variations in the values of the function.

An example of this process, as used during development of the recycling model, is described below. It links production capacity in the materials recovery industry with economies of scale, where cost per unit depends on the size of the industry. The resultant relationship between variables is shown in Figure 8-7.

- The MRF capacity rate and effect of economies of scale on MRF costs were normalised
- Two reference points were identified: at full achievement of the base MRF production capacity for economies of scale the full impact of economies of scale would result (data point 1,1 on the table); a zero MRF capacity rate would achieve zero economies of scale (0,0)
- A reference policy was identified: the 45 degree straight line from (0,0) to (1,1) represents that economies of scale increase 1% for every 1% change in production capacity
- Extreme conditions (no production or huge production) were seen to achieve zero and full economies of scale;
- Initial increases in MRF or PRF capacity are assumed to result in increases of economies of scale below the 45 degree reference policy line. Towards the maximum extreme of production capacity influence on economies of scale, the law of diminishing returns dictates a slow-down in the increase in economies of scale, resulting in the shape shown in Figure 8-7.

Figure 8-7: Example Output from Use of Lookup Table – MRF Production vs. Economies of Scale



The use of lookup tables can sometimes cause problems when it comes to calibration and parameter estimation, especially when data is scarce. In such cases, the calibration routines in Vensim can select sensible values for the reference dependent and independent variables in addition to the sensitivity index. For example, the relative cost of recycling can have an influence on the amount of material collected by LAs for recycling. To determine this relationship, the *relative cost of recycling* was compared with a reference value (*reference relative cost of recycling*) and translated into a recycling fraction through the use of the *sensitivity of collection to relative recycling cost* input assumption.

8.6 Subscripts

Subscripts are a particular feature of Vensim, enabling repetition of structure. For example, in Figure 8-3 subscripts could be used to further elaborate on the various streams of *government spending*: Health, Education, Pensions, Defence, Welfare, Protection, and Transport. To accomplish this in Vensim, a subscript *range* would be created, called “government spending category”, and the subscript *elements* (listed above) added. If *government spending* is subscripted by the subscript range *government spending category* then it will allow for the spending of each and every category in the range. It follows that categories can be changed, added or removed without changing the structure of the model, simply by changing the list of subscript elements.

8.7 Calibration

Calibration involves finding the values of model constants that make the model generate behaviour curves that best fit the real world data. Manual calibration is a slow, painstaking process involving manipulation of the input assumptions, the running of the model, and the visual assessment of ‘goodness of fit’ for a range of performance indicators. Over the years, SD software tools have evolved in order to assist in this process, the most notable being the use of optimisation algorithms.

In the so-called ‘calibration optimisation’, the payoff is calculated as the accumulated differences between each historical and model-generated data point, the minimisation of which will result in a tendency to select model constant values minimising the difference between the historical data and the results generated by the model over the same historical period. Once a good fit has been achieved, the software provides a list of the constant values selected during calibration and these can be automatically used as input assumptions for future simulation runs.

8.8 Validation

What is validation? One definition from (Gross 1999) is: *‘In computer modeling and simulation, the process of determining the degree to which a model or simulation is an accurate representation of the real world from the perspective of the intended users of the model or simulation.’* However, (Sterman 2000) states that *’no model can ever be verified or validated. Why? Because all models are wrong’*. More useful definitions of a validated model might be a model that is “useful”, “illuminating”, “convincing” or “inspiring confidence”, rather than simply being “valid”.

In whatever way it may is defined, some level of validation can be achieved via three types of actions:

1. Including policy makers and subject matter experts (the client) in the model development process, allowing them to provide feedback on the model as it is being built. Frequent client feedback brings important project benefits:
    - The client can regularly inspect inputs, outputs, and detail granularity of the model to ensure relevance to the target decisions
    - The client can contribute knowledge towards on-going tests of the model framework, improving reliability
    - Client participation in the model evolution develops familiarity and expertise, which are the basis of model credibility
    - As client personnel become familiar with possible uses for the model, they can direct choices of data management, interface, and organisational process to be optimal.

2. Ensuring model and process transparency. The elicitation and understanding of the problem owners' "mental models" of the real world are central to the successful application of SD. These personally-held hypotheses are derived from information feedback received from direct and indirect observations of the "real world". One important contribution to be made by the SD methodology is to provide a further signal enhancing, testing and validating these mental models. This enables multiple world views to be tested, rejected, negotiated and reformulated. The modelling process should be as transparent as possible to the problem owners – after all, they are ultimately responsible for implementing policy decisions in the real world. Policy makers need to have a significant degree of confidence in the modelling process in order to use the results of the model.
3. Enhancing model robustness and reliability. Confidence in the validity of the model is paramount to its successful use as a tool to inform decision making. One leg to the confidence table is the capability of reproducing past performance; that is, the ability to simulate a period of time over which there exists sufficient data on the key stocks and flows in the system being modelled – for example, commodity prices for an oil production model, sales history for a marketing model, production costs for a manufacturing model. If the model can be shown to closely replicate historical behaviour *for the right reasons* then the user will have greater confidence in the lessons learned from the simulator. Recent software and hardware improvements in SD modelling have enabled increasingly complex representations of reality to be developed and have made the task of calibration to historical data easier.

9.0 APPENDIX B: Detailed Description of Meadows' Places to Intervene

Title	Explanation
Numbers: constants and parameters such as subsidies, taxes, standards	Numbers can increase or decrease flow rates, and often seem highly important to those directly affected by flow rates. But changing these variables rarely changes the behaviour of the system. Parameters can become leverage points when they are set within ranges that kick off one of the other leverage points; they can control the gains around reinforcing feedback loops.
Buffers: the sizes of stabilising stocks relative to their flows	In some cases, systems can be stabilised by increasing the size of buffers, such as the level of inventory or the size of water reservoirs. But when buffers are too large they can make the system less flexible and able to respond. Changing the size of buffers can take a long time.
Stock and Flow Structures: physical systems and their nodes of intersection	Stocks and flows and their physical arrangement can have a huge effect on how a system operates. If a system is laid out poorly, the only way to fix it is to rebuild, if possible, but often physical rebuilding is the slowest and most expensive type of change, and sometimes there's not much that can be done about it. Physical structure is rarely a leverage point; the real leverage point is in good initial design. Once a structure is built, leverage can be found in understanding its limitations and bottlenecks, using it with maximum efficiency, and avoiding straining its capacity.
Delays: the lengths of time relative to the rates of system changes	Delays are critical determinants of system behaviour and common causes of oscillations e.g. the length of time it takes to build infrastructure or bring a new technology to market. Delays in feedback are critical relative to the rates of change in the stocks the feedback loop is trying to control. If they are too short they cause over reaction (chasing tails), and if too long they can cause damped, sustained or exploding oscillations. Delays are often not easily changeable, and it's usually easier to slow down the change rate.
Balancing Feedback Loops: the strength of the feedbacks relative to the impacts they are trying to correct	Balancing loops enable systems to self-correct, and some are only active in extreme conditions (although essential at those times). The strength of balancing loops depends on accuracy of monitoring, speed and power of response, and directness and size of corrective flows. For example, the market can be self correcting but only if prices include the full cost of impacts. Policy can strengthen and clarify market signals by creating a level playing field. The strength of a balancing loop is important relative to the impact it is designed to correct.
Reinforcing Feedback Loops – the strength of the gain of driving loops	Reinforcing loops are self-reinforcing and the sources of growth, erosion, and collapse in systems. Examples include population (more people born, more people grow up to have children) and interest (more money in the bank, more interest earned, more money in the bank). An unchecked reinforcing loop will eventually destroy itself, or a balancing loop will kick in at some point. Reducing the gain in a reinforcing loop is usually more powerful than strengthening related balancing loops. Leverage points can be found around birth rates, "success to the successful" loops, erosion rates – anywhere that the more you have the more possibility of having more.
Information Flows: the structure of who does and does not have access to information	Adding information can be a high leverage point; it delivers feedback to a new place; it can be easier and cheaper than rebuilding infrastructure. For example, fisheries may crash when there's little feedback about the state of the fish population going into the decision to invest in fishing infrastructure. In fact, the price of fish goes up as fish become more scarce, leading to more incentive to catch fish – a reinforcing loop that leads to collapse. The problem is that the information needed is not price but rates of change in population. Information also needs to be in a compelling form – e.g. pricing resources higher as they get scarcer. A lack of information feedback is often due to a desire to avoid accountability.
Rules: Incentives, punishments, constraints	Rules define a system's scope, boundaries, and degrees of freedom. There are social rules such as a constitution, absolute rules such as physical laws, and other types such as laws, punishments, incentives, and informal social agreements. Rules are high leverage points, which is why there is so much lobbying when rules are made. Rule making that does not allow for feedback from different sectors of society can lead to trends such as "race to the bottom" between countries, as nations compete to reduce environmental and social safeguards to attract corporate investment.

Self-Organisation: the power to add, change or evolve system structure	Self-organisation is the ability of a system to change itself by creating new structures and behaviours. It can lead to changing any aspect of a system that's lower on this list (6 to 12). Self-organisation enables systems to be more resilient. It can be governed by rules that define how, where and what the system can add onto or subtract from itself and under what conditions. The diversity of human cultures are the stock out of which social evolution can arise, and the more cultures become homogenised, the less learning and resilience. The intervention is to encourage variability, experimentation and diversity.
Goals – the purpose or function of the system	The goal of a system is a higher leverage point than all of the previous ones, which can be twisted to conform to the system goal. People within systems often don't recognise what the system goal is. For example, the corporate goal of "more profits" is a rule to allow it to continue trading, but the point of the game is to increase market share and ultimately to "engulf everything". This is bad when it isn't balanced by higher level balancing loops. The goal of keeping populations in balance has to trump the goal of each population to reproduce without limit. A single person can have the power to change the system goal when he or she is at the top, swinging the whole system off in a new direction.
Paradigms: the mind-set out of which the system – its goals, structure, rules, delays, parameters - arises	The shared idea in the minds of society and peoples' unstated assumptions constitute the society's paradigm, or deepest set of beliefs about how the world works. Paradigms are the sources of systems. From them come system goals and information flows, feedback, stocks, flows, and everything else. Although they hold great potential, paradigms are the hardest thing to change in a system. The paradigm of a single individual can change in a second, but societies will strongly resist a challenge to their paradigm. A societal paradigm can be changed by pointing out the anomalies and failures of the old one, and speaking and acting loudly from the new one; by working with active change agents and the vast middle ground of people who are open-minded. Systems modellers change their paradigm by building a model of the system, which takes them outside it and enables them to see it whole.
Transcending Paradigms	To keep oneself unattached in the arena of paradigms, to stay flexible, to realise that no paradigm is "true", is to understand the paradigm that "there are paradigms" and thus to embrace not-knowing. This can be a basis for radical empowerment. If no paradigm is right, you can choose whichever one helps you to achieve your purpose.

(adapted from (Meadows & Wright 2009)*)*

10.0 APPENDIX C: Parameters, Range and Calibration Values for Variables in the PPR Model

1) 20000 <= initial PRF push rate = 49313.7 <= 70000
2) 10 <= reference cost of prf = 20 <= 120
3) 0.5 <= MRF Channel priority weight[MRF Export] = 0.751423 <= 2
4) <= MRF Channel priority weight[MRF to PRF] = 1.99999 <= 2
5) 0.5 <= PRF Channel priority weight[PRF Export] = 1.92714 <= 2
6) 0.25 <= MRF stock adjustment period = 0.5 <= 3
7) <= collection policy change period[Household] = 6.4505 <= 12
8) 0.5 <= collection policy change period[Commercial] = 1 <= 12
9) -3 <= sensitivity of collection to relative recycling cost[Household] = -2.99989 <= 1
10) -3 <= sensitivity of collection to relative recycling cost[Commercial] = -0.876353 <= 0.95
11) 0.6 <= reference relative cost of recycling[Household] = 0.650941 <= 0.95
12) 0.6 <= reference relative cost of recycling[Commercial] = 0.73398 <= 1.4
13) 0.25 <= reference fraction of plastic packaging waste sent for recycling[Household] = 0.63048 <= 0.75
14) 0.25 <= reference fraction of plastic packaging waste sent for recycling[Commercial] = 0.280524 <= 0.75
15) <= initial recycling participation = 0.425114 <= 0.5
16) 0.0625 <= initial fraction of plastic packaging waste sent for recycling[Household] = 0.199547 <= 0.2
17) 0.0625 <= initial fraction of plastic packaging waste sent for recycling[Commercial] = 0.274705 <= 1
18) <= growth rate in recycling participation = 1.44576 <= 9
19) <= multiplier of UK reprocessed plastic demand = 1.5 <= 2
20) 1.2 <= "multiplier of collection data to account for losses and non PRN/PERN" = 1.83345 <= 1.9
21) 0.4 <= plastic packaging reprocessing as fraction of total = 0.831624 <= 1
22) 0 <= initial fraction accredited reprocessors = 0.680879 <= 1
23) 0 <= initial fraction accredited MRF = 0.787873 <= 1
24) 10 <= reference MRF cost = 108.514 <= 190
25) 100 <= reference cost of reprocessing = 516.352 <= 1000
26) 0.25 <= PRF stock adjustment period = 0.438472 <= 0.95
27) 0.0625 <= desired PRF inventory coverage = 0.855292 <= 0.95
28) 0.0625 <= desired reprocessor inventory coverage = 1 <= 1.5
29) 0.2 <= fraction of UK reprocessor demand from PRF = 0.497651 <= 0.5
30) 0.25 <= reference fraction accredited reprocessors = 0.766942 <= 1
31) 0.25 <= reference fraction accredited MRF = 0.455612 <= 1
32) 0.92 <= quality of MRF = 0.949999 <= 0.95
33) 0.92 <= quality of plastic packaging waste = 0.949993 <= 0.95
34) 0.25 <= "% of residual waste going to landfill" = 0.714645 <= 0.95
35) 0.001 <= Reference Inventory Coverage = 0.0659573 <= 0.15
36) 0.01 <= Reprocessor Reference Inventory Coverage = 0.0711816 <= 0.375
37) 0.01 <= MRF reference Inventory Coverage = 0.0271116 <= 1
38) 0.01 <= PRF reference Inventory Coverage = 0.0139547 <= 1
39) 0.01 <= MRF target markup = 1.53724 <= 3
40) 0.01 <= PRF target markup = 0.420922 <= 3
41) 0 <= fraction of PERN income passed on = 0.652322 <= 1
42) 0 <= fraction of PRF PERN income passed on = 0.689893 <= 1
43) -6 <= sensitivity of Price to MRF Inventory Coverage = -0.017014 <= -0.01
44) -6 <= sensitivity of Price to PRF Inventory Coverage = -0.265405 <= -0.01
45) 0.125 <= fraction of PRN income passed on = 0.999896 <= 1
46) 0.1 <= sensitivity of MRF accreditation to PRN price = 0.11763 <= 6
47) 1 <= MRF investment period = 4.41628 <= 5
48) 1 <= PRF investment period = 1.05348 <= 5

49) 1e+006 <= base MRF production capacity for economies of scale = 3.0952e+006 <= 1.05e+007
50) 1e+006 <= base PRF production capacity for economies of scale = 1.04845e+007 <= 1.05e+007
51) 500000 <= base reprocessor production capacity for economies of scale = 506595 <= 1.05e+007
52) 0.5 <= Reprocessor margin expectation smoothing period = 6.75 <= 10.125
53) 0.125 <= MRF margin expectation smoothing period = 3 <= 4.5
54) 0.125 <= PRF margin expectation smoothing period = 0.836389 <= 3
55) 0.1 <= reprocessor accreditation response period = 0.323098 <= 3
56) 0.2 <= MRF accreditation response period = 1.10121 <= 6.75
57) 10 <= reference PRN Price for reprocessor participation = 22.9333 <= 30
58) 5 <= reference PRN Price for MRF participation = 14.9036 <= 30
59) 0.2 <= sensitivity of reprocessor accreditation to PRN price = 0.424661 <= 6
60) 21.2 <= Initial expected PRN Price = 39.677 <= 126
61) -2 <= sensitivity of Price to Inventory Coverage = -1.34682 <= -0.75
62) 0.75 <= reprocessor target markup = 2.60753 <= 3
63) -1.8 <= sensitivity of Price to reprocessor Inventory Coverage = -0.188354 <= -0.1
64) 0.125 <= Coverage Perception Time = 0.701093 <= 7.5
65) 0.1 <= sensitivity reprocessor investment to projected profitability = 0.232034 <= 3
66) 0.1 <= sensitivity MRF investment to projected profitability = 0.884902 <= 3
67) 0.1 <= Time to Adjust Traders' Expected PRN Price = 1.5 <= 2.25
68) 0.64 <= reprocessing investment period = 3.45513 <= 5

11.0 APPENDIX D: Values Used in PPR Model Baseline Scenario

Parameter Name	Subscript	Value	Units
% of residual waste going to landfill		0.83	Dmnl
annual change in non consumer plastic packaging waste		0.02	tonne/Year
annual growth in fraction of plastic packaging waste collected separated	Household	0.00	tonne/Year
annual growth in fraction of plastic packaging waste collected separated	Commercial	0.00	tonne/Year
annual growth in global demand for plastic		0.01	tonne/Year
base MRF production capacity for economies of scale		419,467	tonne/Year
base PRF production capacity for economies of scale		3,617,630	tonne/Year
base reprocessor production capacity for economies of scale		502,624	tonne/Year
collection policy change period	Household	1.00	tonne/Year
collection policy change period	Commercial	1.00	tonne/Year
Coverage Perception Time		0.22	Years
desired PRF inventory coverage		0.42	Year
desired reprocessor inventory coverage		0.50	Year
end time scenario packaging waste improvement		2,015	Year
export tariff		0.00	Dmnl
export transport cost		56.00	gbp/tonne
extra		1.00	Dmnl
FINAL TIME		2018	Year
fraction consumer away from home waste collected		0.02	Dmnl
fraction of PERN income passed on		0.96	Dmnl
fraction of PRF PERN income passed on		1.00	Dmnl
fraction of PRN income passed on		1.00	Dmnl
fraction of UK reprocessor demand from PRF		0.60	Dmnl
future annual increase in landfill tax		0.00	Dmnl/Year
future annual increase in obligation		0.00	Dmnl/Year
future export demand change		1.00	Dmnl
future export demand change time		2015	Year
growth rate in recycling participation		3.64	Percent/Year
increase landfill tax until		2020	Year
increase obligation until		2020	Year
Initial expected PRN Price		43.18	gbp/tonne
initial fraction accredited MRF		0.15	Dmnl
initial fraction accredited PRF		1.00	Dmnl
initial fraction accredited reprocessors		0.71	Dmnl
initial fraction of plastic packaging waste collected separated	Household	0.25	Dmnl
initial fraction of plastic packaging waste collected separated	Commercial	0.90	Dmnl
initial fraction of plastic packaging waste sent for recycling	Household	1.00	Dmnl
initial fraction of plastic packaging waste sent for recycling	Commercial	0.35	Dmnl
initial Global demand for reprocessed plastic		6,250,000	tonne/Year
initial MRF utilisation		0.75	Dmnl
initial non consumer plastic packaging waste		654,000	tonne/Year
initial PRF push rate		62,163	tonne/Year
initial PRF utilisation		0.90	Dmnl
initial prop plastic which comes under obligation		0.20	Dmnl
initial recycling participation		0.02	Dmnl
initial reprocessor utilisation		0.65	Dmnl
INITIAL TIME		2001	Year

Parameter Name	Subscript	Value	Units
integer type		0.00	Dmnl
landfill gate fee		20.00	gbp/tonne
landfill tax experiment time		2015	Year
max MRF economies of scale effect on costs		0.41	Dmnl
max PRF economies of scale effect on costs		0.50	Dmnl
Max PRN ratio of recovered plastic price		0.50	Dmnl
max reprocessor economies of scale effect on costs		0.74	Dmnl
Minimum MRF Processing Time		0.10	Years
Minimum PRF Processing Time		0.10	Years
minimum PRN Price		1.00	gbp/tonne
Minimum PRN Processing Time		0.01	Years
Minimum Reprocessor Processing Time		0.10	Years
MRF accreditation response period		0.10	Year
MRF Channel priority weight	MRF Export	0.78	Dmnl
MRF Channel priority weight	MRF to PRF	3.00	Dmnl
MRF Channel priority weight	MRF to Reprocessor	1.00	Dmnl
MRF Coverage Perception Time		0.97	Years
MRF export unit revenue		0.80	Dmnl
MRF investment period		2.77	Dmnl
MRF margin expectation smoothing period		4.50	Dmnl
MRF reference Inventory Coverage		1.00	Years
MRF stock adjustment period		1.07	Year
MRF target markup		3.00	Dmnl
multiplier of collection data to account for losses and non PRN/PRN		1.60	tonne/Year
multiplier of UK reprocessed plastic demand		1.21	Dmnl
obligation experiment time		2018	Year
override accreditation		0.00	Dmnl
percent		100	Percent
plastic packaging reprocessing as fraction of total		0.67	tonne
PRF accreditation response period		0.20	Year
PRF Channel priority weight	PRF Export	2.94	Dmnl
PRF Channel priority weight	PRF to Reprocessor	1.00	Dmnl
PRF cost premium		1.20	Dmnl
PRF Coverage Perception Time		0.10	Years
PRF export unit revenue		1.00	Dmnl
PRF investment period		0.80	Year
PRF margin expectation smoothing period		0.25	Year
PRF relative import cost		0.90	Dmnl
PRF stock adjustment period		0.50	Year
PRF target markup		0.63	gbp/tonne
priority type		1.00	tonne
priority width		5.00	tonne
proportion consumer packaging away from home		0.16	Dmnl
quality of MRF		0.95	Dmnl
quality of plastic packaging waste		0.95	Dmnl
quality of PRF		0.92	Dmnl
quality of reprocessor		0.80	Dmnl
quality of separated plastic packaging waste		0.92	Dmnl
reference cost of PRF		82.84	gbp/tonne
reference cost of reprocessing		353.52	gbp/tonne
reference fraction accredited MRF		0.25	Dmnl
reference fraction accredited PRF		1.00	Dmnl

Parameter Name	Subscript	Value	Units
reference fraction accredited reprocessors		1.00	Dmnl
reference fraction of plastic packaging waste sent for recycling	Household	0.43	Dmnl
reference fraction of plastic packaging waste sent for recycling	Commercial	0.36	Dmnl
Reference Inventory Coverage		0.22	Years
reference MRF cost		95.00	gbp/tonne
reference PRN Price for MRF participation		45.00	gbp/tonne
reference PRN Price for PRF participation		5.10	gbp/tonne
reference PRN Price for reprocessor participation		14.47	gbp/tonne
reference relative cost of recycling	Household	1.40	Dmnl
reference relative cost of recycling	Commercial	0.89	Dmnl
reprocessing investment period		2.23	Year
reprocessor accreditation response period		0.39	Year
Reprocessor Coverage Perception Time		0.06	Years
Reprocessor margin expectation smoothing period		5.00	Year
Reprocessor relative import cost		0.90	Dmnl
reprocessor stock adjustment period		0.50	Year
reprocessor target markup		4.50	Dmnl
scenario multiplier of recovered plastic price		1.00	Dmnl
scenario multiplier of reprocessor investment		1.00	Dmnl
scenario packaging waste improvement		0.00	Percent
sensitivity MRF investment to projected profitability		0.75	Percent
sensitivity of collection to relative recycling cost	Household	-0.43	Percent
sensitivity of collection to relative recycling cost	Commercial	-0.05	Percent
sensitivity of MRF accreditation to PRN price		3.00	Percent
sensitivity of PRF accreditation to PRN price		0.43	Percent
Sensitivity of Price to Inventory Coverage		-2.58	Percent
Sensitivity of Price to MRF Inventory Coverage		-0.01	Percent
Sensitivity of Price to PRF Inventory Coverage		-4.00	Percent
Sensitivity of Price to reprocessor Inventory Coverage		-0.57	Percent
sensitivity of reprocessor accreditation to PRN price		4.09	Percent
sensitivity PRF investment to projected profitability		1.60	Percent
sensitivity reprocessor investment to projected profitability		0.03	Percent
separate waste export %	Household	25.00	tonne/Year
separate waste export %	Commercial	77.00	tonne/Year
separate waste to reprocessor %	Household	0.00	tonne/Year
separate waste to reprocessor %	Commercial	19.00	tonne/Year
start time scenario packaging waste improvement		2015	Year
TIME STEP		0.02	Year
Time to Adjust Traders' Expected PRN Price		0.66	Years
UK share of Global reprocessed plastic demand		3.25	Percent
unit cost of collection for landfill and incineration		220.00	gbp/tonne
unit cost of collection of comingled plastic		61.71	gbp/tonne
unit cost of collection of plastic (separated at kerbside)		229.71	tonne/Year
unit cost of incineration of plastic		54.00	gbp/tonne

12.0 APPENDIX D: Overview Causal Loop Diagram of PPR Model