Evidence Building for Waste Prevention: Understanding the Causal Influences that Result in Waste

Rachel Freeman[1,2], Dr Mike Yearworth[1], Dr Maria Angulo[3], Dr Tom Quested[4]

[1]Systems Centre, Faculty of Engineering, University of Bristol BS8 1TR, UK

[2]Sustain Ltd, Royal London Buildings, 42-46 Baldwin Street, Bristol BS1 1PN, UK

[3]Department for Environment, Food and Rural Affairs (Defra), Nobel House, 17 Smith Square, London, SW1P JR, UK

[4]Waste and Resource Action Programme (WRAP), The Old Academy, 21 Horse Fair, Banbury, OX16 0AH, UK

rachel.freeman@sustain.co.uk, mike.yearworth@bris.ac.uk, maria.angulo@defra.gsi.gov.uk, tom.quested@wrap.org.uk

Abstract— *Waste prevention can be viewed as a set of practices that reduce the amount of waste generated in the economy; these practices can be undertaken during the design, manufacture, distribution, use and disposal phases of the product lifecycle. A research project funded by the UK's Department for Environment, Food and Rural Affairs (Defra) applied systems methodologies to support development of new waste prevention policy in England. The project developed a system dynamics model designed to capture existing knowledge on the causal influences that lead to waste generation. The model was developed firstly through several group model building workshops with key stakeholders to produce a set of basic causal loop diagrams, and then through the development of a comprehensive system dynamics model by an expert modelling team. The key structure in the model is a flow map of materials and products through the economy; material flows are driven by the dynamics described in seven sub-models. Preliminary results from the project are presented in this paper. Policy interventions referred to in this paper are solely for the purposes of explaining the modelling approach and the views expressed are those of the authors and do not necessarily reflect those of Defra.*

Keywords—*policy development, interventions, waste prevention, sustainability, circular economy, group model building, systems thinking, system dynamics*

1 INTRODUCTION

The concept of Waste Prevention (WP) encompasses a wide range of the everyday practices and decision-making of individuals and organisations. WP can be seen as an effort to reduce the inefficient consumption of materials and increase the value or utility gained from materials in products. WP practices result in increased efficiency of material use during the design and manufacture of products and/or an increase in the useful lifetime of products. WP can include industry practices such as product lifetime stewardship and alternative consumption models (e.g. car sharing). WP practices can involve multiple actors – citizens, businesses, social enterprises, and central and local government – at every stage along the lifetime of a product. WP is a key approach to achieving more sustainable use of material resources and reducing the associated environmental impacts of waste. Some WP practices such as *'switching to longer-lasting products, modularization and remanufacturing, component reuse, and designing products with less material'* (Preston 2012) are talked about within the concept of the "circular economy", which envisions resource use occurring within closed loops so that finite resources are captured and reused instead of going into the waste system.

The revised EU Waste Framework Directive 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*[1]', known as decoupling. The UK's Department for Environment, Food and Rural Affairs (Defra) is committed to publishing the first Waste Prevention Programme for England by December 2013, which will aim to enable businesses, local authorities, and civil society to maximise 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. These combined benefits have led the EU to put WP at the top of its waste hierarchy, saying that it '*represents the most efficient and sustainable use of resources'* (European Commission 2012).

Defra is continuing to build the evidence base to support policy making for this new programme. A research project using the methodologies of systems thinking and system dynamics was run over a six month period, finishing in March 2013. The aim was to provide a more systemic understanding of the problem and enhance understanding beyond that provided by more traditional methods such as cost-benefit analysis. The project used systems modelling to bring to the surface the mental models of policy and subject experts, and to reveal the complex dynamics of "the system that produces waste" and whereabouts in that system WP practices already exist and could be expanded or could be introduced.

Causal Loop Diagramming was used at the start of the project for problem structuring. Some specific dynamics within the system were fairly well understood, such as producer responsibility or the decline of the repair industry, but the modelling of more distant relationships which include delays and several layers of interactions were less clear – such as how product design affects the ability of consumers to repair goods. Later on, system dynamics was used to model the structure of the whole system of interest. The model includes the impact of the decision making of consumers and businesses on waste generation trends, the physical infrastructure that moves materials around, and economic and policy factors.

The modelling process has so far led to:

- Development of a framework for structuring the WP problem throughout the whole economy, rather than in separate parts of it;
- New and improved shared understandings between a range of outside stakeholders, government analysts, and policy makers, established through a series of group model building days;
- A map of the physical structure of the system that produces waste and how materials flow through it;
- Development of a basic understanding of how key system variables are related and how the interactions between them have evolved over time;
- Insights into the endogenous sources of system behaviour and identification of exogenous factors (for example, international markets for raw materials).

The main expected benefit from the project is that the risk of unintended consequences from WP policies will be reduced, as cumulative and feedback effects within "the system that

[1] 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)

produces waste" are identified.

2 BACKGROUND

This section presents some relevant literature on WP practices and policy.

2.1 Relevant Literature on Waste Prevention Practices and Policy

A study by (Tucker & Douglas 2006) reveals the wickedness of the WP problem. They find that household WP behaviours: i) are largely private activities that lack explicit normative pressures and with an unknown social norm; ii) can be socially misjudged or carry an unwarranted social stigma; iii) are more heterogeneous and involve more decision points than simple behaviours like recycling; iv) are generally not recognised as part of the environmental toolkit; v) have little tangible infrastructure and are difficult to facilitate externally; and vi) are often devoid of any feedback cues. This last point, the lack of feedback cues, indicates a very weak or non-existent reinforcing loop when individuals practice WP, meaning they must get their rewards inwardly, impeding the spread and consolidation of WP.

A Discrete Event Simulation (DES) model of the causes of food waste has been developed at WRAP[2]. The model estimates the impact on food waste of household decision making about shopping, storage, and consumption of food. The model successfully explains results observed in previous research, such as the trend in food waste levels for households of different sizes and allows the effects of factors such as product shelf life and size of container to be evaluated. The application of DES to food waste provides many useful insights and suggests that systems-based approaches to improving WP in the home can increase understanding of the issues and provide estimates of the potential impact of behavioural change.

An approach to problem structuring for waste in industry is provided in (Shaw & Blundell 2010) which presents a methodology called Waste And Source-matter Analyses (WASAN). WASAN is designed to be used by industrial managers who are working to safely minimise avoidable waste by enabling them to build agreement on actions. It integrates influences from operational research, problem structuring, systems thinking, simulation modelling, and sensitivity analysis, as well as the industry approaches of Waste Management Hierarchy, Hazard Operability Studies, and "As Low As Reasonably Practicable" (ALARP). WASAN provides a method for compiling these approaches into facilitative structures that support managers in reducing avoidable waste. The paper describes its use in two problem structuring workshops conducted on radioactive waste in the nuclear industry.

Commercial and industrial organisations produce around double the tonnage of waste than households in the UK, so a large potential for reducing waste from these sectors may exist. (Brouillat & Oltra 2011) built an agent based model of the impact of environmental policy instruments for WP upon firms' innovative strategies and market structure. They found that responses to regulatory pressure are not simple, involving multiple compromises and trade-offs to be made between different characteristics of products. The authors describe policy instruments as complex objects, with their effects dependent on both the design of the instrument and the context in which it is applied. These findings are supported by (Wilson et al. 2012) who reviewed WP practices in business and found that although WP appears to be reducing overall waste generation, the quality of the evidence available is insufficient to provide statistically defendable estimates of WP's effects. This lack of a clear signal from WP interventions indicates variable implementation and success rates across industry.

A 2007 study into household WP policy options for Defra by (Eunomia Research and

[2] WRAP: www.wrap.org.uk/content/milk-model-simulating-food-waste-home-0

Consulting 2007) revealed that there were few policies in place in the UK, or any of the other countries they surveyed at that time, that have been primarily aimed at reducing waste. The authors found that although concerns about ongoing waste growth and its environmental implications had recently started to focus attention on WP, WP policy had not yet been developed and implemented in a way that is strategic enough to address the important factors of product design and delivery – through the supply chain and into consumer hands – in an integrated way. However, increasing numbers of programmes have been run in the UK that are achieving notable WP results, including the Courtauld Agreement[3], WRAP's Love Food Hate Waste[4] scheme, and the Community RePaint[5] scheme. 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.

Several barriers to WP were identified in (Brook Lyndhurst 2009), (Wilson et al. 2012), and (DEFRA 2013):

- Social norms: Accepted social standards on consumerism and waste, influencing individual decision-making
- The role of politics: WP behaviours grounded in long-standing, deeply personal beliefs and values, difficult territory for politics
- Environmental externalities: 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.
- Informational: Consumers and businesses may not be aware of the full costs of waste or preventative actions they could take to reduce it.
- Financial: WP actions may require initial investments before benefits can be realised, which can be affected by reduced access to credit.
- 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
- Competing Goals: The widespread practices of recycling and landfill diversion can act as barriers to preventing waste at source.

Because WP is a relatively new area of policy making, and because there is such a wide and difficult range of barriers to overcome, an understanding of the dynamics of waste generation throughout the system of interest is an important piece of evidence to feed into WP policy.

2.2 Systems Methodologies to Support Government Policy Making

Systems methodologies have been advocated to support policy making in selected areas of government, and so it is relevant to compare them with the more standard approach of Evidence Based Policy Making (EBPM). In (Parsons 2002) EBPM is compared with Schön's reflective practice and systems thinking. The EBPM philosophy rebuts Schön's view that the policy process is '*a swampy lowland where solutions are confusing messes'* (Schön 1991) and holds the belief that there exists some firm ground upon which can be laid some hard facts to support modernised policy-making. But because problems are constantly changing and mutating, to Schön the deficit is less to do with information than our capacity for public and private learning; institutions must be '*learning systems'*, capable of bringing about their own continuing transformation.

[3] http://sd.defra.gov.uk/2010/03/courtauld-2-aiming-for-more-sustainable-use-of-resources/

[4] www.lovefoodhatewaste.com

[5] www.communityrepaint.org.uk

Other recent works, such as that of (Cartwright & Hardie 2012), critique EBPM as only being able to show that a policy worked somewhere and at some time, which does not guarantee that it will work where we would like it to, "at this place and now". This is because the support factors required to ensure the policy would play the same causal role as in the case that provided the evidence may not be present. This is especially true when scaling up a pilot programme, when heterogeneity can cause a range of responses to the same intervention.

The structures within which WP policies would be implemented are both physical and social. While physical flows are relatively easy to identify and model, and for which there is some data available, social structures are far more "messy". Lane and Husemann see system dynamics as a suitable tool for modelling social structures, which evolve '*in forms such as laws, customs and resource allocations'* (Lane et al. 2008). These structures are encountered by individuals in their daily lives as discouraging or encouraging certain acts, and there is an on-going feedback between individuals and social systems – individuals are influenced by societal attitudes, values, and roles, which become part of their mental models; their mental models are expressed as actions within society, and these actions create new structural effects or enforce existing ones.

Part of the approach used was, therefore, to work towards gaining an understanding of the different types of structures influencing the decision making of individuals and organisations and how much agency individuals have to change their decision making. The use of system dynamics enables a grounding of this structure-agency theory through relating it to empirical data, as the effects of changing behaviours can be measured through observing changes in flows of materials and products – albeit with some delay.

3 METHOD

3.1 Modelling Purpose and Boundary

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.

After some discussion, 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 and government were excluded.

3.2 Group Model Building Workshops

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[6]. 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

[6] 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.

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 creating CLDs from scratch.

The first workshop started with a general discussion on modelling purpose and on 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. 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[7]. 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 with pencil, changed some of the connections, and added 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 model structure. At the end of the day each team again presented their models (each team produced several rather than a single CLD) to the other teams.

3.1 System Dynamics Model Building

A review of the workshop CLDs found that four main themes had emerged: consumption, reuse 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,

[7] http://vensim.com/

and it included no causality. The map was then combined with the four summary CLDs through several workdays with the project team to create a more complete system dynamics model structure, with material flows driven by the causality from sub-models. This version of the model had seven sub-models, which was necessary as the four summary CLDs produced from the first two workshops had not covered all of the dynamics needed to model the whole system of interest.

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

The next step was to document the dynamic hypotheses for each of the sub-models and to produce some relevant evidence for the hypotheses. Evidence came from data gathered on the system-wide, macroeconomic trends for key variables over the last 15 years. The data were gathered from mainly government data sources, augmented by academic and trade literature, and then analysed and compiled to show a history of different system behaviours. The dynamic hypotheses for each of the sub-models were written based on discussions from all of the workshops and evidence from the literature. The dynamic hypotheses and the available data were then compared and this comparison revealed some confirmation of hypotheses and the need to further investigate where there was ambiguity on trends.

The model is currently runnable but not parameterised with values that reflect the real world. In other words, it can show the direction of influence between variables, but not by how much variables influence each other and drive the stocks and flows.

4 RESULTS

This section provides an overview of the model structure, the Material Flows Map, and two of the sub-system models; it was not possible to include all of the sub-models due to space limitations. These are preliminary results and likely to evolve as they are shared more widely.

4.1 Overall Model Structure

The WP model's structure combines the Material Flows Map and seven dynamic sub-models (as "views" in Vensim) which drive the flows of materials through the system. Table 1 lists the main elements in the model structure.

Table 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 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

Grouping	View Name	Description
	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 1. For simplicity, this diagram does not include all of the connections between the modules and shows only a few of the key exogenous variables. Connections are material flows of different types, drivers of behaviour, and drivers of consumption. Key exogenous variables include the price of virgin materials and imported goods, and disposable income. Key endogenous variables include social norms on waste, design lifetime of goods, and producer responsibility. The model has been designed to be driven principally by consumer pull – the desire for goods by consumers – which drives the consumption of new or rented goods coming through retailers and distributors, and the take up of 2nd hand goods through the reuse/repair/remanufacture pathways. The rate and material efficiency of goods supplied to retailers by producers drives the rates of virgin materials and components supplied to them.

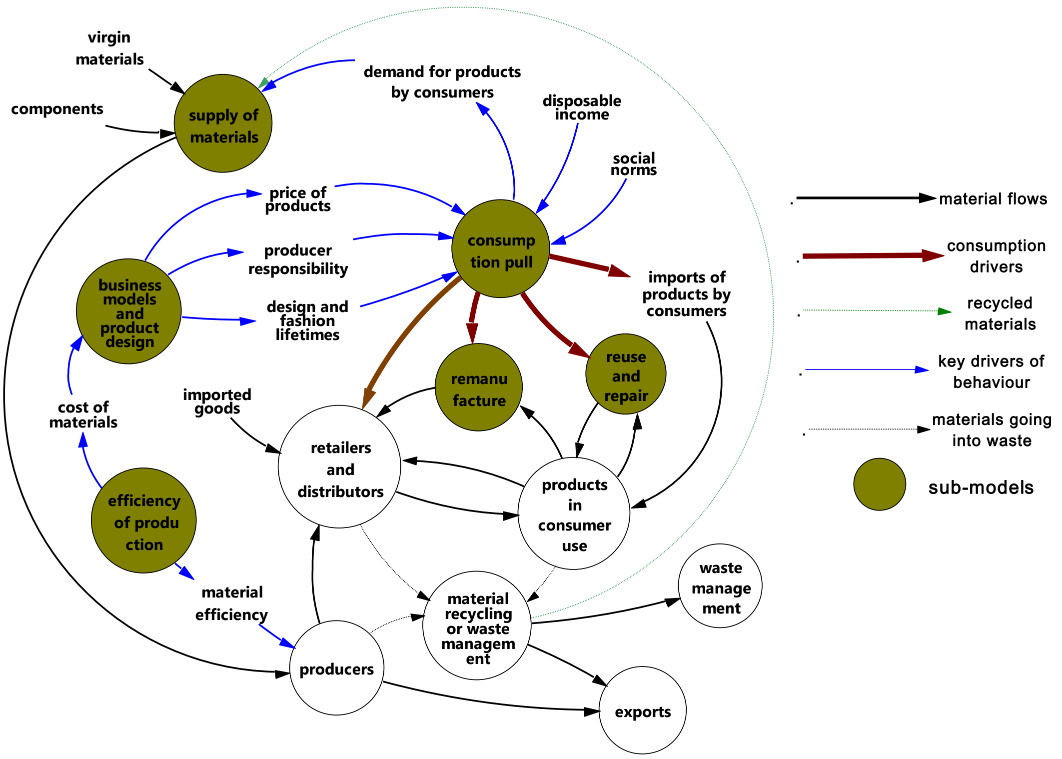


Figure 1. Model Structure Overview Diagram

4.2 The Material Flows Map

The Material Flows Map represents the modelling team's understanding of the overall physical structure of the system of interest. Materials flow into and out of the system of interest as:

- **Incoming:** Imported[8] virgin materials or components supplied to manufacturers, imported recovered materials, raw materials sourced within the UK, and materials in imported products (green);

[8] By "imported" or "exported" we mean into or out of England/ the UK.

- **Outgoing:** Exported products and exported recovered materials (purple); waste materials landfilled, incinerated (or other forms of treatment), or exported by producers, retailers, and consumers (red); and material unaccounted for and/or not measurable (orange)

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).

The flows in the Material Flows Map are driven by the decision making of three categories of actors: producers, retailers and distributors, and consumers (which can be households or organisations), which are modelled in the seven sub-models. In the left side of the map, within the producer and retailer/distributor sectors, no circularity is shown and business models drive the amount of waste generated. In the right side of the map, once products are in the hands of consumers, materials in products can "circulate" by flowing through five WP pathways, which keep them in use for longer than if they had a single owner and were thrown away when broken or not wanted.

The theory of the WP pathways, numbered in red on Figure 2 from one to five, 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*.
5. **Materials recycling:** 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.

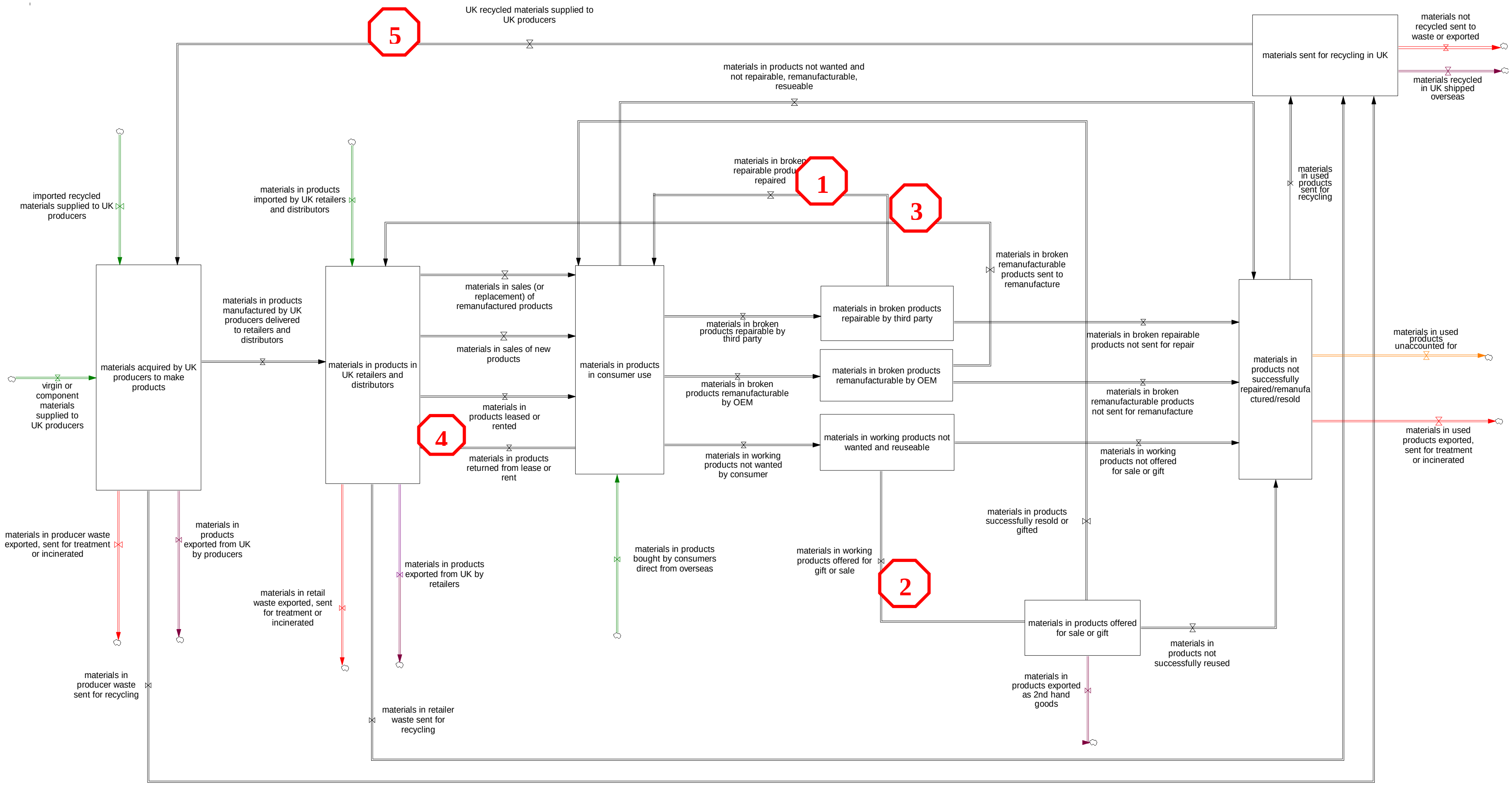


Figure 2. Material Flows Map; units are tonnes for material stocks and tonnes/year for material flows

The evidence and dynamic hypothesis for two of the sub-models follows.

4.3 Reuse Sub-Model

The Reuse sub-model drives the flow of second hand goods offered for resale or gift and the demand for second hand goods that are bought from a person or a shop or accepted as gifts. 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.

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:

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. Much of the activity in moving products from one user to another, either by gifting or selling, goes through unofficial channels such as person to person sales (e.g. classifieds, ebay), market stalls, retail buy-back schemes, leaving products on the street, or gifting of products between friends and relations. There is little data available for these types of trades.

A report by (Stevenson & Gmitrowicz 2013) examined the issue of displacement for consumer reuse practices for electronics, furniture, and textile products, displacement being defined as ‘*the quantity of second-hand purchases that have replaced what would otherwise have been a purchase of a new item’* (ibid). The study found that the average reuse displacement rate in the UK is 27%, which means that over two thirds of second hand reacquisitions are additional to new goods. The implication is that if the flows in the reuse pathway 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 reuse of products will likely delay those products from entering the waste system.

Figure 3 shows a simplified version of the Reuse sub-model diagram. 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 easier it becomes and therefore more attractive.

- The availability of second hand goods increases the relative attractiveness of acquiring products as second hand – also driven by the relative cost of new products to second hand. The percentage of second hand 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 controls 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).

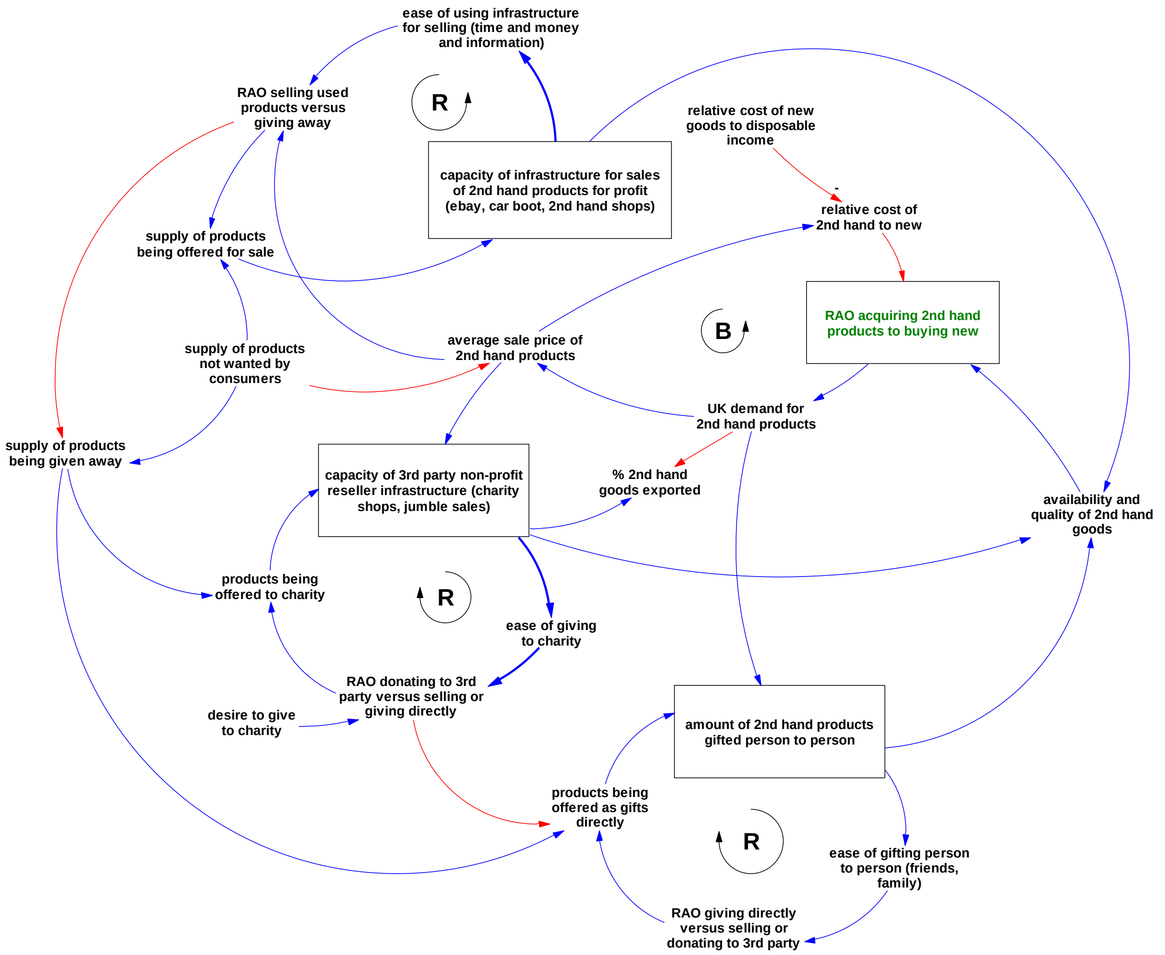


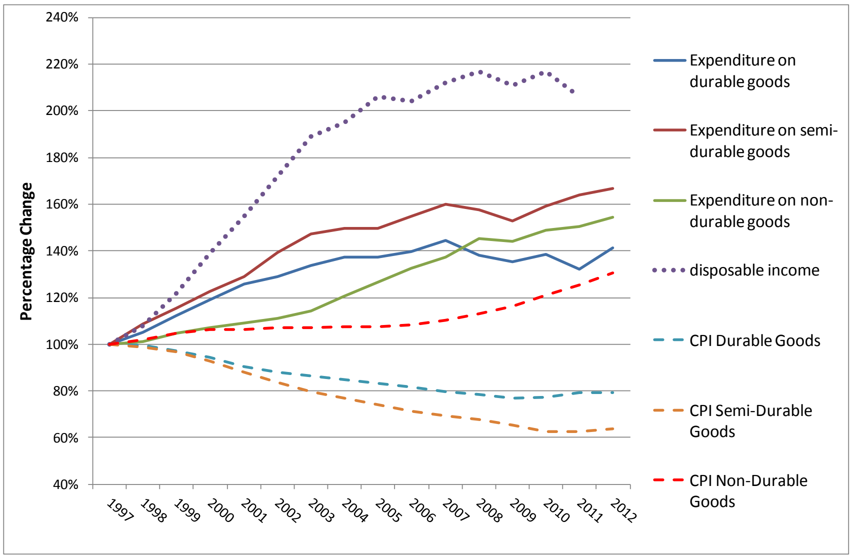
Figure 3. Reuse Sub-Model; three main paths of reuse combine to drive the total flow of reused products; the flow of products available for reuse comes from the Material Flows Map and is based on the fashion, design, or useful life of products

4.4 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.

Two statistical trends are important in this sub-model: unit profit on product sales and sales volumes. The ratio between Gross Value Added and the cost of goods, materials and services for the manufacturing, retail, and services sectors (ONS 2010) fell between 1998 and 2007 by approximately 9% for manufacturers and 15% for retailers. This suggests a fall in unit profits, although more research needs to be carried out to increase confidence in this hypothesis..

Sales volumes are usually inversely correlated with unit sales prices, everything else being equal. Figure 4 shows changes in the Consumer Price Index and household expenditure for durable, semi-durable and non-durable goods between 1997 and 2012, plus the change in median disposable income[9]. Both durable and semi-durable goods show a trend for increasing expenditure but reduced prices, indicating a larger volume of sales altogether and/or increasing preference for more high quality products. This is less so for non-durable goods, including food. Additionally, an estimate of net tonnes of products (not shown) per person supplied in the UK indicates an increase of around a third between 1997 and 2007. Thus we see indications that during this period, higher volumes of lower cost goods were bought by households (although probably not for food). Additional evidence and economic analysis needs to be carried out to increase confidence in this hypothesis.



Source: (ONS 2012b), (ONS 2012a) *and* (ONS 2012c)

Figure 4. Change in Disposable Income, Consumer Price Index, and Household Expenditure by Category

Figure 5 shows the Business Models and Design sub-model diagram. 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 very generically a business model that puts the highest priority on short term profits and minimises investment in

[9] The values shown in Figure 4 are not adjusted for inflation and inflation rates for different types of goods are different.

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 improvements 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.

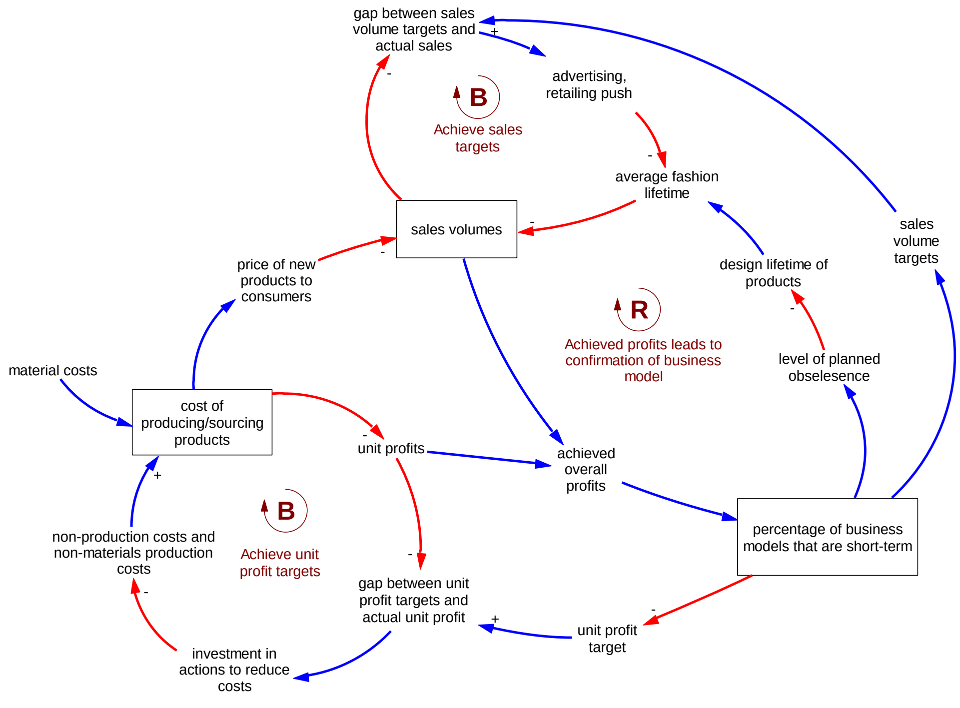


Figure 5. Business Models and Design Sub-Model

5 DISCUSSION

The Reality of WP Practice: WP practices considered in the model can be 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. 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. Influences on attractiveness include the relative cost and convenience of reacquisition versus acquiring new products for consumers, and the cost and feasibility of implementing WP within organisations. For example, for retailers to reuse materials in end of line products 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.

WP Dependency: Some WP practices are dependent on each other. There is a key dependency between 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 are offered. Thus, the model links these factors.

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 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 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: System dynamics 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. 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).

Possible Future Discussions: 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 CONCLUSIONS

This paper describes a non-parameterised system dynamics model of "the system that produces waste" in the UK, which was created to support policy making for waste prevention at the UK's Department for Environment, Food and Rural Affairs. The model's purpose was to enhance the understanding of 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/the UK, and how these drivers interact. The model identifies where within the system there are waste prevention practices happening and what enables or impedes them, and where they could be introduced. The model focuses on materials in products and related waste, excluding heavy industry and government.

The model was initiated through the creation of Causal Loop Diagrams at two group model building workshops, and system dynamics model development was continued by the project team individually and through several team model building days. Because the system of interest is so large, the model lies at a high level of abstraction, yet it provides enough detail to portray the team's dynamic hypotheses about the principal ways that materials are driven around the system, either in products or as materials. Details of the dynamic hypotheses of two of the sub-models have been presented in this paper, "Business Models and Design" and "Reuse", and some evidence is presented related to the hypotheses.

The overarching dynamic hypothesis of the model is that material flows are driven primarily by the consumption pull from consumers, which draws on six different ways to acquire goods – new, repaired, reused, remanufactured, leased or rented, or imported directly by consumers. These are linked to the other sub-models through several variables, such as the price of new goods to consumers and types of business models. Business models promote some combination of low-cost short-life products or higher cost longer-life products, or alternative consumption models that reduce the need for individual ownership. The sub-models are linked to each other through many different shadow variables.

The development of the model enabled policy makers and analysts at Defra to gain a system-wide understanding of the structure and dynamics of the whole system, which is difficult to do in a more linear way. Getting experts to create the initial models through group model building workshops meant that they had ownership in the process and could more easily understand the system dynamics model and suggest changes to it when it was presented to them. One of the benefits of this project has been that it allowed a problem structuring and interpretivist stance to be taken to view the problem of waste prevention – different from the more common functionalist policy engineering view; however, the 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 the functionalism paradigm.

The modelling process has so far led to:

- Development of a framework for structuring the waste prevention problem throughout the whole economy, rather than in separate parts of it;
- New shared understandings between a range of outside stakeholders, government analysts, and policy makers, created through a series of group model building days;
- A map of the physical structure of the system that produces waste, and how materials flow through it;
- Development of a basic understanding of how key system variables are related and how the interactions between them have been evolving over time;
- Insights into the endogenous sources of system behaviour, and identification of exogenous factors.

The model is currently runnable but not parameterised with values that reflect the real world. In other words, it can show the direction of influence between variables, but not by how much variables influence each other and drive the stocks and flows. Further model development is in progress.

ACKNOWLEDGMENTS

The authors would like to warmly thank all those experts from academia, local authorities, industry, trade bodies, research institutes, and government who participated in the group model building. The model developed through this project is a combination of their mental models, the literature, and empirical data, and we could not have created it without their input. We would like to especially thank the waste prevention policy experts from Defra, the Department for Business Innovation and Skills, and the Waste and Resources Action Programme who provided invaluable feedback to the modelling team on the model structure. Rachel Freeman's work is supported by the EPSRC funded Industrial Doctorate Centre in Systems (Grant EP/G037353/1) at the University of Bristol.

REFERENCES

Andersen, D. et al., 2007. Group Model Building: Problem Structuring, Policy Simulation and Decision Support. *Journal of the Operational Research Society*, 58(5), pp.691–694.

Andersen, D. & Richardson, G., 1997. Scripts for group model building. *System Dynamics Review*, 13(2), pp.107–129.

Brook Lyndhurst, 2009. *WR1204 Household Waste Prevention Evidence Review: Future Waste Growth, Modelling & De-coupling*, Brouillat, E. & Oltra, V., 2011. Dynamic Efficiency of Extended Producer Responsibility Instruments in a Simulation Model of Industrial Dynamics. *Industrial and Corporate Change*, 21(4), pp.971–1009.

Cartwright, N. & Hardie, J., 2012. *Evidence-Based Policy: A Practical Guide to Doing It Better*, OUP USA.

DEFRA, 2013. *Waste Prevention Programme for England: Call for Evidence*, London.

Eunomia Research and Consulting, 2007. *Household Waste Prevention Policy Side Research Programme; Final Report for Defra, WR0103_6297*, London.

European Commission, 2012. *Preparing a Waste Prevention Programme: Guidance Document,*

Lane, D., 2001. Rerum cognoscere causas: Part I: How do the ideas of system dynamics relate to traditional social theories and the voluntarism/determinism debate? *System Dynamics Review*, 17(2), pp.97–118.

Lane, D., C, A. & Husemann, E., 2008. Circe : Attending to Reinforcing Loops in Social Systems. *System Dynamics Review*, 24(1), pp.37–61.

ONS, 2010. *Annual Business Enquiry, Division by Country and Government Office Region, 1998-2007*, Available at: Division_by_Region_tcm77-237006.xls.

ONS, 2012a. *Consumer Trends 1997 to 2012,*

ONS, 2012b. *CPI: Detailed goods and services breakdown: 1996 to 2011*, London. Available at: cpidetailedreferencetablesjanuary2012_tcm77-255278.xls.

ONS, 2012c. *Growth in median equivalised disposable household income and GDP per person: % difference from 1984 level*, London. Available at: www.ons.gov.uk/ons/rel/household-income/middle-income-households/1977---2010-11/rpt--middle-income-households.html#tab-Growth-in-median-household-income-compared-with-GDP-per-person.

Parsons, W., 2002. From Muddling Through to Muddling Up - Evidence Based Policy Making and the Modernisation of British Government. *Public Policy and Administration*, 17(3), pp.43–60.

Pierce, J. & Paulos, E., 2011. Second-Hand Interactions : Investigating Reacquisition and Dispossession Practices around Domestic Objects. In *Computer Human Interface*. Vancouver BC, pp. 2385–2394.

Preston, F., 2012. *A Global Redesign? Shaping the Circular Economy; Chatham House Briefing Paper*, London.

Schön, 1991. *The Reflective Practitioner: How Professionals Think in Action*, Ashgate Publishing Limited; New edition edition.

Shaw, D. & Blundell, N., 2010. WASAN: The development of a facilitated methodology for structuring a waste minimisation problem. *European Journal of Operational Research*, 207(1), pp.350–362.

Sterman, J., 2000. *Business dynamics : systems thinking and modeling for a complex world*, Boston ; London: Irwin/McGraw-Hill.

Stevenson, A. & Gmitrowicz, E., 2013. *Study into Consumer Second-hand Shopping Behaviour to Identify the Re-use Displacement Effect*, Available at: http://www.wrap.org.uk/sites/files/wrap/Re-use displacement report executive summary v2.pdf.

Tucker, P. & Douglas, P., 2006. Understanding Waste Reduction Attitudes and Behaviours. In *Waste 2006, Sustainable Waste and Resource Management.* Stratford Upon Avon.

Vennix, J., 1996. *Group model building: Facilitating team learning using system dynamics*, J. Wiley (Chichester and New York).

Watson, M., 2008. *A Review of Literature and Research on Public Attitudes, Perceptions and Behaviour Relating to Remanufactured, Repaired and Reused Products,*

Wilson, D.C. et al., 2012. Business Waste Prevention: A Review of the Evidence. *Waste Management and Research: the Journal of the International Solid Wastes and Public Cleansing Association*, 30(9 Suppl), pp.17–28.

Yearworth, M. et al., 2013. Integrating Problem Solving and Research Methods Teaching for Systems Practice in Engineering. *Procedia Computer Science*, 16, pp.1072–1081.